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**Duke Energy**  
**Marshall Steam Station**  
**Catawba County, NC**

**Flue Gas Desulfurization (FGD) Residue Landfill**  
**Permit Application**  
**.0503(2)(d)(ii)(A) Compliance Demonstration Report**

**March 31, 2004**

**APPROVED**  
**DIVISION OF WASTE MANAGEMENT**  
**SOLID WASTE SECTION**  
**DATE 1/14/05 BY *[Signature]***  
*Central Office*  
*18-09*

**Duke Energy**  
**PO Box 1244**  
**Charlotte, NC 28201-1244**



Duke Energy  
Marshall Steam Station  
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William M. Miller, PE  
March 31, 2004

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### Executive Summary

This report provides the demonstration that the design for the Marshall Flue Gas Desulfurization (FGD) residue landfill will ensure that 2L groundwater standards are not exceeded. This conclusion was reached by review of the site-specific conditions, leaching tests performed on the FGD residue, and by the use of groundwater modeling.

The design evaluated in this demonstration ensures that the ground water standards established under 15A NCAC 2L will not be exceeded.

The design evaluated in this demonstration requires:

1. the active landfill will receive FGD residue for a 5 year period.
2. an engineered cover will be placed on the completed landfill at the end of the 5 year period.
3. The engineered cover will consist of a textured 40 mil low density polyethylene geomembrane layer beneath a geocomposite drainage net. The cap and geocomposite drainage net will be topped with two feet of soil for vegetative growth. The geomembrane layer will minimize infiltration of precipitation into the waste. The geocomposite drainage net will provide lateral drainage for water that percolates through the vegetative layer. A detail showing the cover system is shown on drawing MM 6551.00-0001.001 Revision B.
4. The drainage collected by the geocomposite drainage net will drain to the erosion control benches, as well as draining to the anchor trench. This will limit the drainage length of the geocomposite to no greater than 300 feet. The location of the erosion control benches is shown on drawing M-6024-06.00, Revision C.

Other than the engineered cover described above, there are no special engineering features or considerations that must be included or maintained in site construction, operation, maintenance and closure.

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- Attachment 1      FGD Scrubber Sludge Testing (Revision 1), Duke Power Coal Fired Steam Stations in North Carolina, S&ME Project No. 1264-03-57, February 2004.
- Attachment 2      Geochemical Evaluation of Flue Gas Desulfurization Scrubber Waste, letter from William J, Deutsch, Senior Geochemist, Battelle Pacific Northwest Laboratory to Bill Miller, Duke Energy, dated June 23, 2003.
- Attachment 3      HELP Model Input Data and Results
- Attachment 4      MYGRT Manual
- Attachment 5      Input Data for MYGRT Model Runs
- Attachment 6      MYGRT Model Inputs and Results

***Note: The information contained in Attachments 1, 2, and 4 was used in the preparation of this report. The parties indicated on the covers of these reports prepared these reports and documents. The engineering certification on the cover page of this report does not imply that the engineering certification of this report includes certification of these particular documents.***

## 1.0 Regulatory Requirements

The regulatory requirements for the design of a solid waste, industrial landfill are found in North Carolina Administrative Code, Title 15A, Chapter 13 Solid Waste Management, Section .0503 Siting and Design Requirements for Disposal Sites. In particular, Section .0504(2)(d)(ii) requires that:

*(A) a design that will ensure that the ground water standards established under 15A NCAC 2L will not be exceeded in the uppermost aquifer at the compliance boundary established by the Division in accordance with 15A NCAC 2L. The design shall be based upon modeling methods acceptable to the Division, which shall include, at a minimum, the following factors:*

- (I) the hydrogeologic characteristics of the facility and surrounding lands;*
  - (II) the climatic factors of the area; and*
  - (III) the volume and physical and chemical characteristics of the leachate;*
- or*

*(B) a design with a leachate collection system, a closure cap system, and a composite liner system consisting of two components: the upper component shall consist of a minimum 30-mil flexible membrane (FML), and the lower components shall consist of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than  $1 \times 10^{-7}$  cm/sec. FML components consisting of high density polyethylene (HDPE) shall be at least 60-mil thick. The FML component shall be installed in direct and uniform contact with the compacted soil component.*

This report was prepared to demonstrate that the conceptual design submitted in the Duke Power, Marshall Steam Station, Catawba County, N.C., Flue Gas Desulfurization (FGD) Residue Landfill Permit Application, Site Suitability Information August 29, 2003 [Reference 1] will ensure that the ground water standards established under 15A NCAC 2L will not be exceeded in the uppermost aquifer at the compliance boundary established by the Division in accordance with 15A NCAC 2L.

## 2.0 Description of Flue Gas Desulphurization (FGD) System

The Clean Smokestacks Act passed in 2002 requires significant reductions in emissions from coal-fired power plants operating in North Carolina. NC utilities must reduce the actual emissions of nitrous oxides (NO<sub>x</sub>) by 77% by the year 2009 and must reduce actual sulfur dioxide (SO<sub>2</sub>) emissions by 49% by the year 2009 and by 73% by 2013. As part of Duke Power's effort to meet the SO<sub>2</sub> reduction requirements, a Flue Gas Desulphurization (FGD) system will be installed at the Marshall Steam Station. Duke will also install similar FGD systems at other power plants located in NC. Duke's intent is that a large portion of the residue from this process will be utilized in beneficial products and the remainder will be placed in the proposed FGD residue landfill.

The FGD system contracted for installation at Marshall is a Wet Scrubber system. In a Wet Scrubber system the SO<sub>2</sub> component of the flue gas produced from the coal combustion process is removed by reaction with a limestone-water slurry.

The particular system to be used at Marshall will collect the flue gas after it passes through the electrostatic precipitator and route the gas into the lower end of a vertical tank. As the gas rises through the tank to the outlet at the top, the gas passes through a spray header. An atomized slurry of water and limestone droplets is continually sprayed through this header into the stream of flue gas. The SO<sub>2</sub> in the flue gas reacts with the calcium in the limestone and produces SO<sub>3</sub>. The SO<sub>3</sub> slurry falls to the bottom of the tank where a stream of air is injected to oxidize the slurry to form gypsum (CaSO<sub>4</sub>·H<sub>2</sub>O). The gypsum slurry is then drawn off to a hydroclone and subsequently routed to a vacuum belt filter. The liquid waste from this process will be treated as wastewater.

Duke is presently investigating beneficial uses for the FGD residue (gypsum). If these options are determined to be viable, the FGD residue meeting the material requirements for the beneficial uses will not be disposed in the landfill. FGD residue material that does not meet the specifications for the end use product will be placed in the landfill.

### **3.0 Description of Conceptual Design**

The conceptual design for the proposed gypsum landfill is shown on the drawings included in the construction plan application, submitted on April 1, 2004. The landfill will consist of a gypsum monofill, utilizing gypsum produced at the Marshall Steam Station and at other Duke plants located within NC. The gypsum will be transported to the landfill by truck, where it will be placed and compacted.

The engineered cover will consist of a textured 40 mil low density polyethylene geomembrane layer beneath a geocomposite drainage net. The cap and geocomposite drainage net will be topped with two feet of soil for vegetative growth. The geomembrane layer will minimize infiltration of precipitation into the waste. The geocomposite drainage net will provide lateral drainage for water that percolates through the vegetative layer.

The vegetative layer protects the geomembrane and geocomposite from ultraviolet degradation, desiccation, freeze-thaw, wind, and vectors. The vegetative layer will be stabilized and seeded appropriately to prevent erosion.

#### 4.0 Description of Demonstration Approach

The general approach to demonstrate compliance with 2L standards was:

- Step 1. Perform SPLP leaching tests on the FGD residue (gypsum) and determine if gypsum leachate constituents exceed the NCAC T15A 2L groundwater standards.
- Step 2. Develop conceptual groundwater flow model of site.
- Step 3. Use of HELP model to determine the infiltration rates expected at the landfill. These values will be the rate of leachate that will infiltrate into the soil beneath the landfill.
- Step 4. Determine the groundwater concentrations of the leachate at the compliance boundary with use of the MYGRT model.
- Step 5. Compare the modeled groundwater concentrations to NCAC T15A 2L standards.

## 5.0 SPLP Leaching Analyses Performed on FGD Residue Samples

### 5.1.1 Gypsum Samples

As described in Reference 1, the typical parameters for the FGD material produced by the scrubber system to be used at Marshall are:

**Typical FGD Residue Parameters**

Gypsum	93% to 95%
Sulfite	0.35%
CO <sub>3</sub>	1.3%
CaF <sub>2</sub>	0.2%
Inerts	2.5% to 3.5%
Fly ash Content	0.5% to 0.8%
pH	6.0 to 8.3
Unit Weight	76 lb/ft <sup>3</sup> to 97 lb/ft <sup>3</sup>
Specific Gravity	2.35
Moisture	10% to 12%

FGD residue material that is not suitable for beneficial use will be placed in the landfill. In addition to this material, material will periodically be removed from the clarifier stage of the waste-water treatment system and placed in the landfill. The material from the clarifier stage will be the same composition as the FGD residue, but will consist of smaller particles.

Gypsum samples obtained from two power plants were obtained by Duke for analysis. These plants are identified as the CO Plant and the HC Plant.<sup>1</sup> The CO Plant uses a FGD process designed by the same vendor supplying the Marshall FGD system and has similar system design parameters. The CO plant also uses coal that is similar in origin to the coal used by Marshall.

These FGD residue samples were sent to the Pacific Northwest National Laboratory (PNNL)<sup>2</sup> for geochemical evaluation. This evaluation included SPLP<sup>3</sup> leaching studies, analysis of solid samples by x-ray diffraction (XRD), and calculation of saturation indices to identify minerals in equilibrium with the solution phase.

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<sup>1</sup> At the time the material was obtained, Duke had not finalized the equipment vendor selection. Therefore material from two different vendors was obtained for these analyses.

<sup>2</sup> PNNL is managed by the US Department of Energy and operated by Battelle.

<sup>3</sup> USEPA Method 1312.

To better understand the changes in leachate over time, sequential leaching tests were performed. The report is provided in Attachment 2. The results from the report are summarized below:

*The total dissolved solids and sulfate concentrations exceeded the 2L standards for both types of waste in all leachates by factors of about 4 and 6, respectively. The initial leaches of both waste types exceeded the fluoride 2L standard by a factor of about 2; however, the fluoride concentrations decreased with subsequent leaches and either dropped below or were very close to the standard of 2 mg/L by the fifth leach. The arsenic concentrations in all leachates started below the 2L standard of 0.01 mg/L, but the concentrations increased with subsequent leaches and exceeded the standard by a small amount in all cases after the second or third leach. XRD analysis showed that the dominant mineral in the waste was gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). Saturation index calculations confirm that gypsum is controlling the calcium and sulfate concentrations in the leachate and producing the major ions in solution.*

#### 5.1.2 Comparison of Results of SPLP Leaching Analyses to 2L Standards

The comparison of the results of the leaching analyses to the NCAC T15A 2L Groundwater Standards is presented in Table 5-1. As this table shows, the concentrations of sulfate ( $\text{SO}_4$ ) and fluoride ( $\text{F}_2$ ) exceed the 2L groundwater standards in the initial leaches.

As described in the report summary, arsenic was found to leach at concentrations above the 2L standard in subsequent leaches. This will be discussed in *Section 9.1 Constituents Requiring Modeling*.

Table 5-1 Results of SPLP Analyses of Gypsum Samples from CO and HC Plants

Analyte	Units	NCAC 2L Groundwater Standards	Maximum Value from Initial Leaches	CO Plant Leach #1	CO Plant Leach Dup #1	HC Plant Leach #1
pH	std units	6.5 to 8.5	7.35	7.35	7.31	7.14
Arsenic	mg/L	0.010	<0.010	<0.010	<0.010	<0.010
Barium	mg/L	2.0	0.0507	0.0411	0.0429	0.0507
Boron	mg/L	0.32	0.162	0.149	0.162	0.13
Cadmium	mg/L	0.005	<0.0020	<0.0020	<0.00020	<0.0020
Calcium	mg/L	n/a	614	597	614	612
Chloride	mg/L	250.0	5.33	5.33	4.98	3.67
Chromium	mg/L	0.05	<0.0060	<0.0060	<0.0060	<0.0060
Copper	mg/L	1.0	0.0035	0.0031	0.0035	<0.0030
Fluoride	mg/L	2.0	<b>4.45</b>	<b>4.45</b>	<b>4.02</b>	<b>3.05</b>
Iron	mg/L	0.3	0.051	<0.020	0.051	0.026
Lead	mg/L	0.015	<0.0050	<0.0050	<0.0050	<0.0050
Magnesium	mg/L	n/a	1.73	1.6	1.73	1.23
Manganese	mg/L	0.05	0.0292	0.0286	0.0292	0.0187
Mercury	mg/L	0.0011	<0.00020	<0.00020	<0.00020	<0.00020
Nickel	mg/L	0.1	<0.010	<0.010	<0.010	<0.010
Potassium	mg/L	n/a	0	<1.0	<1.0	<1.0
Selenium	mg/L	0.05	<0.010	<0.010	<0.010	<0.010
Silver	mg/L	0.018	<0.0050	<0.0050	<0.0050	<0.0050
Sodium	mg/L	n/a	2.83	0.93	0.94	2.83
Sulfate, SO <sub>4</sub>	mg/L	250.0	<b>1510</b>	<b>1,490</b>	<b>1,500</b>	<b>1,510</b>
TDS	mg/L	n/a	2200	2,160	2,180	2,200
Zinc	mg/L	2.1	0.0157	0.012	0.0133	0.0157

**Bold** denotes concentrations greater than NCAC 2L groundwater standards.

## 6.0 Site Conceptual Hydrogeologic Model

### 6.1 Site Climatic Information

The site is located in southeastern Catawba County. Catawba County has long, hot summers because moist tropical air from the Gulf of Mexico persistently covers the area. Winters are cool and fairly short. Precipitation is fairly heavy throughout the year. The climatic information provided in Table 6-1 taken from Soil Survey of Catawba County, North Carolina, United States Department of Agriculture [Reference 2].

**Table 6-1 Catawba County Average Daily Temperature and Precipitation**

	<b>Average Daily Temperature (°F)</b>	<b>Average Monthly Precipitation (inches)</b>
January	41	4.1
February	42	4.1
March	49	4.7
April	59	3.8
May	67	3.6
June	75	3.9
July	77	5.0
August	76	5.6
September	70.5	3.8
October	60.5	3.4
November	49	3.1
December	41.5	4.1
Annual Average	59	49.2

### 6.2 Site Soil

The Soil Survey of Catawba County, North Carolina, United States Department of Agriculture [Reference 2] describes the site surface soils in the area of the landfill as Cecil sandy loam. The NC Erosion and Sediment Control Planning and Design Manual [Reference 3] classifies these soils into Hydrologic Group B soils.

### 6.3 Site Geology

The site geology is described in the hydrogeology report for the site, Reference 4.

### 6.4 Site Hydrogeology

The site hydrogeology is described in Reference 4.

## 6.5 Site Conceptual Hydrogeologic Model

### 6.5.1 Description of Site Conditions

As described in Reference 4, the geology and groundwater flow at the site are consistent with the conceptual groundwater model of the Piedmont region as described by Legrand [Reference 5]. The key points of this conceptual model for determining the direction of groundwater flow at the landfill site are:

- The topography of the water table is crudely similar to that of the land surface, but its relief is less.
- The path of natural ground-water movement is relatively short and is almost invariably restricted to the zone underlying the gross topographic slope extending from the surface divide to the stream. Only under extremely rare conditions does ground water pass beneath a perennial stream to a more distant stream. Thus, the concept of a local slope-aquifer system applies. [Reference 5, page 321]
- Environmental concerns relating to water supply or waste disposal are commonly related to only one slope aquifer system. However, if a pumping well or a contamination zone is near a hilltop, both slope aquifer systems are likely to be involved. [Reference 5, page 325]

As shown on Figure 1, the FGD landfill will be located on Duke Power property, northwest of the Marshall plant and to the west of the Marshall Ash Basin.

- The landfill is located to the east of a railroad line, running north-to-south.
- Located to the west of this railroad line is Sherrill's Ford Road, which runs north-south along a surface water divide.
- Located within the landfill footprint and to the east of the railroad line is a surface water drainage feature. This feature drains to the south, to an intermittent stream that drains to Beaverdam Creek, which drains to Lake Norman. A berm or ridge of earthen material was placed across the drainage feature at some point in the past. This berm extends west to east across the flow of the drainage feature. As described in Reference 4, page 2, to the north of the berm, the flow in this reach of the drainage feature is controlled by rainfall and storage in the wetlands, with the stream appearing to dry up during dry periods. To the south of the ridge or berm, the stream channel appears to become a groundwater discharge feature.
- There is a topographic divide running NNW through the landfill footprint, along Steam Plant Road.
- Surface drainage to the west of Steam Plant Road drains to the surface drainage feature and surface drainage to the east of Steam Plant Road drains to the Marshall Ash Basin.

As described in the site hydrogeological study (Hydrogeological Study FGD Scrubber Landfill, Duke Power – Marshall Steam Station, Terrell, North Carolina, S&ME Project No: 1264-02-578, May 30, 2003), the subsurface conditions in the landfill area consist of residual soils and partially weathered rock which have been formed by the in-place weathering of the parent rock.

As described in Reference 4, the material in the subsurface at the site is divided into four layers:

1. Residuum – Weathered, unconsolidated material found beneath the topsoil. The residuum encountered in the landfill borings ranged from silty clays to clayey silts to sandy silts. The residuum extended to depths ranging from 2.5 to 14 feet below land surface and is located above the groundwater surface.
2. Saprolite – A product of weathered rock and usually contains some characteristics of the parent rock. This unconsolidated material usually grades with depth to partially weathered rock (described below) or bedrock. This material is classified as silts to clayey silts and sandy silty to silty sands. The saprolite at the site extends to depths ranging from 13.5 to 58.5 feet below land surface.
3. Partially Weathered Rock (PWR) – PWR is defined as material exhibiting Standard penetration Resistances in excess of 100 blows per foot and is often classified as penetrable, residual materials typically classified as coarse to fine silty sands to medium to fine sandy silts. The PWR extended to depths ranging from 25.5 to 90 feet below land surface.
4. Bedrock – When sampled, the bedrock at the site was found to be granite, schist and gneiss. Horizontal to high-angle fractures are present in the upper ten feet of bedrock. Bedrock was encountered at depths ranging from 25.5 to 79.5 feet below land surface.

#### 6.5.2 Groundwater Flow

As is typical in the groundwater systems located in the Piedmont region and consistent with the conceptual model of groundwater flow in the Piedmont region, groundwater at the landfill site occurs within the residuum and saprolite under unconfined aquifer conditions. The predominant groundwater discharge areas are expected to be the ash basins located to the east of the landfill.

As depicted on Figure 2 of 7 and Figure 3 of 7 (Reference 4), the groundwater flow at this site is generally from the northwest of the landfill footprint towards the east and southeast in the direction of the Ash Basin arms located east of the landfill. The groundwater flow underneath the landfill footprint is generally defined by two discharge locations: a discharge to the northernmost arm of the Ash Basin, near boring B-1 and by a discharge to the southern arm of the Ash Basin, near boring MS-2.

#### 6.5.3 Discussion of 2L Compliance Boundary

The compliance boundary is defined by NCAC 2L 0.107 (b) as:

*(b) For disposal systems individually permitted on or after December 30, 1983, a compliance boundary shall be established 250 feet from the waste boundary, or 50 feet within the property boundary, whichever point is closer to the source.*

Since it is greater than 300 feet from the footprint of the proposed landfill to the nearest property boundary in the direction of groundwater flow, a distance of 250 feet from the footprint will be used to evaluate compliance with 2L groundwater standards.

## 7.0 Conceptual Description of Modeling Approach

The modeling approach selected to demonstrate compliance of the landfill design was:

- 1) The Hydrologic Evaluation of Landfill Performance (HELP) model was used to predict quantities of water infiltrating through the landfill and into the soil beneath the landfill during the Operational Period,<sup>4</sup> (prior to placement of the engineered cover). The HELP model was also used to predict the quantities of water infiltrating through the completed landfill and into the soil beneath the landfill during the Closed Period,<sup>5</sup> after the placement of the engineered cover.
- 2) The MYGRT model was used to predict the fate and transport of constituents leaching into the groundwater during the Operational Period and during the Post-Operational Period.

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<sup>4</sup> The Operational Period refers to the period of landfill operation prior to the placement of the engineered cover.

<sup>5</sup> The Closed Period is the period of time after the placement of the engineered cover.

## 8.0 HELP Model Description and Results

### 8.1 Description of HELP Program

The Hydrological Evaluation of Landfill Performance (HELP) program is a quasi-two-dimensional hydrologic model for conducting water balance analyses of landfills, cover systems, and other solid waste containment facilities. The model accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners.

Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives. The model is a tool for both designers and permit writers. [Reference 6]

The HELP model requires general climate data for computing potential evapotranspiration; daily climatologic data; soil characteristics; and design specifications to perform the analysis. The required general climate data include growing season, average annual wind speed, average quarterly relative humidities, normal mean monthly temperatures, maximum leaf area index, evaporative zone depth and latitude. Default values for these parameters were compiled or developed from the "Climates of the States" (Ruffner, 1985) and "Climatic Atlas of the United States" (National Oceanic and Atmospheric Administration, 1974) for 183 U.S. cities. Daily climatologic (weather) data requirements include precipitation, mean temperature and total global solar radiation. Daily rainfall data may be input by the user, generated stochastically, or taken from the model's historical data base. The model contains parameters for generating synthetic precipitation for 139 U.S. cities. The historical data base contains five years of daily precipitation data for 102 U.S. cities. Daily temperature and solar radiation data are generated stochastically or may be input by the user.

Necessary soil data include porosity, field capacity, wilting point, saturated hydraulic conductivity, initial moisture storage, and Soil Conservation Service (SCS) runoff curve number for antecedent moisture condition II. The model contains default soil characteristics for 42 material types for use when measurements or site-specific estimates are not available. The porosity, field capacity, wilting point and saturated hydraulic conductivity are used to estimate the soil water evaporation coefficient and Brooks-Corey soil moisture retention parameters. Design specifications include such items as the slope and maximum drainage distance for lateral drainage layers; layer thickness; layer description; area; leachate recirculation procedure; subsurface inflows; surface characteristics; and geomembrane characteristics.

## 8.2 HELP Model Version:

The HELP model used for this demonstration is Visual HELP, Version 2.2.0.1 August 2000. This version of Visual HELP uses HELP Version 3.07.<sup>6</sup> Also used as reference material were the HELP User's Guide for Version 3, [Reference 7 ] and the HELP Engineering Documentation for Version 3 [Reference 6]. Visual HELP is a Windows based program that serves as an interface and provides graphical features for designing the model and evaluating the modeling results. The actual model analysis is performed by running the HELP Model Version 3.07, developed by the USAE Waterways Experiment Station.

## 8.3 HELP Model Inputs:

### 8.3.1 Weather Data

The HELP model uses data developed by NOAA for growing season dates, average annual wind speed, average quarterly relative humidity, and normal mean monthly temperatures. The user selects a location from the database and the values are used to generate synthetic data for the desired length of time. The values used in this analysis were from the Charlotte, NC location, with the following items modified as described.

1. The average daily temperatures and monthly average rainfall values from Catawba County (from Table 6-1) were used.
2. The maximum leaf area index (LAI) was modified to be 2.0 (a LAI of 2.0 is associated with a fair stand of grass).
3. The evaporative zone depth was modified to 10 inches.
4. The latitude and longitude for the site was used.

### 8.3.2 Runoff Curve Numbers

Runoff curve numbers were selected from Reference 3. The curve numbers used in the HELP analyses are listed below. The curve numbers were selected based on the site soil being classified as Hydrologic Group B soils. The gypsum (FGD residue) material would likely have hydrologic properties similar to Hydrologic Group C soils, due to the fine grained nature of the particles.

Condition	Land Use/Cover Description (from Table 8.03b, Reference 3)	Curve Number
Operational Condition	Area will be primarily gypsum. Selected CN for "Newly graded area"	93
Closed Condition	Area will have maintained grass cover. Selected CN for "open spaces, lawns, parks, golf courses, etc."	61

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<sup>6</sup> The weather files used to generate the temperature and rainfall data are dated 1999.

### 8.4 Cases Modeled with HELP

Two cases were modeled with HELP. These cases are:

- Operational Period – models the infiltration that occurs during the period of gypsum placement.
- Closed Period – models the infiltration that occurs after placement of the engineered cover.

#### 8.4.1 Operational Period

The landfill was modeled during the operational period (the 5 year period of gypsum placement) to determine the quantity of infiltration that would pass through the gypsum, becoming leachate. The properties described in the previous sections were used, along with a 100 year period of simulated weather conditions to determine the amount of infiltration that would occur.

Since the thickness of the gypsum will change during the operational period. Two separate runs were made to approximate these changing conditions. One HELP analysis was made with the thickness of gypsum equal to 80.5' and a second HELP analysis was made with the thickness of the gypsum equal to 40'.

The layers modeled in HELP for this condition are shown in the following schematic.

Marshall FGD Residue Landfill  
 HELP Model Layers  
 Operational Period

Description of Layer	Thickness of Layer
<b>Layers 1 through 6</b> <b>FGD Residue</b>	80.5 feet and 40 feet
<b>Layer 7</b> <b>Undisturbed Site Soil</b>	4 feet

#### 8.4.2 Closed Period

The landfill was modeled during the Closed Period (after placement of engineered cover) to determine the quantity of leachate that would infiltrate through the assumed holes in the engineered cover.

The engineered cover will consist of a textured 40 mil low density polyethylene geomembrane beneath a geocomposite drainage net. The cap will be topped with two feet of soil for vegetative growth. The geomembrane is a barrier layer that prevents rainwater from entering the waste cell of the landfill. The geocomposite drainage net allows water that percolates through the vegetative layer to drain laterally to a collection system.

A detail showing the cover system is shown on drawing MM 6551.00-0001.001 Revision B. The drainage collected by the geocomposite drainage net will drain to the erosion control benches and to the anchor trench. The location of the erosion control benches is shown on drawing M-6024-06.00, Revision C. These drawings are included as part of the Construction Plan Application Submittal [Reference 8]. The average slope of the geocomposite drainage net is 12.5%. The horizontal distance used for the length of flow for this layer is 300 feet. (See M-6024-06.00, Revision C).

The vegetative layer protects the geomembrane and geocomposite from ultraviolet degradation, desiccation, freeze-thaw, wind, and vectors. The vegetative layer shall be stabilized and seeded appropriately to prevent erosion. Native material cut from open areas within the landfill will be used for the vegetative layer. Debris will be removed, and the soil will be amended as needed.

The low density polyethylene (LDPE) geomembrane layer modeled has a hydraulic conductivity of  $4.0E-13$  cm/sec. The assumed placement quality for the geomembrane cover is good. This will be assured through a QA/QC program developed in coordination with the manufacturer and NCDENR.

The assumed number of holes in the cover used in the HELP analyses is:

- pinhole density is 1 hole/acre
- installation defects are 4 holes/acre

The period modeled was 100 years. This is the maximum period of time that can be run with HELP.

The layers modeled in HELP for the Closed Period are shown in the following schematic.

**Marshall FGD Residue Landfill  
 HELP Model Layers  
 Closed-Period**

Description of Layer	Thickness of layer
<p style="text-align: center;"><b>Layer 1</b>  <b>Compacted Site Soil - Upper</b>  <b>Vegetated Layer</b></p>	0.75 ft
<p style="text-align: center;"><b>Layer 2</b>  <b>Compacted Site Soil - Lower</b>  <b>Vegetated Layer</b></p>	1.25 ft
<p style="text-align: center;"><b>Layer 3</b>  <b>Drainage Net</b></p>	0.0164 ft
<p style="text-align: center;"><b>Layer 4</b>  <b>Low Density Polyethylene</b>  <b>Geomembrane</b></p>	40 mil (.0033 ft)
<p style="text-align: center;"><b>Layer 5</b>  <b>Compacted Site Soil</b></p>	1.5 ft
<p style="text-align: center;"><b>Layers 6 through 11</b>  <b>FGD Residue</b></p>	84.48 ft
<p style="text-align: center;"><b>Layer 12</b>  <b>Undisturbed Site Soil</b></p>	4 feet

## 8.5 Soil and FGD Residue Properties

The soil and gypsum properties that are used in the HELP analyses were developed from tests performed on soil samples collected during the site investigation and from gypsum samples provided by the scrubber equipment vendor.

### Properties for Vegetative Soil Layer

The soil properties from borings located within the landfill footprint or adjacent to the footprint were used to determine porosity, field capacity, wilting point, and hydraulic conductivity parameters for the vegetative soil layer. These values are shown in the following tables.

The vegetative soil layer will be constructed from material excavated from the landfill footprint area and compacted as the vegetative cover layer. Therefore, the remolded samples reflect the properties for this layer.

**Table 8-1 Vegetative Soil Layer – Hydraulic Conductivity and Void Ratio**

Boring	Depth	Hydraulic Conductivity, k (cm/sec)	Porosity, n
B-1	0'-10'	1.2E-05	0.40
B-2	0'-10'	3.7E-06	0.44
B-4	0'-10'	4.9E-06	0.41
B-5	0'-10'	6.1E-06	0.47
B-7	0'-10'	1.7E-05	0.49
	Arithmetic Mean	8.8E-06	0.44
	Geometric Mean	7.4E-06	0.44

The geometric mean value was used in the HELP analysis.

If default soil properties are used, the HELP program automatically adjusts the saturated hydraulic conductivity in the top half of the evaporative zone to account for root penetration by surface vegetation.

Since the soil properties for the vegetated soil layer are not default HELP properties, the saturated hydraulic conductivity in the top half of the evaporative zone must be adjusted to account for root penetration by surface vegetation. An 18" thick evaporative zone was used. Therefore, the adjusted hydraulic conductivity was used on the upper 9" layer. This vegetated saturated hydraulic conductivity,  $(K_s)_v$ , is calculated by Equation A-10 in Reference 6. The value for  $(K_s)_v$  used in the HELP analysis is 2.2E-05 cm/sec.

HELP requires values for field capacity and wilting point. These values are calculated based on the percentages of sand and clay present in the soil.

**Table 8-2 Vegetative Soil Layer – Percentage of Sand and Clay**

<u>Boring</u>	<u>Sample ID</u>	<u>USCS Soil Classification</u>	<u>Depth</u>	<u>% Sand (USDA) 0.05 - 2.0 mm</u>	<u>% Clay (USDA) &lt;0.002 mm</u>
MS-7	S-2	CH	8.5' - 10'	19.0%	53.2%
B-1	S-1	CL	3.5' - 5'	44.0%	28.7%
B-3	S-4	MH	18.5' - 20'	32.2%	7.5%
B-4	S-1	MH	3.5' - 5'	32.4%	29.9%
B-5	S-2	SM	8.5' - 10'	57.5%	5.6%
B-6	S-1	SM	3.5' - 5'	56.2%	17.6%
Arithmetic Mean				40%	24%
Geometric Mean				38%	18%

**Table 8-3 Vegetative Soil Layer – Values Used In HELP**

	<u>Hydraulic Conductivity, k (cm/sec)</u>	<u>Porosity, n</u>	<u>Field Capacity (HELP Eqn A-3)</u>	<u>Wilting Point (HELP Eqn A-4)</u>
Upper Vegetative Layer	2.2E-05	0.44	0.242	0.122
Lower Vegetative Layer	7.4E-06	0.44	0.242	0.122

Note: The equations (Eqn. A-3 and A-4) used for these calculations are found in the HELP Users Manual, Appendix A.

Properties for Gypsum Layer

Samples of the gypsum material were sent to the geotechnical firm S&ME Inc. for testing. The results of the lab analyses on these samples is found in the report, FGD Scrubber Sludge Testing, (Revision 1) Duke Power Coal Fired Steam Stations in North Carolina, S&ME Project No. 1264-03-57, February 2004. A copy of this report is included as Attachment 1.

Lab analyses were performed on these samples to determine the following properties:

- Grain size Distribution
- Atterburg Limits
- Specific Gravity
- Natural Moisture
- pH
- Standard Proctor Compaction
- Remolded Permeability
- Consolidation Properties ( $C_c$ )
- Total Porosity
- Triaxial Shear Strength

The grain size analyses, void ratio, porosity, and saturated hydraulic conductivity's from these analyses were used in the HELP model analyses.

**Table 8-4 FGD Residue – Hydraulic Conductivity and Void Ratio**

Remolded Sample Conditions	Porosity (at 8 ksf)	Hydraulic Conductivity, k (cm/sec)
90% compaction @ 12% moisture	0.43	5.09E-04
92% compaction @ 25% moisture	0.41	2.25E-04
95% compaction @ 19% moisture	0.4	2.53E-04

**Table 8-5 FGD Residue – Values Used In HELP**

Hydraulic Conductivity, k (cm/sec)	Porosity, n	Field Capacity (HELP Eqn A-3)	Wilting Point (HELP Eqn A-4)
2.53E-04	0.41	0.180	0.055

Properties for Soil Layer Beneath the Landfill

The soil properties from borings located within the landfill footprint or adjacent to the footprint were used to determine porosity, field capacity, wilting point, and hydraulic conductivity parameters for the layer of soil located beneath the FGD residue. These values are shown in the following tables.

**Table 8-6 Soil Layer Beneath FGD – Hydraulic Conductivity and Void Ratio**

Boring	Cross Section (Reference 4)	Hydraulic Conductivity, k (ft/day)	Hydraulic Conductivity, k (cm/sec)	Total Porosity, n
MS-11	A-A	5.0E-01	1.8E-04	0.43
MS-8	A-A	5.5E-01	1.9E-04	0.43
B-2	A-A	5.0E-01	1.8E-04	0.43
MS-10	G-G	4.0E-01	1.4E-04	0.42
OW-1	G-G	1.6E+00	5.6E-04	0.43
OW-2	G-G	1.0E+00	3.5E-04	0.43
MS-7	G-G	8.7E-01	3.1E-04	0.43
MS-6	G-G	2.9E-01	1.0E-04	0.42
	Arithmetic Mean	7.1E-01	2.5E-04	0.43
	Geometric Mean	6.2E-01	2.2E-04	0.43

Values for hydraulic conductivity and total porosity are taken from Table 5, Reference 4.

The geometric mean value was used in the HELP analysis.

**Table 8-7 Soil Layer Beneath FGD – Percentage of Sand and Clay**

Boring	Sample ID	Depth	Per Cent Sand (USDA) 0.05 - 2.0 mm	Per Cent Clay (USDA) <0.002 mm
MS-7	S-2	8.5' - 10'	19.0	53.2
MS-7	S-4	18.5' - 20'	67.7	1.6
MS-8	S-5	23.5'-25'	65.7	2.6
B-3	S-4	18.5' - 20'	32.2	7.5
B-6	S-12	58.5' - 60'	65.4	3.4
		Arithmetic Mean	46.2	16.2
		Geometric Mean	40.6	6.3

**Table 8-8 Soil Layer Beneath FGD Residue – Values Used in HELP**

Hydraulic Conductivity, k (cm/sec)	Total Porosity, n	Field Capacity (HELP Eqn A-3)	Wilting Point (HELP Eqn A-4)
2.2E-04	0.43	0.252	0.115

## 8.6 HELP Model Results

### 8.6.1 Infiltration During Operational Period

The HELP model calculated that the average annual infiltration through the landfill and into the saturated zone during the operational period is:

**Table 8-9 HELP Model Results**

Thickness of FGD Residue	Infiltration During Operational Period (in/yr)
40 feet	9.34
80.5 feet	9.22

These values are based on 100 years of simulated weather conditions.

### 8.6.2 Infiltration During Closed Period

The HELP model calculated that the average annual infiltration rate through the engineered cover (HELP Layer 4) is 0.00039 inches/year. This value will be used in the MYGRT analyses for the infiltration value during the closed period. These results indicate the effectiveness of the engineered cover to reduce infiltration through the landfill.

These values are based on 100 years of simulated weather conditions.

Copies of the HELP input data and results are located in Attachment 3.

## 9.0 MYGRT Model Description and Results

The MYGRT software predicts the migration of both inorganic and organic solutes in the unsaturated and saturated zones down gradient of sources. The processes included are advection, dispersion, retardation, and decay. The code can simulate problems in one, two, or three dimensions using either horizontal or vertical views. The model uses inputs such as seepage velocity, dispersion and retardation factors.

The reviewer should refer to the MYGRT manual for detailed definition of the inputs and for the description of the computational processes used by MYGRT. A copy of the MYGRT manual is included as Attachment 4.

MYGRT Version 3.0 was used for these analyses. [Reference 9]

## 9.1 Constituents Requiring Modeling

The comparison of the results of the leaching analyses to the NCAC T15A 2L Groundwater Standards is presented in Table 5-1. As this table shows, the concentrations of sulfate ( $\text{SO}_4$ ) and fluoride ( $\text{F}_2$ ) exceed the 2L groundwater standards in the initial leaches. As described in the PNNL report summary, arsenic was found to leach at concentrations above the 2L standard in subsequent leaches.

As described in the site suitability information, the design requires that the landfill will be capped with an impermeable cover after 5 years. Table 9-1 provides the approximate number of years of infiltration required to be equivalent to one SPLP leach, based on a 1 foot thickness of gypsum and the infiltration rate calculated by HELP.

As this table shows, even for a 1 foot thick layer of gypsum, it would take approximately 36 years for the volume of infiltration experienced to be equivalent to the volume of liquid in the initial SPLP leach (based on the 20:1 mass ratio used in the SPLP test). The 5 year period that the landfill will be uncapped is well below the time required for a volume equivalent to the initial SPLP leach to be exchanged through the landfill. Therefore, only the constituents whose concentrations exceed the NCAC 2L groundwater standards (sulfate and fluoride) in the initial SPLP leaches will require modeling.

The concentrations for the other constituents in the initial SPLP leaches were below the 2L standards. Therefore, only  $\text{SO}_4$  and  $\text{F}_2$  will require further evaluation in this demonstration. The concentrations of these constituents used in the MYGRT analyses are presented in Table 9-2.

**Table 9-1 Approximate Number of Years per SPLP Leach**

In SPLP test a 20:1 liquid to solid (mass) ratio is used.

The table below presents the approximate number of years to represent one SPLP leach, based on only a 1 foot thickness of gypsum and the infiltration from the HELP analyses.

Specific Gravity of gypsum = 2.35

Porosity of gypsum = 0.42

Infiltration when gypsum is not covered with synthetic cap = 9.34 in/year for 40 feet of gypsum and 9.22 in/yr for 80.5 feet of gypsum.

**Approximate Number of Years per SPLP Leach**

Thickness	Mass of Gypsum	Mass of Water (From Infiltration for 20:1 ratio)	Volume of Infiltration (Volume of water for 20:1 ratio)	Number of Years per Leach (Volume of Infiltration ÷ 9.22 in/yr)
ft	lbs	lbs	ft <sup>3</sup>	
1	87	1740	28	36

**Table 9-2 Source Concentrations Used in MYGRT Model**

	Results from SPLP Leaching	Concentration Used in MYGRT	NCAC 2L Groundwater Standard
Sulfate, SO <sub>4</sub>	1510 mg/l	1600 mg/l	250 mg/l
Fluoride, Fl <sub>2</sub>	4.45 mg/l	5 mg/l	2.0 mg/l

## 9.2 Description of Model Runs

Two cross sections of the site were modeled in MYGRT to evaluate compliance with 2L standards. The groundwater flow at this site is generally from the northwest of the landfill footprint towards the east and southeast in the direction of the Ash Basin arms located east of the landfill. The groundwater flow underneath the landfill footprint is generally defined by two discharge locations: a discharge to the northernmost arm of the Ash Basin, near boring B-1 and by a discharge to the southern arm of the Ash Basin, near boring MS-2.

The groundwater flow along these cross sections, underneath the landfill footprint and towards these two discharge locations was modeled in MYGRT to determine the concentrations of  $\text{SO}_4$  and  $\text{Fl}_2$  at the compliance boundary.

The borings used to determine the cross section characteristics are listed below.

MYGRT Run 1 - Cross Section 1-1 (See Figure 1 and Figure 2)  
MS-11 to MS-7 to B-6 to B-5 to MS-2

MYGRT Run 2 - Cross Section 2-2 (See Figure 1 and Figure 2)  
MS-10 to B-2 to B-1

### 9.3 Model Inputs

The landfill area is represented as a source with an input length and width. The source concentrations are entered as a function of time. For the modeling used in this demonstration, the 3-D modeling scenario was used. Since the FGD material is placed a minimum of 4 feet above the saturated zone, the source (the FGD Residue) was considered to be located at the top of the unsaturated zone. The model calculated the concentrations after the constituents pass through the unsaturated zone and into the saturated zone.

Table 9-3 provides a list of the parameters and provides references to the sources for the MYGRT input parameters.

SO<sub>4</sub> and F1<sub>2</sub> are generally considered to be conservative substances. Therefore, no attenuation by the site soils is assumed to occur and a K<sub>d</sub> value of 0 mL/g is used in the MYGRT analyses.

MYGRT has the capability to change the infiltration rate at a specified time, so the Operational and the Closed conditions can be modeled in the same MYGRT model run. The infiltration value for the Operational period was used for 5 years (year 2006 through year 2010). The infiltration value was then changed to the infiltration value for the Closed period (for years 2011 and beyond).

#### Modeling Period

As described in Section 8.6.2, after placement of the engineered cover, the infiltration decreases to 0.00039 inches/year. If this number is used to calculate the approximate number of years of infiltration to equal the volume of liquid in one SPLP leach, the number of years required for the volume of one SPLP leach to move through an 80 foot thick layer of gypsum is too large to be meaningful.

Therefore, for the MYGRT analyses the period of time for the source concentrations to be active was arbitrarily selected to be 3000 years. The infiltration value was decreased from the values calculated by HELP for the Operational Period (years 2006 to 2010) to the value for the Closed Period in year 2011.

The MYGRT analyses showed the concentrations decreasing to steady state values after year 2100 (approximately). The attainment of steady state values indicates that the length of time used for the source term is valid.

Table 9-3 MYGRT Model Input Parameters

Input Parameter	Units	Source of Input	Values for MYGRT Cross Section 1-1	Values for MYGRT Cross Section 2-2
<b>Unsaturated Zone Parameters</b>				
Width of Source	ft	Figure 1	1440	1440
Length of Source Parallel with Aquifer Flow Direction	ft	Figure 1	1300	760
Input Source Concentration, SO <sub>4</sub>	mg/l	Table 9-2	1600	1600
Input Source Concentration, Fl <sub>2</sub>	mg/l	Table 9-2	5	5
Infiltration Rate - Operational Period Years 2006 to 2010	ft/year	HELP Table 8-9	0.78	0.78
Infiltration Rate - Closed Period Years 2011 to 3000	ft/year	HELP, See Note 1	0.0001	0.0001
Volumetric Moisture Content of Soil (Unsaturated)	vol/vol	Attachment 5	0.25	0.25
Depth to water table below source	ft	Attachment 5 See Note 2	4	6
Rd, Unsaturated layer, SO <sub>4</sub> , Fl <sub>2</sub>		See Note 3	1	1
<b>Saturated Zone Parameters</b>				
Hydraulic Gradient	ft/ft		0.01	0.03
Hydraulic Conductivity	ft/yr	Attachment 5	219.4	183.9
n <sub>e</sub> , effective porosity		Attachment 5	0.28	0.27
Scale Distance for Dispersion Calculation	ft	See Note 4	250	250
Aquifer Thickness	ft	Attachment 5, Note 5	27.8	24.3
<b>Solute Plume Properties</b>				
Bulk Density	g/ml	Note 6	N/A	N/A
K <sub>d</sub> for SO <sub>4</sub> , Fl <sub>2</sub>	ml/g	See Note 6	0	0

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**Table 9-3 MYGRT Model Input Parameters**

**Notes:**

1. HELP calculated an infiltration rate of 0.00039 inches/year after placement of the engineered cover. This calculates to a value of 0.00003 ft/yr. A value of 0.0001 ft is conservatively used in the MYGRT analyses for infiltration during the closed period.
2. As found in Attachment 5, the depths to groundwater (below the excavated bottom of the landfill) are 5' (for Section 1-1) and 8.5' for (for Section 2-2). The depths to groundwater used in the MYGRT analyses are 4' for Section 1-1 and 6' for Section 2-2.
3. No attenuation is assumed to occur with SO<sub>4</sub> and Fl<sub>2</sub>, therefore the K<sub>d</sub> term would be = 0 and the Rd, retardation factor, would be equal to 1.
4. The scale distance for dispersion calculations used is 250 feet. The longitudinal, transverse, and vertical coefficients are calculated by MYGRT as follows:  
Longitudinal Dispersion Coefficient    1/10<sup>th</sup> of scale distance multiplied by the seepage velocity  
Transverse Dispersion Coefficient    1/10<sup>th</sup> of horizontal dispersion coefficient  
Vertical Dispersion Coefficient        1/100<sup>th</sup> horizontal dispersion coefficient
5. The geometric mean value for thickness of the aquifer was used for each cross section. This value is based on the minimum measured groundwater elevation for the wells. These groundwater elevations are found in Attachment 5.
6. MYGRT uses the bulk density and K<sub>d</sub> to calculate a retardation factor. Since no attenuation is assumed to occur with SO<sub>4</sub> and Fl<sub>2</sub>, the K<sub>d</sub> term would be = 0 and the retardation factor would be equal to 1.

### 10.0 MYGRT Model Results and Comparison to 2L Standards

The results from the MYGRT runs are located in Attachment 6. The results are summarized in the table below.

These results are calculated at the compliance boundary and at a depth below the groundwater surface that is equal to the depth of the aquifer. MYGRT calculates the source plume mixing depth and compares the calculated depth to the input aquifer thickness. If the plume mixing depth is greater than the aquifer thickness, the MYGRT completely mixes the source plume across the depth of the aquifer. In both cross sections, the plume mixing depth was greater than the aquifer thickness, so the source plume was completely mixed across the depth(s) of the aquifer(s).

**Table 10-1 MYGRT Model Results**

Constituent	MYGRT Cross Section 1-1  Maximum Concentration from MYGRT model at Compliance Boundary	MYGRT Cross Section 2-2  Maximum Concentration from MYGRT model at Compliance Boundary	NCAC 2L Groundwater Standard
Sulfate	164 mg/L	232 mg/L	250.0 mg/L
Fluoride	0.51 mg/L	0.72	2.0 mg/L

As shown in Table 10-1, the design of the landfill ensures the concentrations of SO<sub>4</sub> and F<sub>l</sub><sub>2</sub> are below the NCAC 2L groundwater standards at the compliance boundary.

## 11.0 Conclusions

As shown in Section 10.0, the design evaluated in this demonstration ensures that the ground water standards established under 15A NCAC 2L will not be exceeded.

The design evaluated in this demonstration requires:

1. the active landfill will receive FGD residue for a 5 year period.
2. an engineered cover will be placed on the completed landfill at the end of the 5 year period.
3. The engineered cover will consist of a textured 40 mil low density polyethylene geomembrane layer beneath a geocomposite drainage net. The cap and geocomposite drainage net will be topped with two feet of soil for vegetative growth. The geomembrane layer will minimize infiltration of precipitation into the waste. The geocomposite drainage net will provide lateral drainage for water that percolates through the vegetative layer. A detail showing the cover system is shown on drawing MM 6551.00-0001.001 Revision B.
4. The drainage collected by the geocomposite drainage net will drain to the erosion control benches, as well as draining to the anchor trench. This will limit the drainage length of the geocomposite to no greater than 300 feet. The location of the erosion control benches is shown on drawing M-6024-06.00, Revision C.

Other than the engineered cap described above, there are no special engineering features or considerations that must be included or maintained in site construction, operation, maintenance and closure.

## 12.0 References

**Note: The information and sources listed below were used in the preparation of this report. The parties listed in the references prepared these reports and documents. The engineering certification on the cover page does not imply that the engineering certification of this report includes certification of these particular references.**

- 1 Duke Power, Marshall Steam Station, Catawba County, N.C., Flue Gas Desulfurization (FGD) Residue Landfill Permit Application, Site Suitability Information, August 29, 2003, Volume 1.
- 2 Soil Survey of Catawba County, North Carolina, United States Department of Agriculture, Issued October 1975.
- 3 North Carolina Erosion and Sediment Control Planning and Design Manual, May 1994.
- 4 Duke Power, Marshall Steam Station, Catawba County, N.C., Flue Gas Desulfurization (FGD) Residue Landfill Permit Application, Site Suitability Information, August 29, 2003, Hydrogeologic Study, S&ME Project No. 1264-02-578, Volume 2.
- 5 A Conceptual Model of Ground Water Settings in the Piedmont Region, Harry E. LeGrand, in Groundwater in the Piedmont: Proceedings of a Conference on Ground Water in the Piedmont of the Eastern United States, October 16-18, 1989, Daniel, White, and Stone.
- 6 THE HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL, ENGINEERING DOCUMENTATION FOR VERSION 3, Environmental Laboratory, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
- 7 The Hydrologic Evaluation of Landfill Performance (HELP) Model – User's Guide for Version 3, USEPA September 1994.
- 8 Construction Plan Application, Duke Power Marshall Steam Station, Flue Gas Desulfurization (FGD) Residue Landfill, Catawba County, NC, submitted by letter dated April 1, 2004.
- 9 User's Guide for MYGRT Version 3.0: Software for Simulating Migration of Organic and Inorganic Chemicals in Groundwater, Electric Power Research Institute, 1998, TR-111748, Prepared by Tetra Tech and Ish Inc.

Attachment 1

**Attachment 1**

**FGD Scrubber Sludge Testing (Revision 1),  
Duke Power Coal Fired Steam Stations in North Carolina,  
S&ME Project No. 1264-03-57, February 2004.**

Carmen Johnson  
Fac/Perm/Co ID# 18-09 Date 1/23/12 Doc ID#  
DIN

**FGD SCRUBBER SLUDGE TESTING  
(REVISION 1)  
DUKE POWER  
COAL FIRED STEAM STATIONS  
IN NORTH CAROLINA  
S&ME Project 1264-03-057**

Prepared For:



**Charlotte, North Carolina**

Prepared By:



**Spartanburg, South Carolina**

February 2004



**Since 1973**

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February 2, 2004

Mr. William M. (Bill) Miller, P.E.  
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Reference: **FGD SCRUBBER SLUDGE TESTING (REVISION 1)**  
Duke Power Coal-Fired Steam Stations  
In North Carolina  
S&ME Project 1264-03-057

Ladies and Gentlemen:

S&ME is pleased to submit the results of laboratory testing performed on a sample of flue gas desulfurization (FGD) scrubber sludge. This letter presents a brief discussion of the project, the testing performed, the test results and their comparison to published reference literature, and stability analyses of conceptual FGD scrubber sludge slopes. This submittal supercedes the April 30, 2003 submittal in that consistent earthquake loadings have been applied throughout the conceptual slope stability analyses, the minimum factors of safety have been updated accordingly, and the earthquake references have been included in Appendix B.

### **PROJECT INFORMATION**

In response to the Clean Air Act of 1990 and its subsequent amendments mandating the reduction of sulfur dioxide (SO<sub>2</sub>) emissions from power plants, Duke Power is evaluating installation of flue gas desulfurization (FGD) scrubber systems at several of its existing coal-fired power plants. Literature suggests the present FGD technology most favorable, particularly in terms of by-product produced, is limestone wet scrubbing with oxidation, which is the process being evaluated by Duke Power. These processes, followed by drying via vacuum filter, produce a calcium sulfate dihydrate scrubber sludge, or gypsum, that can potentially be used as raw

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product for the production of wallboard and/or exhibits more favorable engineering properties for landfill disposal than some other scrubbing process by-products.

In considering development of disposal landfills for the output product, in the absence of wallboard production or should wall board production not fully utilize the output product, Duke Energy obtained a sample of calcium sulfate dihydrate (gypsum) from a confidential source powerplant. We understand that the confidential powerplant comprises FGD scrubber equipment by the same manufacturer contracted by Duke Power to install FGD scrubber equipment at their facilities. Therefore, it is anticipated that the scrubber sludge produced at the confidential powerplant will at least be similar to that produced at the Duke Power facilities. Duke Energy requested S&ME to subject the scrubber sludge sample to selected geotechnical laboratory testing in an effort to gain understanding of its engineering properties relative to disposal practices akin to conventional landfill disposal, referred to as "dry-stacking" for this material. This letter presents the testing performed and the results, including comparison to engineering properties referenced in available literature. Furthermore, toward the consideration of landfill slope height and inclination, we performed stability analyses of conceptual FGD scrubber sludge slopes, the results of which are also presented herein.

### **SELECTED LABORATORY TESTING PERFORMED**

Duke Energy and S&ME agreed the for this initial round of laboratory testing to comprise the following:

- Grain Size Distribution
- Atterberg Limits
- Specific Gravity
- Natural Moisture
- pH
- Standard Proctor Compaction
- Remolded Permeability
- Consolidation
- Total Porosity
- Triaxial Shear Strength

## **LABORATORY TESTING RESULTS**

The laboratory results are summarized on the attached *Table 1, Summary of Laboratory Testing Results – Index Properties* and *Table 2 – Summary of Laboratory Testing Results – Engineering Properties* along with published data for comparison. Laboratory test reports are provided in Appendix A. A brief discussion of the testing results and comparison to published literature is provided below.

### **Grain Size Distribution**

The confidential powerplant sample exhibited approximately 97.2 percent of its particle sizes in the silt size range [0.005 to 0.075 millimeters (mm)], 2.5 percent of its particle size in the clay/colloid range (<0.005-mm), and only 0.2 percent of its particle size in the fine sand range (> 0.075 mm). Published literature references calcium sulfate (gypsum) particle sizes predominately in the silt size range, with some samples exhibiting a greater particle size percentage in the fine sand range, a bit coarser than the confidential powerplant sample. For visual comparison of grain size distribution between the confidential powerplant sample and published literature, we produced the attached *Plate 1 - Grain Size Distribution Comparison*.

### **Atterberg Limits**

The confidential powerplant sample tested as largely non-plastic, exhibiting a Liquid Limit of 27, a Plastic Limit of 26, and a resulting Plasticity Index of only 1. This non-plastic characteristic agrees with the published literature. It is noteworthy that the Liquid Limit, the moisture content at which the material begins to act as a liquid (flow), is relatively low at only 27 percent. Comparatively, the Liquid Limit for residual sandy silts from the Piedmont Geologic Province may be expected on the order of 30 to 50.

### **Specific Gravity**

The confidential powerplant sample solids exhibited a specific gravity of 2.35, an exact match to the specific gravity for gypsum sludge cited in the literature of 2.35. This specific gravity means the gypsum material is lighter than soil, which often exhibits a solids specific gravity on the order of 2.6 to 2.7.

### **Natural Moisture**

The “natural” moisture of the confidential powerplant sample as delivered was 11.8 percent. It is our understanding that the materials “natural” moisture will be a function of the drying process, anticipated being by vacuum filter, that follows the scrubber reaction.

### **pH**

The confidential powerplant sample’s pH was near neutral, at 6.5. This pH is less than that most cited in the referenced literature at or above 10.

### **Standard Proctor Compaction**

The confidential powerplant sample exhibited a standard Proctor maximum dry density (MDD) of 88.5 pounds per cubic foot (pcf) at an optimum moisture content (OMC) of 19.5 percent. These values are within the ranges cited in the published literature for gypsum sludge MDDs ranging from 76 to 97 pcf and OMCs ranging from 13 to 32 percent. For visual comparison of standard Proctor compaction between the confidential powerplant sample and several standard Proctor test results from the published literature, we produced the attached *Plate 2 – Standard Proctor Comparison*.

### **Remolded Permeability**

Based on the standard Proctor compaction results, we selected the following three remolded conditions to test permeability and obtained the following results:

Percent Compaction	Moisture Content	Comments	Permeability (cm/sec)
90	12	Dry of OMC and relatively low compaction.	$5.09 \times 10^{-4}$
92	25	Wet of OMC and correspondingly lower compaction	$2.25 \times 10^{-4}$
95	19	At typical compaction requirement and OMC.	$2.53 \times 10^{-4}$

Confining pressures were set at approximately 2.5 pounds per square inch (psi), just to stabilize the specimen inside the test chamber.

The less compacted and dryer specimen (90 percent at 12 percent moisture) exhibited a higher (faster) permeability than the two better-compacted and wetter specimens. The permeability variability between the two better compacted and wetter specimens was low. As discussed in the published literature, we would expect permeability to decrease (be slower) with increased overburden (confining) pressure, but the lower confining pressure is considered more conservative for a fate and transport modeling scenario.

The measured permeabilities are within the range of those referenced in the literature of  $1 \times 10^{-3}$  to  $1 \times 10^{-6}$  cm/sec, but all are toward the faster end of this spectrum.

### Consolidation

Consolidation tests were performed at the same three remolded conditions as the permeability testing. For variability and evaluation however, two of the consolidation tests (on samples remolded to 90 percent compaction at 12 percent moisture and 95 percent compaction at 19 percent moisture) involved saturating the specimen during the test and one of the consolidation tests (on sample remolded to 92 percent compaction at 25 percent moisture) involved not saturating the sample during the test.

The two saturated specimens represent the more conventional analysis and more conventional results. That is, primary consolidation occurs as water is expelled from the internal structure voids. The more unconventional unsaturated test analysis exhibited more unconventional results, as consolidation in this unsaturated sample is likely occurring as a combination of water displacement, air displacement, particle realignment, and potentially secondary consolidation, or creep.

In any event, the compression index,  $C_c$ , ranged from 0.03 to 0.12 for the consolidation tests on the confidential powerplant sample. These values are less than those cited in the reference literature ranging from 0.2 to 0.3. Relatively speaking, the confidential powerplant samples, exhibiting lower compression indices, would undergo less consolidation than the gypsum cited in the referenced literature exhibiting higher compression indices. Related to compression indices cited for soil,  $C_c$  between 0 and 0.19 are considered to represent a material of "slight or low permeability" (Sowers, 1979). Both the laboratory tests and literature suggest that primary consolidation will occur relatively rapidly. Contrary to what might be expected,  $C_c$  did not vary inversely with the percent compaction, being highest (0.12) for the sample remolded to 95 percent compaction, lowest (0.03) for the sample remolded to 92% compaction, and between the two (0.09) for the sample remolded to 90 percent compaction.

### Total Porosity

Total porosity was computed from the void ratios measured during the consolidation testing at the initial remolded conditions and at the maximum loading conditions [8 kips per square foot (ksf)] as follows:

Percent Compaction	Moisture Content	Initial Total Porosity	Total Porosity at 8 ksf Loading
90	12	0.47	0.43
92	25	0.44	0.41
95	19	0.44	0.40

Total porosity for pure calcium sulfate was not cited in the referenced literature.

### Triaxial Shear Strength

Triaxial Shear Strength tests were performed at the same three remolded conditions as the permeability and consolidation testing. Again for variability and evaluation however, we varied the triaxial shear strength test conditions. We initially analyzed two of the specimens (samples remolded to 90 percent compaction at 12 percent moisture and 95 percent compaction at 19 percent moisture) under consolidated undrained (CU) test conditions with pore water pressure measurements and one of the specimens (sample remolded to 92 percent compaction at 25 percent moisture) to unconsolidated undrained (UU) test conditions. Theoretically, the UU test more closely models the initial placement conditions and the CU test more closely models conditions longer term after placement. The reference literature and initial test results confirmed that the UU condition was perhaps the more conservative from a strength standpoint (i.e., lower angle of internal friction). Therefore, we elected to retest two specimens remolded to 90 percent compaction at 12 percent moisture and 95 percent compaction at 19 percent moisture under the UU test conditions. A summary of the test results is provided below.

Percent Compaction	Moisture Content	Test Conditions	Total Stresses		Effective Stresses	
			Cohesion (psf)	Internal Friction Angle	Cohesion (psf)	Internal Friction Angle
90	12	UU	250	36.0	---	---
92	25	UU	470	32.1	---	---
95	19	UU	340	37.9	---	---
90	12	CU	1920	47.3	0	39.3
95	19	CU	3680	51.2	0	39.7

Overall, the triaxial shear results are the same order of magnitude as the ranges cited in the published literature, which reference one UU test condition sample exhibiting total stresses of 8 psi [1,152 pounds per square foot (psf)] cohesion and a 39 degree friction angle, and a range of effective stresses from 0 to 5 psi (720 psf) cohesion and 31 to 39 degree friction angles. Interestingly, the compaction conditions for the cited literature data are not specified.

## CONCEPTUAL SLOPE STABILITY

Complimentary to the laboratory testing data obtained, a preliminary yet primary consideration is the ability to landfill the gypsum in terms of potential development heights and slopes. While any and all site-specific landfill development cross-section(s) will need to be analyzed individually, we took this opportunity to evaluate several generalized cross-section heights and slopes for static and dynamic stability for preliminary planning purposes.

Slope stability analyses were performed using a computerized version (PCSTABL6H) of the Bishop's Modified Method of slope stability analysis. These analyses were performed for a typical cross-section of 100 feet in height (the approximate maximum being considered for the proposed gypsum disposal landfills) at inclinations of 2:1, 3:1, and 4:1 (horizontal to vertical) using undrained and drained strength parameters (total and effective stresses) with and without seismic loading. In determining the seismic loading, the probabilistic ground motions were obtained for the locations of the Cliffside, Marshall, and Belews Creek Steam Station facilities based on latitude and longitude. From the USGS seismic data, it was determined that the peak ground acceleration (PGA) for the Cliffside facility was most critical (0.18g) and therefore was used in the conceptual slope stability analysis.

The results of the stability analysis are summarized in the following table. In addition, a graphical representation of the critical failure surface for each trial section is presented in Appendix B, along with USGS Seismic Hazard Maps and probabilistic ground motions for each site.

Slope Height	Slope Inclination	Minimum Safety Factor without Seismic Loading		Minimum Safety Factor with Seismic Loading	
		Total Stresses	Effective Stresses	Total Stresses	Effective Stresses
100	2:1	1.72	1.64	1.14	1.02
100	3:1	2.35	2.45	1.34	1.37
100	4:1	2.94	3.16	1.49	1.56

## ADDITIONAL CONSIDERATIONS

Our initial geotechnical testing provides an indication that the confidential powerplant FGD scrubber sludge is at least similar to that cited in the published reference literature. Our slope stability analyses suggest that, under ideal conditions (i.e., conditions in the field similar to those of the laboratory tests), slopes on the order of 100 feet in height (as desired) can be constructed and should, at least in concept, be relatively stable against deep-seated failure. Even though our analyses suggest allowable slope inclinations of as steep as 2:1 (horizontal to vertical) with marginal factors of safety, we recommend that slope inclinations not exceed 3:1 horizontal to vertical considering surface sloughing of steeper embankments, the unfamiliarity of constructing and maintaining slopes with this FGD scrubber sludge material, access for maintenance, and increased factors of safety.

We caution again that any and all landfill development scenarios must be analyzed individually for slope stability using the site specific development cross-section(s) considering actual slope heights, inclinations, benches for access roadways and stormwater management, liner materials, cover material, regulatory requirements, and site-specific loading conditions, etc., that are not specifically included in the conceptual slope stability analysis conducted herein.

There are many aspects of landfill design and operation that are not represented by these individual laboratory tests. These include, but are certainly not limited to, material handling, moisture conditioning, erodibility, wet-weather operations, the gypsum's sensitivity to moisture contents near or above the liquid limit of 27 percent, the gypsum's response to wetting and drying cycles, etc. Accordingly, we recommend that if at all possible, an operational dry-stacking gypsum landfill be located and visited to glean additional information regarding these and other intangible aspects of the landfill development, operation, and maintenance.

Two aspects of the gypsum that we have discussed but not specifically analyzed are the potentials for liquefaction and/or swelling. One characteristic of the gypsum that is an indicator of liquefaction potential is its poor or gap gradation (i.e., most all of the material is of similar grain size). ASTM (1997), however, specifically states that "...FGD material are not susceptible to liquefaction". Later in the same document, however, it recommends "Some structural fills

constructed of...FGD material must be well drained because of the sensitivity of the material to the flow of water (that is, piping). Problems such as ...liquefaction...that may result from saturation...are thus avoided". If saturation is avoided and the FGD scrubber sludge is well compacted (avoiding a low relative density), it is our opinion that liquefaction can be avoided.

Literature (ENR 1999) and our experience indicate that some coal combustion by-products (CCBs), or combinations thereof, can be expansive. At least one combination of calcium, sulfate, aluminum, and water can produce a hydrated mineral termed "ettringite" that is expansive. Based on our discussions, we believe the aluminum component derives from blending FGD gypsum sludge (calcium sulfate) with fly ash that we understand is not anticipated at the project facilities. Nonetheless, it may be prudent to test the FGD scrubber sludge for swelling. It is noteworthy that ASTM (1997) references that "Reactions producing the expansive properties to not commence for a period of more than 30 days after initial ash hydration". Therefore, this test could be set and run as plans for landfill development continue.

## CLOSURE

S&ME certainly appreciates this and every opportunity we have to be of service to Duke Energy and Duke Power. We trust this information is responsive to your needs at this time. If you have questions regarding this report, or if we can be of further assistance, please to not hesitate to contact us at your convenience.

Sincerely,

**S&ME, Inc.**

Larry Armstrong, P.E.  
Senior Engineer/Project Manager



*Howard Perry*  
M. Howard Perry, P.E.  
Senior Engineer/Branch Manager

File: S:\env\2003\projects\6403357\FGD Scrubber Sludge Testing Results (Revision 1)

## REFERENCES

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- Kovacs, Robert D. and Kovacs, William D., 1981, An Introduction to Geotechnical Engineering, Prentice Hall, Inc.
- Krizek, M. ASCE, S. C. Chu, and D. K. Atmatzidis M. ASCE, undated, *Geotechnical Properties and Landfill Disposal of FGD Sludge*.
- S&ME, December 4, 2001, *Soil Sample Laboratory Report*, Belews Creek Ash Landfill.
- Smith, Charles L., 1992, *FGD Waste Engineering Properties are Controlled by Disposal Choice*, from Inyang, Hilary I. And Bergeson, Kenneth L., Utilization of Waste Materials in Civil Engineering Construction, ASCE.
- Sowers, George F., 1979, Introductory Soil Mechanics and Foundations: Geotechnical Engineering, 4<sup>th</sup> Edition, Macmillan Publishing Co., Inc.

Tables

**TABLE 1**  
**SUMMARY OF LABORATORY TESTING RESULTS - INDEX PROPERTIES**  
**DUKE ENERGY FGD SCRUBBER SLUDGE**  
**CHARLOTTE, NORTH CAROLINA**  
**S&ME Project 1264-03-057**

Sample Type or Remolded Conditions	Grain Size Distribution		Atterberg Limits		USCS Classification		Standard Proctor		Natural Moisture (%)	Specific Gravity	pH	
	Clay (%)	Silt (%)	Liquid Limit	Plastic Index	Symbol	Description	MDD (pcf)	OMC (%)				
Bulk	2.5	97.3	27	26	1	ML	Silt	88.5	19.5	11.8	2.35	6.5
Literature	2.2	81.3	Non-Plastic			ML	Silt	76 to 97	13 to 32	No Reference	2.35	10

**NOTES**

1. USCS = Unified Soil Classification System
2. MDD = Maximum Dry Density
3. OMC = Optimum Moisture Content
4. pcf = pounds per cubic foot

**TABLE 2**  
**SUMMARY OF LABORATORY TESTING RESULTS - ENGINEERING PROPERTIES**  
**DUKE ENERGY FGD SCRUBBER SLUDGE**  
**CHARLOTTE, NORTH CAROLINA**  
**S&ME Project 1264-03-057**

Remolded Sample Conditions	Permeability		Consolidation Index, Cc	Total Porosity		Test Type	Triaxial Shear			
	Confining Pressure (psi)	Permeability (cm/sec)		Initial	8 ksf		Total		Effective	
							c (psf)	f (degrees)	c' (psf)	f' (degrees)
90% @ 12%	2.5	$5.09 \times 10^{-4}$	0.09	0.47	0.43	UU	250	36.0	---	---
92% @ 25%	2.5	$2.25 \times 10^{-4}$	0.03	0.44	0.41	UU	470	32.1	---	---
95% @ 19%	2.5	$2.53 \times 10^{-4}$	0.12	0.44	0.40	UU	340	37.9	---	---
90% @ 12%	---	---	---	---	---	CU	1920	47.3	0	39.3
95% @ 19%	---	---	---	---	---	CU	3680	51.2	0	39.7
Literature	No Reference	$1 \times 10^{-3}$ to $1 \times 10^{-6}$	0.2 to 0.3	No Reference		UU	1152	39	---	---
				CU	---	---	0 to 720	31 to 39		

**NOTES**

1. ksf = kips per square foot
2. psi = pounds per square inch
3. cm/sec = centimeters per second
4. psf = pounds per square foot
5. CU = consolidated, undrained
6. UU = unconsolidated, undrained
7. Remolded Sample Conditions not specified for Literature values.

# Appendix A





# Particle Size Analysis of Soils

Laboratory record version 4.0

Report Date:

AY 10, 2003

Project #: 1264-03-057  
 Project Name: Duke Energy FGD Scrubber Output Testing  
 Client Name: \_\_\_\_\_  
 Client Address: \_\_\_\_\_  
 Boring #: Bucket Sample  
 Location: Confidential Powerplant  
 Sample Description: FGD Scrubber Sludge  
 Test Date(s): 2/20/2003-2/24/2003  
 Sample Date: \_\_\_\_\_  
 Elevation: \_\_\_\_\_  
 Liquid Limit: 27  
 Plastic Limit: 26  
 Plastic Index: 1

Pan #:	text	Beaker #:	text	Specific Gravity:	2.350
Hydrometer Jar #:	text		text	Pan # (washed sample):	text
Pan Tare Weight (grams):	0.00		0.00	Moisture Content	Natural
Total Sample Wet Wt. + tare wt. (grams):	381.46		381.46	Tare #	2
Weight of Total Sample Air Dried:	66.29		66.29	Tare Wt.	11.58
Weight of Air Dried Hydrometer Sample (g):	380.76		380.76	Wet Wt. + A	22.53
Total Sample Oven Dried:	66.17		66.17	Dry Wt. + A	22.51
Hydrometer Sample Oven Dried (W):	100.0%		100.0%	Water Wt. (B-C)	0.02
% Passing #10:	1.09		1.09	Dry Wt.(C-A)	10.93
Correction Factor a (Table 1):				% Moisture (100 x D/E)	0.18%

Notes:	Description of Sand & Gravel Particles:	Rounded	Angular	Hard & Durable	Soft	Weathered & Friable
Maximum Particle Size:	0.075 mm	19 mm	< 4.74 mm and > 0.075 mm			
% Gravel:	0.0%	< 75 mm and > 4.75 mm	< 0.075			
Coarse Sand:	0.0%	< 4.75 mm and > 2.00 mm	Silt: 97.2%	< 0.075 and > 0.005 mm		
Medium Sand:	0.2%	< 2.00 mm and > 0.425 mm	Clay: 2.6%	< 0.005 mm		
Fine Sand:	0.0%	< 0.425 mm and > 0.075 mm	Colloids: 2.6%	< 0.001 mm		

Time	Temp. (°C)	Hydrometer Reading	Corrections		Hydrometer R	Percent Passing		Table 2 L	Table 3 K	Diameter D = K x (L/T) <sup>1/2</sup>
			Control Cylinder	Composite Correction		P(-#10) = (R x a / W) x 100	P x % Passing #10			
2	21.6	32.0	6.3	6.3	25.7	42.3%	42.3%	11.1	0.0149	0.03519
5	21.6	13.0	6.3	6.3	6.7	11.0%	11.0%	14.2	0.0149	0.02517
15	21.6	9.0	6.3	6.3	2.7	4.4%	4.4%	14.8	0.0149	0.01484
30	21.5	8.0	6.3	6.3	1.7	2.8%	2.8%	15.0	0.0149	0.01056
60	21.6	8.0	6.3	6.3	1.7	2.8%	2.8%	15.0	0.0149	0.00747
250	22.0	8.0	6.4	6.4	1.6	2.6%	2.6%	15.0	0.0148	0.00362
1440	21.1	8.0	6.2	6.2	1.8	3.0%	3.0%	15.0	0.0149	0.00152
			#N/A	#N/A	#N/A	#N/A	3.0%	16.3	#N/A	0.00152

**References:**  
 ASTM D 421: Dry Preparation of Soil Samples  
 ASTM D 2216: Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass  
 ASTM D 4318: Liquid Limit, Plastic Limit, & Plastic Index of Soils  
 ASTM D 2487: Classification of Soils for Engineering Purposes (Unified Soil Classification System)

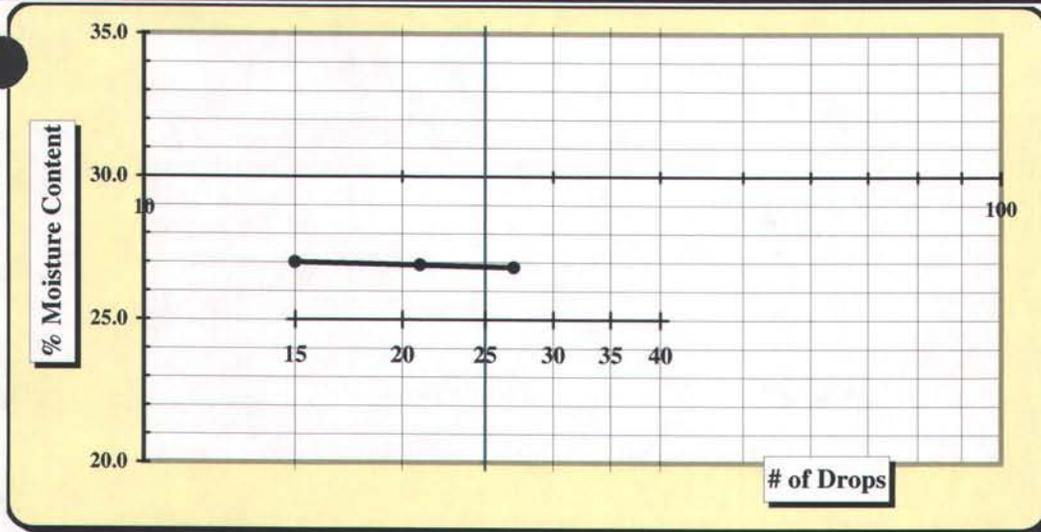
**Technical Responsibility:** William Schwartz  
**Position:** Construction Services Manager  
**Amended Report**



# Liquid Limit, Plastic Limit, and Plastic Index

Project #: 1264-03-057 Report Date: February 24, 2003  
 Project Name: Duke Energy FGD Scrubber Output Testing Test Date(s): 2-20/2-21  
 Client Name: Duke Energy  
 Client Address: Charlotte, North Carolina  
 Boring #: Bucket Sample Lab No. 103 Sample Date:  
 Location: Confidential Powerplant Offset: Elevation:  
 Sample Description: FGD Scrubber Sludge

Pan #	Test #	Liquid Limit						Plastic Limit		
		1	2	3	4	5	6	1	2	3
	Tare #	S-2	18	32				1	S-5	
A	Tare Weight	10.90	12.11	11.52				12.12	10.83	
B	Wet Soil Weight + A	27.31	28.71	26.95				21.91	19.05	
C	Dry Soil Weight + A	23.84	25.19	23.67				19.88	17.34	
D	Water Weight (B-C)	3.47	3.52	3.28				2.03	1.71	
E	Dry Soil Weight (C-A)	12.94	13.08	12.15				7.76	6.51	
F	% Moisture Content (D/E)*100	26.8%	26.9%	27.0%				26.2%	26.3%	
N	# OF DROPS	27	21	15						
LL	LL = F * FACTOR									
Ave.	Average								26.2%	



N	Factor	N	Factor
20	0.974	26	1.005
21	0.979	27	1.009
22	0.985	28	1.014
23	0.990	29	1.018
24	0.995	30	1.022
25	1.000		

Notes: Estimate the % Retained on the #40 Sieve 0.01

Special Sampling Methods:				% Passing #200 Sieve	99.9
Sample Preparation:	Wet Preparation <input type="checkbox"/>	Dry Preparation <input type="checkbox"/>	Air Dried <input checked="" type="checkbox"/>	NP, Non-Plastic	<input type="checkbox"/>
Liquid limit Test:	Multipoint Method <input checked="" type="checkbox"/>	One-point Method <input type="checkbox"/>		Liquid Limit	27
Classification:	ASTM D 2487 <input checked="" type="checkbox"/>	AASHTO M 145 <input type="checkbox"/>		Plastic Limit	26
Liquid limit Test:	ASTM D 4318 <input checked="" type="checkbox"/>	AASHTO T 89 <input type="checkbox"/>		Plastic Index	1
Plastic limit Test:	ASTM D 4318 <input checked="" type="checkbox"/>	AASHTO T 90 <input type="checkbox"/>		Group Symbol	ML

Technician Name / Certification #: P. Birchall  
 Technical Responsibility / Position: William Schwartz / Construction Services Manager

# Moisture - Density Report

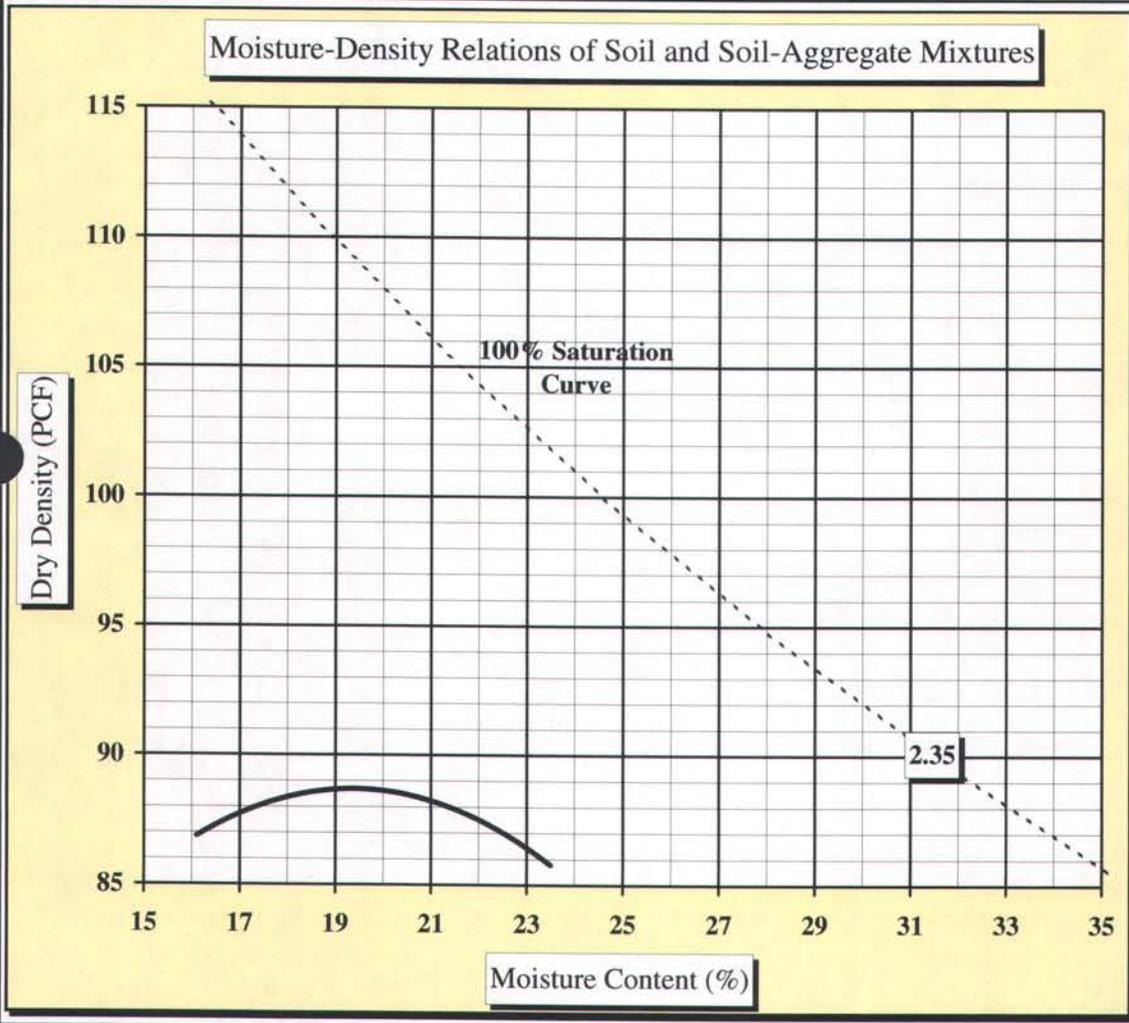


**S&ME Project #:** 1264-03-057  
**Project Name:** Duke Energy FGD Scrubber Output Testing  
**Client Name:** Duke Energy  
**Client Address:** Charlotte, North Carolina

**Report Date:** April 10, 2003  
**Test Date(s):** 2/20/03 - 2/21/03

**Boring #:** Bucket Sample      **Lab No.:** 103      **Sample Date:**  
**Location:** Confidential Powerplant      **Offset:**      **Depth:** 1/0/1900  
**Sample Description:** FGD Scrubber Sludge

<b>Maximum Dry Density</b>	<b>88.5 PCF.</b>	<b>Optimum Moisture Content</b>	<b>19.5 %</b>
ASTM D558 <input type="checkbox"/>	ASTM D 698 <input checked="" type="checkbox"/>	ASTM D1557 <input type="checkbox"/>	AASHTO T99 <input type="checkbox"/>
Method A <input checked="" type="checkbox"/>	Method B <input type="checkbox"/>	Method C <input type="checkbox"/>	Method D (1978) <input type="checkbox"/>
			AASHTO T180 <input type="checkbox"/>
			AASHTO Method D <input type="checkbox"/>



Soil Properties	
Natural Moisture Content	11.8%
Liquid Limit:	27
Plastic Limit:	26
Plastic Index:	1
Specific Gravity:	2.350
% Passing	
3/4"	
1/2"	
3/8"	
#4	
#10	
#40	
#60	
#200	99.8
Oversize Fraction	
Bulk Sp. Gravity	
% Moisture	
Oversize Fraction	

Moisture-Density Curve Displayed: Fine Fraction  Corrected for Oversize Fraction (ASTM D 4718)   
 Sieve Size used to separate the Oversize Fraction: #4 Sieve  3/8 inch Sieve  3/4 inch Sieve   
 Mechanical Hammer  Manual Hammer  Moist Preparation  Dry Preparation

**References:** ASTM D 698: Laboratory Compaction Characteristics of Soil Using Standard Effort

ASTM D 2216: Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

Technical Responsibility: William Schwartz      Construction Services Manager

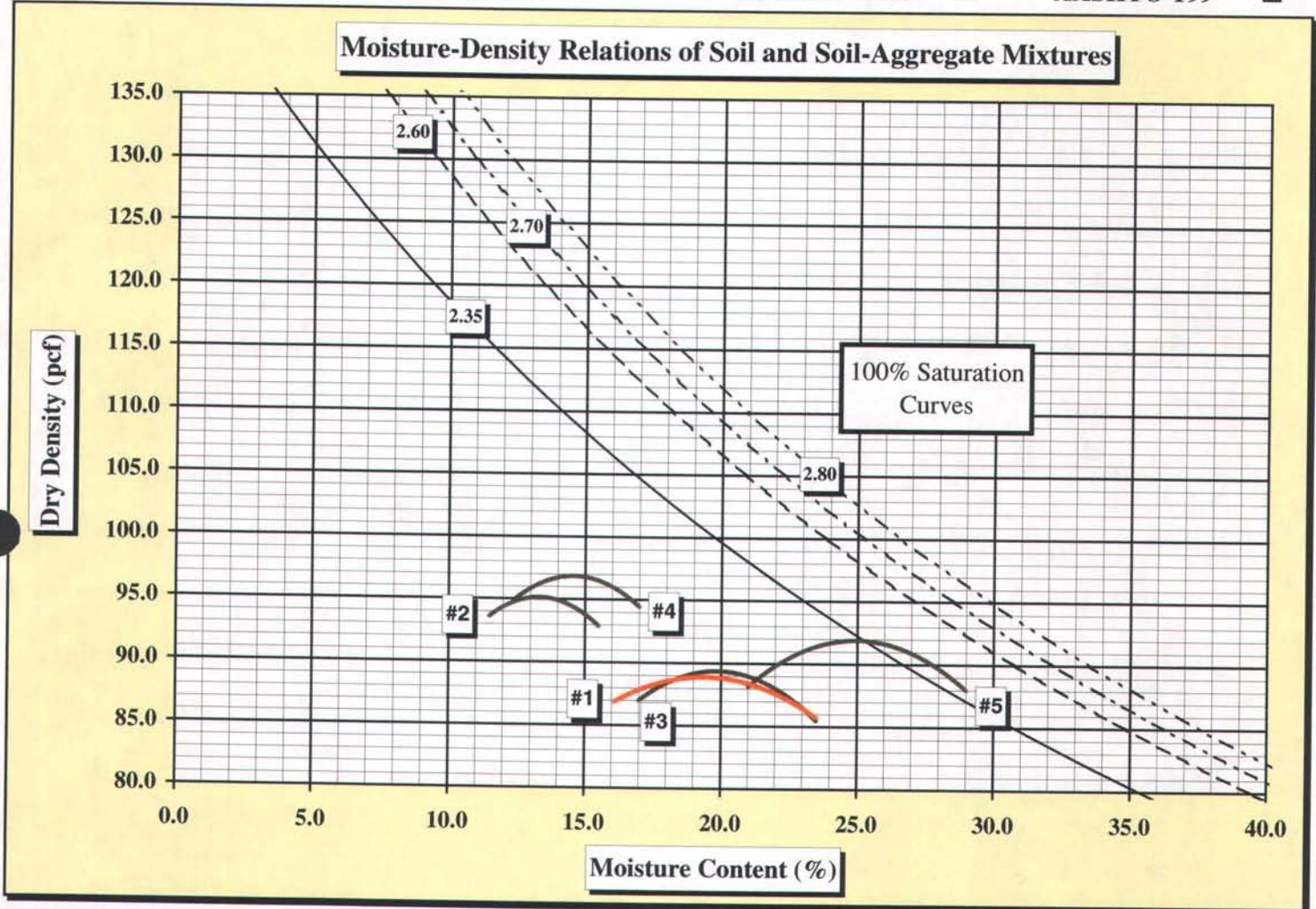
# Plate 2 - Standard Proctor Comparison



**Project #:** 1264-03-057  
**Project Name:** Duke Energy FGD Scrubber Output Testing  
**Client Name:** Duke Energy  
**Client Address:** Charlotte, North Carolina

**Test Date:** April 10, 2003  
**Test Date:** 2/20/03 - 2/21/03

ASTM D 698       ASTM D1557       AASHTO T180       AASHTO T99



Curve #	Soil Description	Method	Opt. MC	MDD	LL	PI	Nat. % W
1	FGD Scrubber Sludge	D 698A	19.50%	88.5	27	1	11.8%
2	Krizek, Chu and Atmatzidis (undated)						
3	Krizek, Chu and Atmatzidis (undated)						
4	Krizek, Chu and Atmatzidis (undated)						
5	Krizek, Chu and Atmatzidis (undated)						

**References:** ASTM D 698: Laboratory Compaction Characteristics of Soil Using Standard Effort  
 ASTM D 2487: Classification of Soils for Engineering Purposes (Unified Soil Classification System)  
 ASTM D 4318: Liquid Limit, Plastic Limit, & Plastic Index of Soils AASHTO T90: Determining the Plastic Limit & Plastic Index of Soil

Name (Technical Responsibility)

Position





## CONSTANT HEAD PERMEABILITY

ASTM D5084

S&ME Project Number: 1264-03-057      Project Name: FGD SCRUBBER WASTE TESTING      Date: 3/26/03

Sample Name: BULK 95%

Sample Description: FGD SCRUBBER SLUDGE

Type of Sample: Remolded

Sample Data	Molding Moisture Content			Target Molding Condition			Additional Data		
	Tare No.	O	$\gamma_{wet}$ (pcf)	$\gamma_{dry}$ (pcf)	Panel No	Panel No	Cell P (psi)	Cell P (psi)	8
D (cm)	7.277								
L (cm)	7.62	261.88							83.5
A (cm <sup>2</sup> )	41.59	232.68							81.0
V (cm <sup>3</sup> )	316.92	29.2	Actual Molding Condition						80.0
WWS (gm)	507.4	81.21	$\gamma_{wet}$ (pcf)		Gs				2.35
		151.47	$\gamma_{dry}$ (pcf)		n				0.31
		19.3	w (%)						

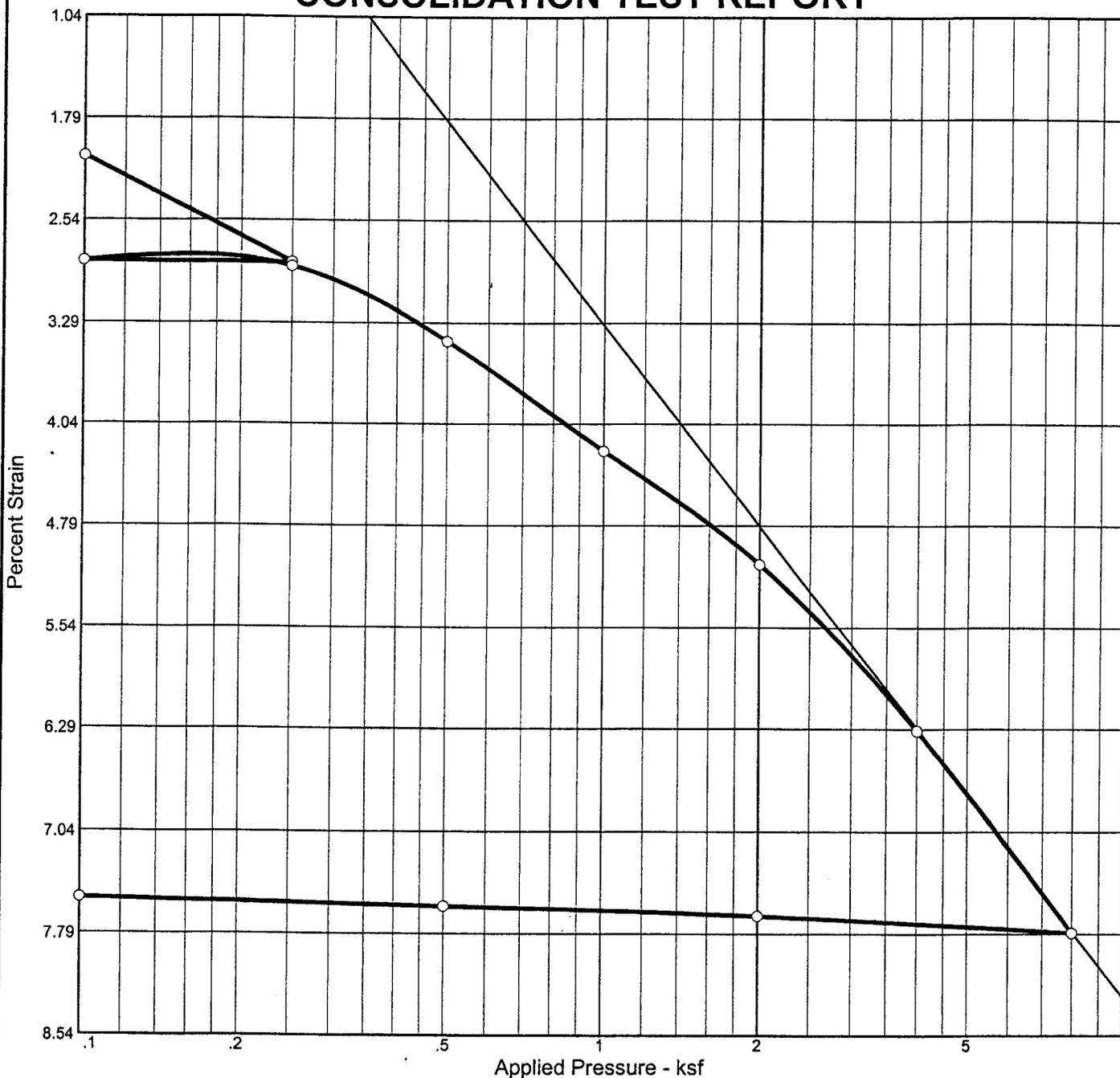
$$K = (Q \times L) / (t \times H \times A)$$

Run	Temp. (°C)	Hour	Minute	Time, t (sec)	BURRETTE 1 (cc)	BURRETTE 2 (cc)	BURRETTE 3 (cc)	Q (cc)	$\Delta H$ (cm)	Temp Corr.	K (cm/sec)
1		0	0		17.8	0.0	24.8	24.8	70.4	0.9530	2.56E-04
2	22	0	4	240	17.9	24.8	0.0	24.8			
3	22	0	4	240	17.9	0.3	24.8	24.8	70.4	0.9530	2.54E-04
4	22	0	4	240	17.9	24.8	0.1	24.8			
5	21	0	4	240	18	0.1	24.6	24.6	70.4	0.9530	2.54E-04
6	21	0	4	240	18	24.5	0.1	24.7	70.4	0.9760	2.59E-04
7					18	0.1	23.0	24.7	70.4	0.9760	2.44E-04
8								1.5			
9											
10											

AVG. K  
(Runs 2 thru 5)

2.53E-04

# CONSOLIDATION TEST REPORT



Natural		Dry Dens. (pcf)	LL	PI	Sp. Gr.	P <sub>c</sub> (ksf)	C <sub>c</sub>	Initial Void Ratio
Saturation	Moisture							
32.2 %	12.1 %	79.1	27	1	2.35	2.43	0.09	0.885

<b>MATERIAL DESCRIPTION</b>		<b>USCS</b>	<b>AASHTO</b>
FGD SCRUBBER SLUDGE		ML	

<p><b>Project No.</b> 1264-03-057    <b>Client:</b> DUKE ENERGY</p> <p><b>Project:</b> FGD SCRUBBER WASTE TESTING</p> <p><b>Location:</b> CONFIDENTIAL POWERPLANT</p> <p style="text-align: center;">CONSOLIDATION TEST REPORT</p> <p style="text-align: center;"><b>S &amp; ME, INC.</b></p>	<p><b>Remarks:</b> SATURATED/REMOLDED</p> <p style="text-align: right;"><b>SAMPLE S-1,(90%)</b></p>
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**CONSOLIDATION TEST DATA**

Client: DUKE ENERGY  
 Project: FGD SCRUBBER WASTE TESTING  
 Project Number: 1264-03-057

**Sample Data**

Source:  
 Sample No.: S-1 (90%)  
 Elev. or Depth: Sample Length (in./cm.):  
 Location: CONFIDENTIAL POWERPLANT  
 Description: FGD SCRUBBER SLUDGE  
 Liquid Limit: 27 Plasticity Index: 1  
 USCS: ML AASHTO: Figure No.: S-1, (90%)  
 Testing Remarks: SATURATED/REMOLDED

**Test Specimen Data**

TOTAL SAMPLE	BEFORE TEST	AFTER TEST
Wet w+t = 294.72 g.	Consolidometer # = 6	Wet w+t = 239.73 g.
Dry w+t = 271.73 g.		Dry w+t = 211.17 g.
Tare Wt. = 82.28 g.	Spec. Gravity = 2.35	Tare Wt. = 111.36 g.
Height = 1.00 in.	Height = 1.00 in.	
Diameter = 2.49 in.	Diameter = 2.49 in.	
Weight = 113.59 g.	Defl. Table = Consolidometer #6	
Moisture = 12.1 %	Ht. Solids = 0.5310 in.	Moisture = 28.6 %
Wet Den. = 88.7 pcf	Dry Wt. = 101.40 g.	Dry Wt. = 99.81 g.*
Dry Den. = 79.1 pcf	Void Ratio = 0.885	Void Ratio = 0.743
	Saturation = 32.2 %	

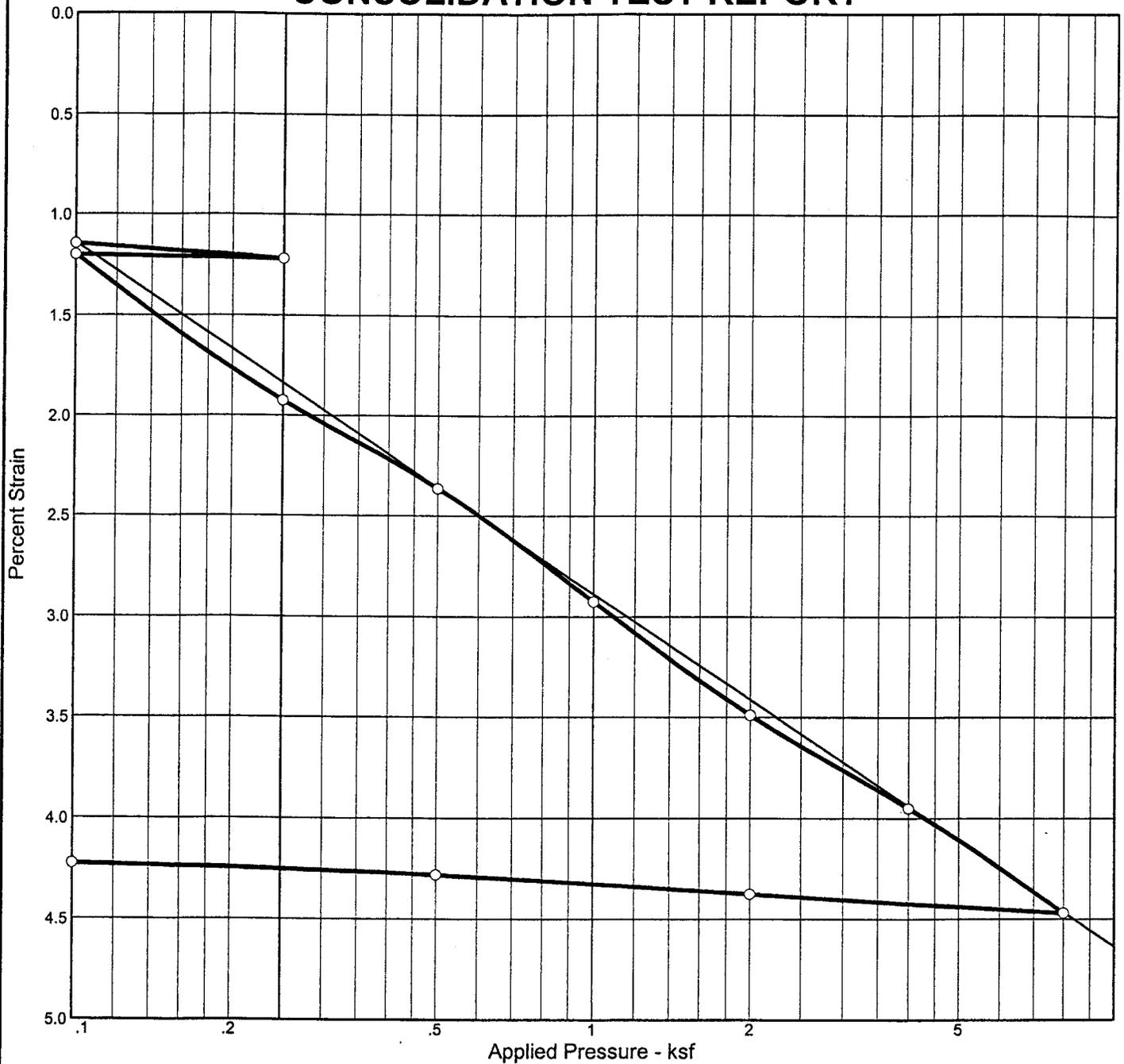
\* Final dry weight used in calculations

**End-of-Load Summary**

Pressure (ksf)	Final Dial (in.)	Machine Defl. (in.)	$C_v$ (ft. <sup>2</sup> /day)	$C_\alpha$	Void Ratio	% Compression /Swell
start	0.22390				0.885	
0.10	0.20320	0.00000	5.89		0.846	2.1 Comprs.
0.25	0.19540	0.00000	0.74		0.832	2.8 Comprs.
0.10	0.19550	0.00000	0.14		0.832	2.8 Comprs.
0.25	0.19510	0.00000	0.66		0.831	2.9 Comprs.
0.50	0.18960	0.00000	0.76		0.821	3.4 Comprs.
1.00	0.18145	0.00000	0.65		0.805	4.2 Comprs.
2.00	0.17310	0.00000	0.68		0.790	5.1 Comprs.
4.00	0.16080	0.00000	0.76		0.766	6.3 Comprs.
8.00	0.14600	0.00000	0.11		0.739	7.8 Comprs.
2.00	0.14725	0.00000	0.62		0.741	7.7 Comprs.
0.50	0.14795	0.00000	0.08		0.742	7.6 Comprs.
0.10	0.14855	0.00000	0.59		0.743	7.5 Comprs.

$C_c = 0.09$     $P_c = 2.43$  ksf    $C_r = 0.00$

# CONSOLIDATION TEST REPORT



Natural		Dry Dens. (pcf)	LL	PI	Sp. Gr.	P <sub>c</sub> (ksf)	C <sub>c</sub>	Initial Void Ratio
Saturation	Moisture							
74.5 %	24.8 %	81.7	27	1	2.35	0.01	0.03	0.783

<b>MATERIAL DESCRIPTION</b>							<b>USCS</b>	<b>AASHTO</b>
FGD SCRUBBER SLUDGE							ML	

<p><b>Project No.</b> 1264-03-057    <b>Client:</b> DUKE ENERGY</p> <p><b>Project:</b> FGD SCRUBBER WASTE TESTING</p> <p><b>Location:</b> CONFIDENTIAL POWERPLANT</p> <p style="text-align: center;">CONSOLIDATION TEST REPORT</p> <p style="text-align: center;"><b>S &amp; ME, INC.</b></p>	<p><b>Remarks:</b> UNSATURATED/REMOLDED</p> <p style="text-align: right;">SAMPLE S-3,(92%)</p>
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**CONSOLIDATION TEST DATA**

Client: DUKE ENERGY  
 Project: FGD SCRUBBER WASTE TESTING  
 Project Number: 1264-03-057

**Sample Data**

Source:  
 Sample No.: S-3 (92%)  
 Elev. or Depth: Sample Length (in./cm.):  
 Location: CONFIDENTIAL POWERPLANT  
 Description: FGD SCRUBBER SLUDGE  
 Liquid Limit: 27 Plasticity Index: 1  
 USCS: ML AASHTO: Figure No.: S-3, (92%)  
 Testing Remarks: UNSATURATED/REMOLDED

**Test Specimen Data**

TOTAL SAMPLE	BEFORE TEST	AFTER TEST
Wet w+t = 375.53 g.	Consolidometer # = 6	Wet w+t = 218.86 g.
Dry w+t = 317.04 g.		Dry w+t = 216.79 g.
Tare Wt. = 81.49 g.	Spec. Gravity = 2.35	Tare Wt. = 111.37 g.
Height = 1.00 in.	Height = 1.00 in.	
Diameter = 2.49 in.	Diameter = 2.49 in.	
Weight = 130.69 g.	Defl. Table = Consolidometer #6	
Moisture = 24.8 %	Ht. Solids = 0.5608 in.	Moisture = 2.0 %
Wet Den. = 102.0 pcf	Dry Wt. = 104.69 g.	Dry Wt. = 105.42 g.*
Dry Den. = 81.7 pcf	Void Ratio = 0.783	Void Ratio = 0.708
	Saturation = 74.5 %	

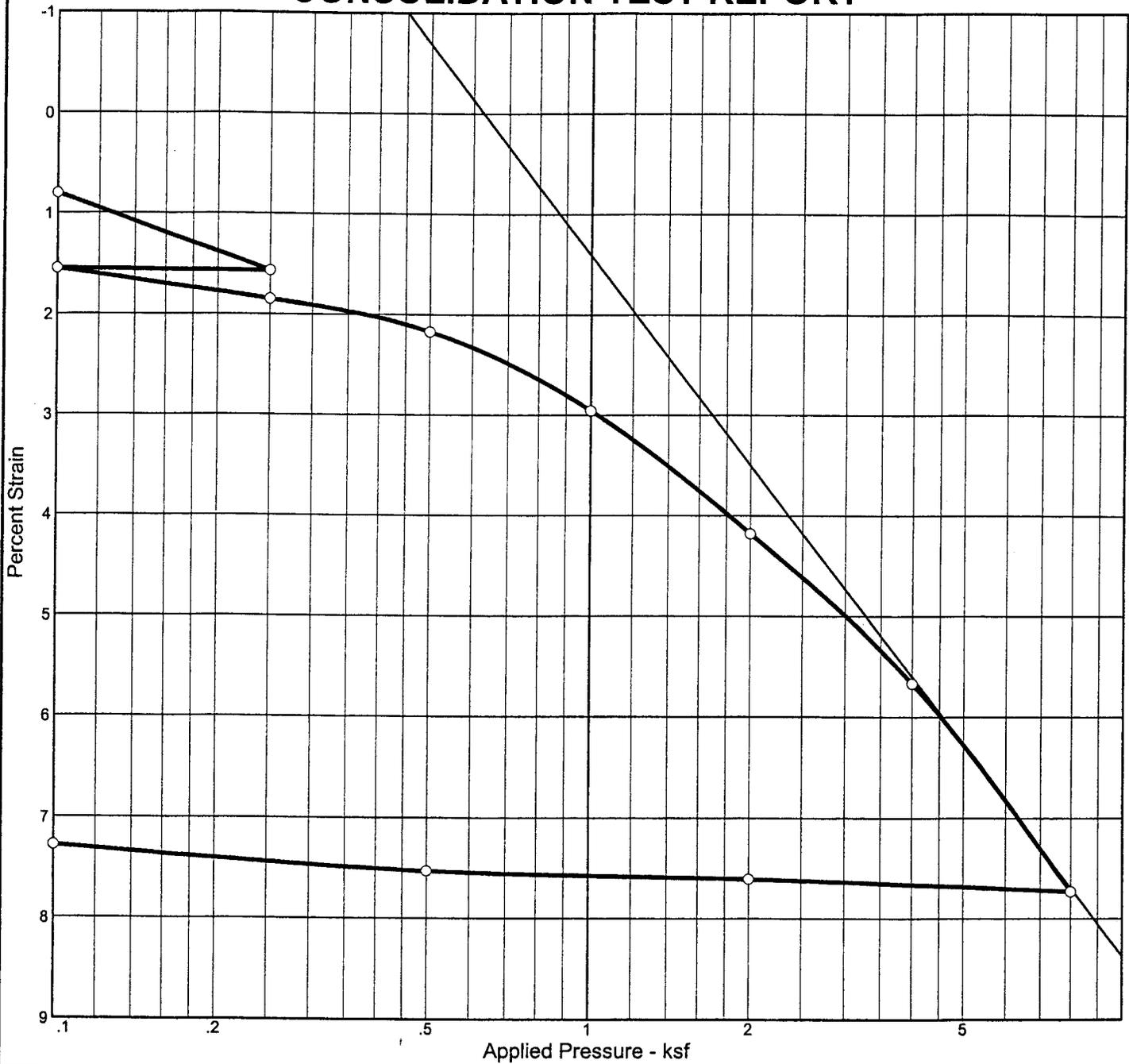
\* Final dry weight used in calculations

**End-of-Load Summary**

Pressure (ksf)	Final Dial (in.)	Machine Defl. (in.)	$C_v$ (ft. <sup>2</sup> /day)	$C_\alpha$	Void Ratio	% Compression / Swell
start	0.24230				0.783	
0.10	0.23085	0.00000	0.10		0.763	1.1 Comprs.
0.25	0.23010	0.00000	0.24		0.761	1.2 Comprs.
0.10	0.23030	0.00000	0.09		0.762	1.2 Comprs.
0.25	0.22305	0.00000	0.11		0.749	1.9 Comprs.
0.50	0.21865	0.00000	0.44		0.741	2.4 Comprs.
1.00	0.21305	0.00000	0.18		0.731	2.9 Comprs.
2.00	0.20740	0.00000	0.10		0.721	3.5 Comprs.
4.00	0.20280	0.00000	0.12		0.713	3.9 Comprs.
8.00	0.19760	0.00000	0.22		0.703	4.5 Comprs.
2.00	0.19855	0.00000	0.04		0.705	4.4 Comprs.
0.50	0.19950	0.00000	5.87		0.707	4.3 Comprs.
0.10	0.20005	0.00000	5.88		0.708	4.2 Comprs.

$C_c = 0.03$     $P_c = 0.01$  ksf    $C_r = 0.01$

# CONSOLIDATION TEST REPORT



Natural		Dry Dens. (pcf)	LL	PI	Sp. Gr.	P <sub>c</sub> (ksf)	C <sub>c</sub>	Initial Void Ratio
Saturation	Moisture							
57.5 %	19.4 %	83.3	27	1	2.35	1.96	0.12	0.791

<b>MATERIAL DESCRIPTION</b>		<b>USCS</b>	<b>AASHTO</b>
FGD SCRUBBER SLUDGE		ML	

<b>Project No.</b> 1264-03-057 <b>Client:</b> DUKE ENERGY <b>Project:</b> FGD SCRUBBER WASTE TESTING <b>Location:</b> CONFIDENTIAL POWERPLANT	<b>Remarks:</b> SATURATED/REMOLDED
CONSOLIDATION TEST REPORT <h2 style="margin: 0;">S &amp; ME, INC.</h2>	
<b>SAMPLE S-2,(95%)</b>	

TRIAXIAL COMPRESSION TEST  
Unconsolidated Undrained

4-22-2003  
11:08 am

Project and Sample Data

Date: 4/13/2003  
Client: DUKE ENERGY  
Project: FGD SCRUBBER WASTE TESTING  
Sample location: CONFIDENTIAL POWERPLANT  
Sample description: FGD SCRUB. SLUDGE  
Remarks: BULK-90% @12%

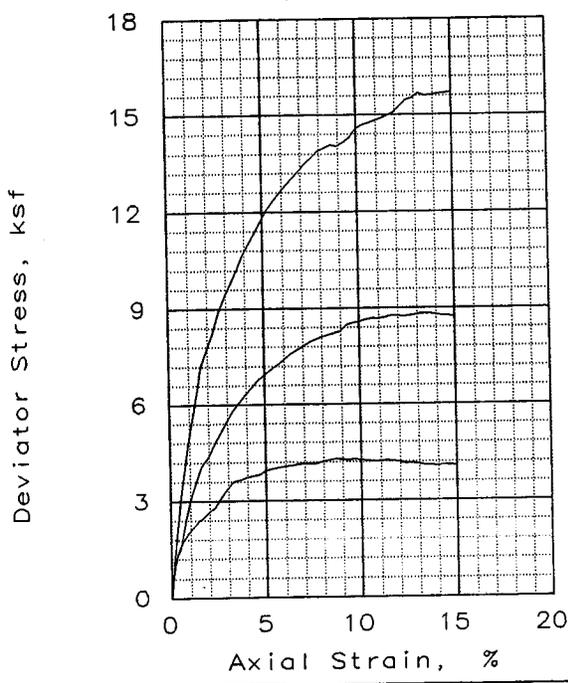
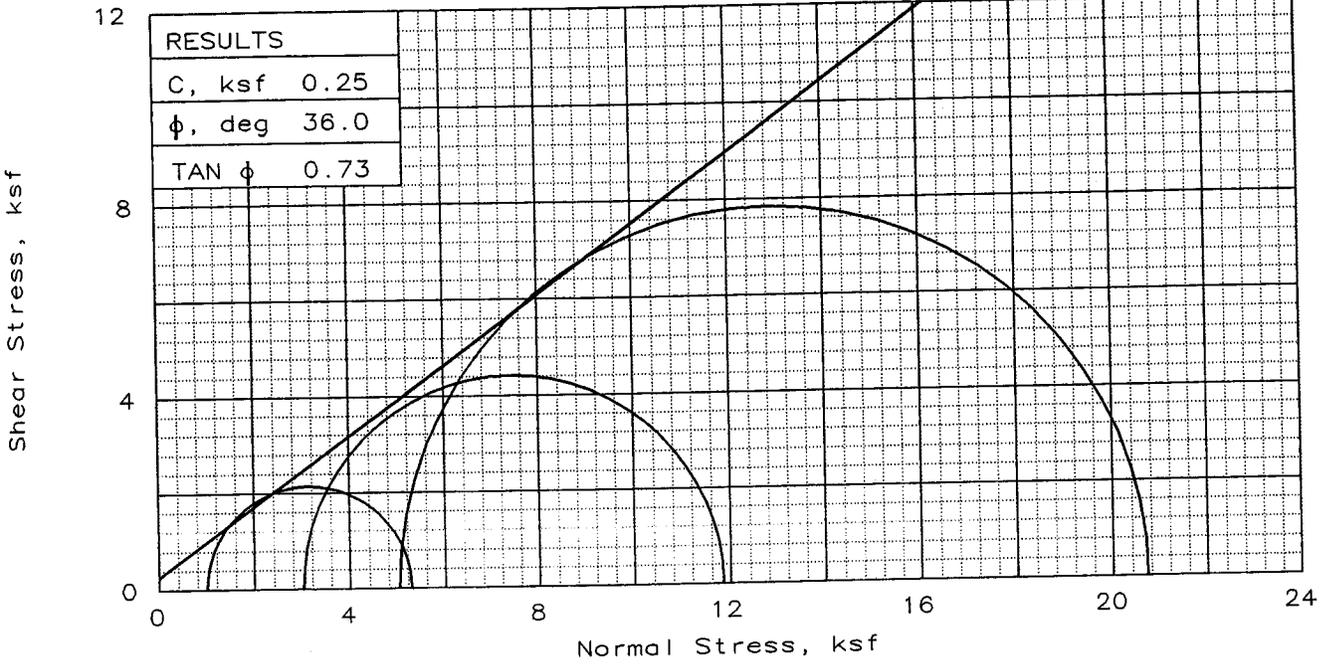
Fig no.: BULK-90% 2nd page Fig no. (if applicable):  
Type of sample: REMOLDED  
Specific gravity= 2.35 LL= 27 PL= 26 PI= 1  
Test method: ASTM - Method A

Specimen Parameters for Specimen No. 1

Specimen Parameter	Initial	Saturated	Final
Wt. moist soil and tare:	338.960		622.500
Wt. dry soil and tare:	310.480		570.100
Wt. of tare:	81.840		153.260
Weight, gms:	908.2		
Diameter, in:	2.873	2.873	
Area, in <sup>2</sup> :	6.483	6.483	
Height, in:	6.000	6.000	
Net decrease in height, in:		0.000	
% Moisture:	12.5	12.6	12.6
Wet density, pcf:	89.0	89.0	
Dry density, pcf:	79.1	79.1	
Void ratio:	0.8547	0.8547	
% Saturation:	34.2	34.6	

Test Readings Data for Specimen No. 1

Deformation dial constant= 0.001 in per input unit  
Primary load ring constant= 1 lbs per input unit  
Secondary load ring constant= 1 lbs per input unit  
Crossover reading for secondary load ring= 45 input units  
Cell pressure = 7.00 psi = 1.01 ksf  
Back pressure = 0.00 psi = 0.00 ksf  
Effective confining stress = 1.01 ksf  
Strain rate, in/min = 0.0040  
FAIL. STRESS = 4.28 ksf at reading no. 31  
ULT. STRESS = not selected



SAMPLE NO.:		1	2	3
INITIAL	WATER CONTENT, %	12.5	12.5	12.5
	DRY DENSITY, pcf	79.1	79.0	78.4
	SATURATION, %	34.2	34.1	33.6
	VOID RATIO	0.855	0.858	0.871
	DIAMETER, in	2.87	2.87	2.87
	HEIGHT, in	6.00	6.00	6.03
AT TEST	WATER CONTENT, %	12.6	12.5	12.1
	DRY DENSITY, pcf	79.1	79.0	78.4
	SATURATION, %	34.6	34.3	32.7
	VOID RATIO	0.855	0.858	0.871
	DIAMETER, in	2.87	2.87	2.87
	HEIGHT, in	6.00	6.00	6.03
Strain rate, in/min		0.0040	0.0040	0.0040
BACK PRESSURE, ksf		0.0	0.0	0.0
CELL PRESSURE, ksf		1.0	3.0	5.0
FAIL. STRESS, ksf		4.3	8.8	15.7
STRAIN, %		8.7	13.7	14.9
ULT. STRESS, ksf				
STRAIN, %				
$\sigma_1$ FAILURE, ksf		5.3	11.9	20.7
$\sigma_3$ FAILURE, ksf		1.0	3.0	5.0

TYPE OF TEST:  
Unconsolidated Undrained

SAMPLE TYPE: REMOLDED

DESCRIPTION: FGD SCRUB. SLUDGE

LL= 27      PL= 26      PI= 1

SPECIFIC GRAVITY= 2.35

REMARKS: BULK-90% @12%

Fig. No.: BULK-90%

CLIENT: DUKE ENERGY

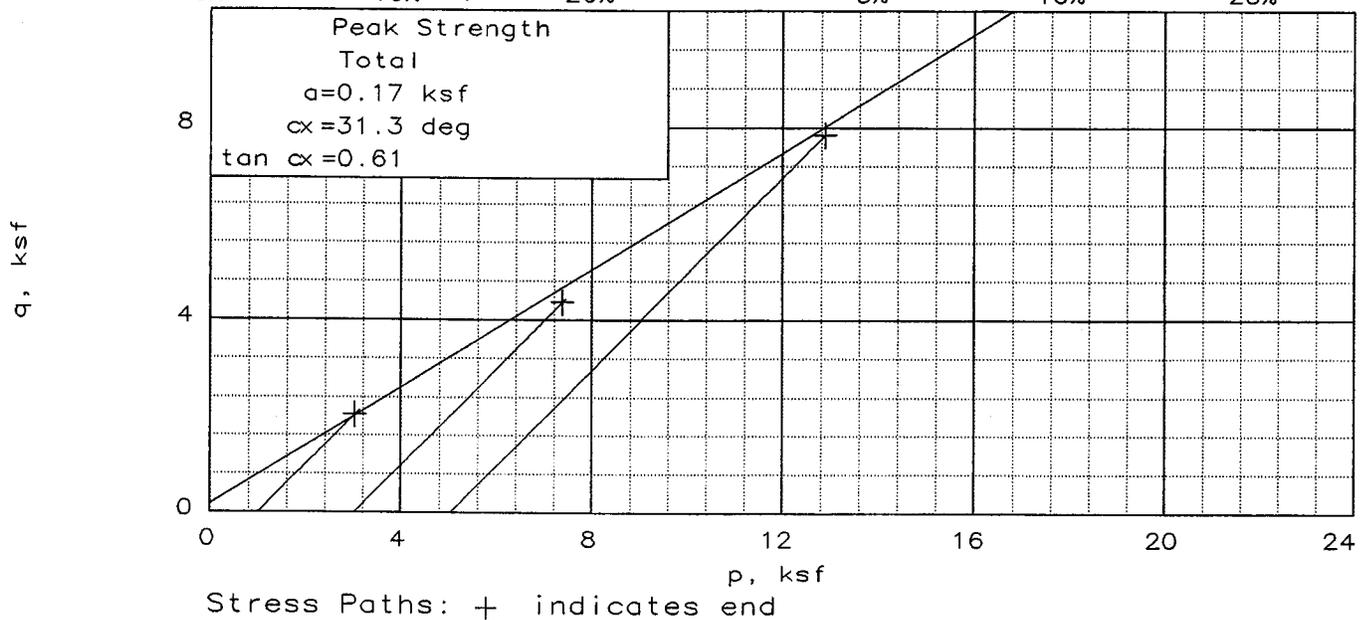
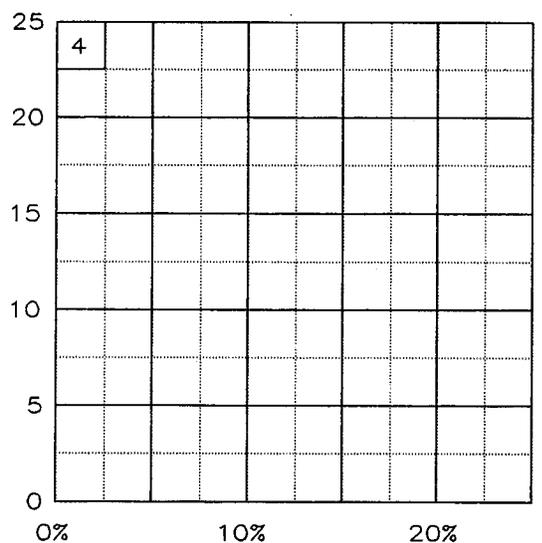
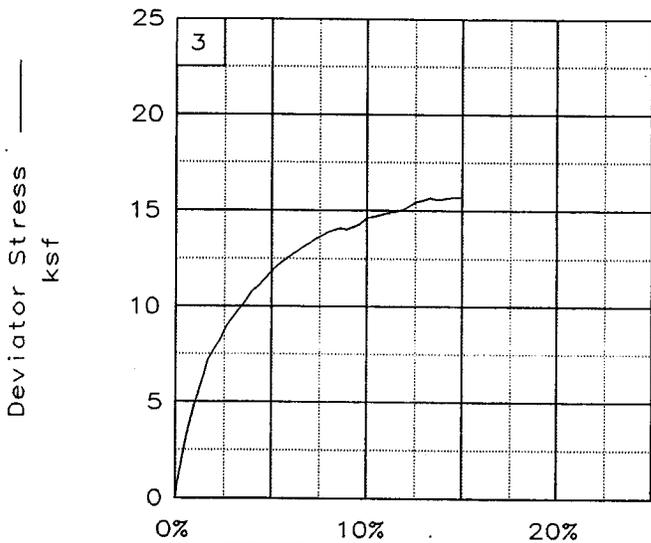
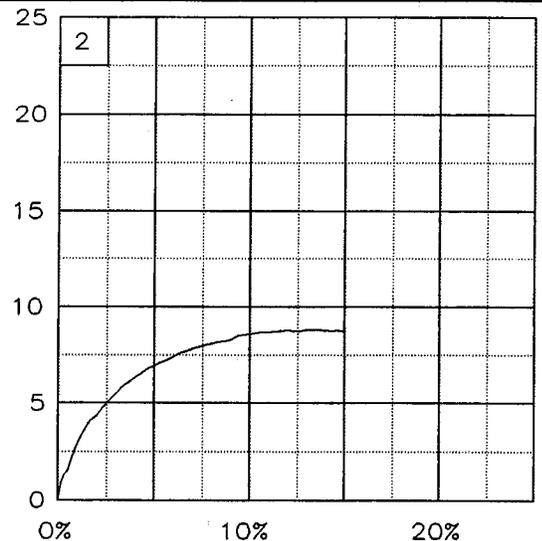
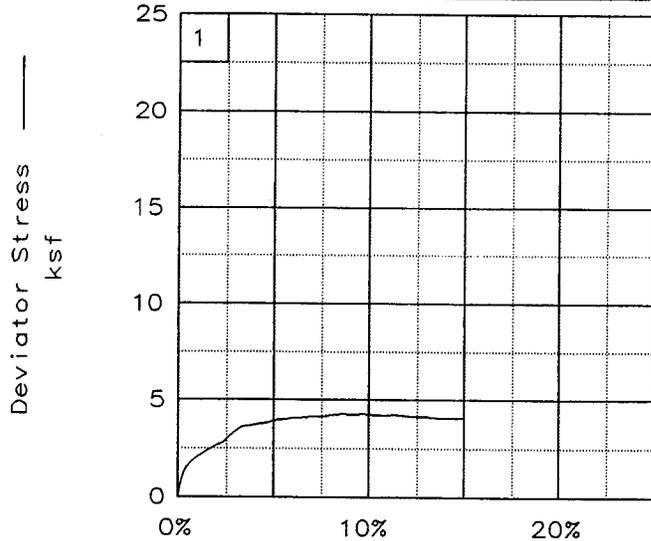
PROJECT: FGD SCRUBBER WASTE TESTING

SAMPLE LOCATION: CONFIDENTIAL POWERPLANT

PROJ. NO.: 1264-03-057      DATE: 4/13/2003

TRIAXIAL SHEAR TEST REPORT

**S & ME, INC.**



Client: DUKE ENERGY

Project: FGD SCRUBBER WASTE TESTING

Location: CONFIDENTIAL POWERPLANT

File: FGD-90%

Project No.: 1264-03-057

Fig. No.: \_\_\_\_\_

TRIAXIAL COMPRESSION TEST  
Unconsolidated Undrained

4-22-2003  
10:14 am

Project and Sample Data

Date: 3-27-03  
Client: DUKE ENERGY  
Project: FGD SCRUBBER WASTE TESTING  
Sample location: CONFIDENTIAL POWERPLANT  
Sample description: FGD SCRUB. SLUDGE  
Remarks: BULK-92% @ 25%

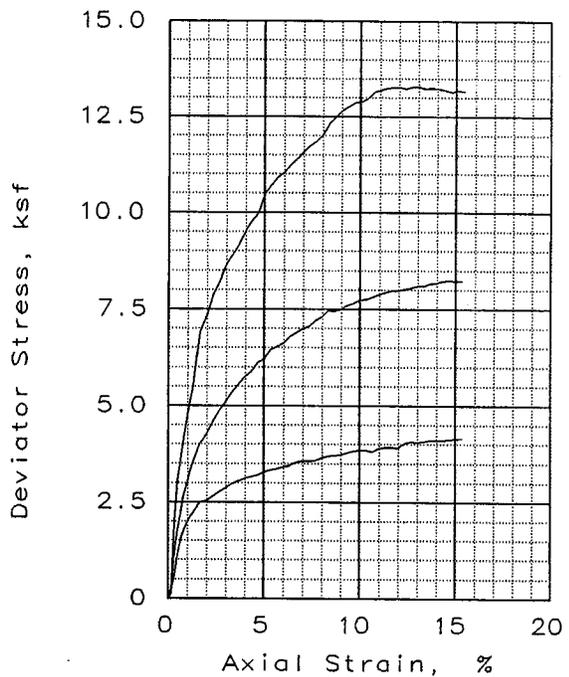
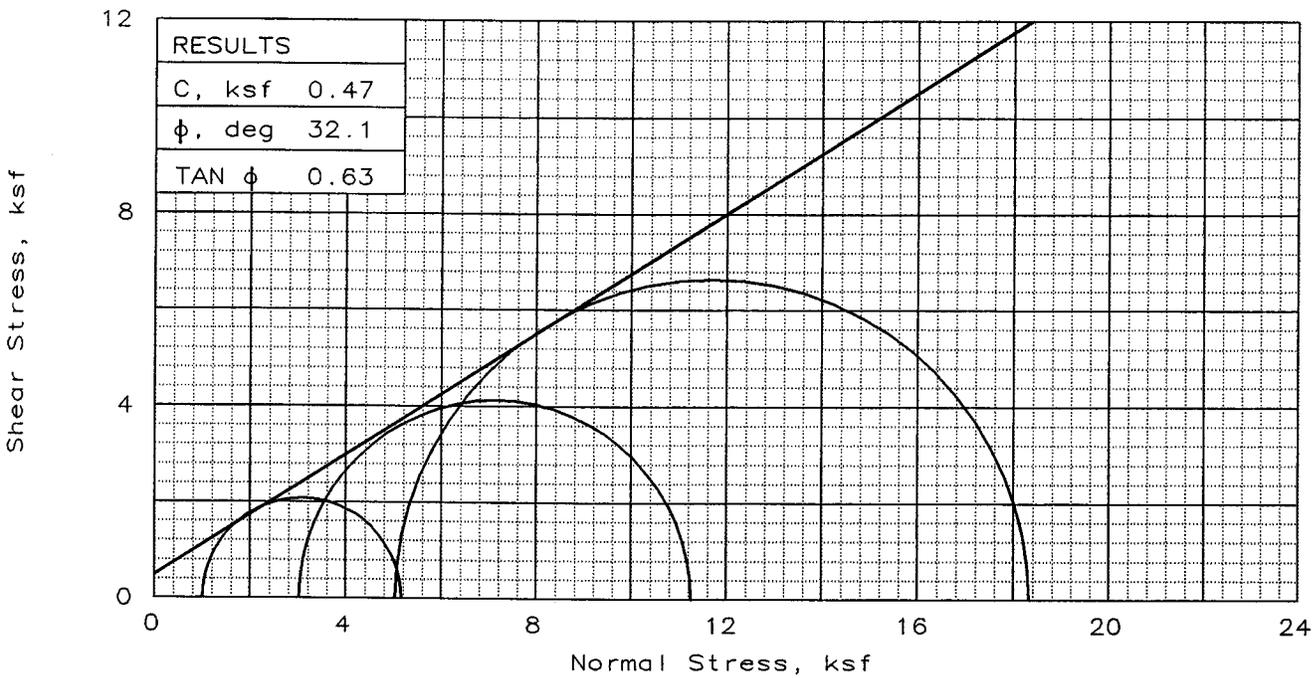
Fig no.: BULK-92% 2nd page Fig no. (if applicable):  
Type of sample: REMOLDED  
Specific gravity= 2.35 LL= 27 PL= 26 PI= 1  
Test method: ASTM - Method A

Specimen Parameters for Specimen No. 1

Specimen Parameter	Initial	Saturated	Final
Wt. moist soil and tare:	358.150		691.600
Wt. dry soil and tare:	304.650		591.000
Wt. of tare:	81.570		153.660
Weight, gms:	1034.0		
Diameter, in:	2.872	2.872	
Area, in <sup>2</sup> :	6.478	6.478	
Height, in:	6.000	6.000	
Net decrease in height, in:		0.000	
% Moisture:	24.0	23.0	23.0
Wt density, pcf:	101.3	100.5	
Dry density, pcf:	81.7	81.7	
Void ratio:	0.7948	0.7948	
% Saturation:	70.9	68.0	

Test Readings Data for Specimen No. 1

Deformation dial constant= 0.001 in per input unit  
Primary load ring constant= 1 lbs per input unit  
Secondary load ring constant= 1 lbs per input unit  
Crossover reading for secondary load ring= 45 input units  
Cell pressure = 7.00 psi = 1.01 ksf  
Back pressure = 0.00 psi = 0.00 ksf  
Effective confining stress = 1.01 ksf  
Strain rate, in/min = 0.0040  
FAIL. STRESS = 4.16 ksf at reading no. 50  
ULT. STRESS = not selected



SAMPLE NO.:		1	2	3
INITIAL	WATER CONTENT, %	24.0	24.0	24.0
	DRY DENSITY, pcf	81.7	81.4	81.8
	SATURATION, %	70.9	70.2	71.1
	VOID RATIO	0.795	0.803	0.793
	DIAMETER, in	2.87	2.88	2.88
	HEIGHT, in	6.00	6.00	5.97
AT TEST	WATER CONTENT, %	23.0	25.6	25.6
	DRY DENSITY, pcf	81.7	81.4	81.8
	SATURATION, %	68.0	74.9	75.7
	VOID RATIO	0.795	0.803	0.793
	DIAMETER, in	2.87	2.88	2.88
	HEIGHT, in	6.00	6.00	5.97
Strain rate, in/min		0.0040	0.0040	0.0040
BACK PRESSURE, ksf		0.0	0.0	0.0
CELL PRESSURE, ksf		1.0	3.0	5.0
FAIL. STRESS, ksf		4.2	8.2	13.3
STRAIN, %		15.3	14.7	13.1
ULT. STRESS, ksf				
STRAIN, %				
$\sigma_1$ FAILURE, ksf		5.2	11.3	18.3
$\sigma_3$ FAILURE, ksf		1.0	3.0	5.0

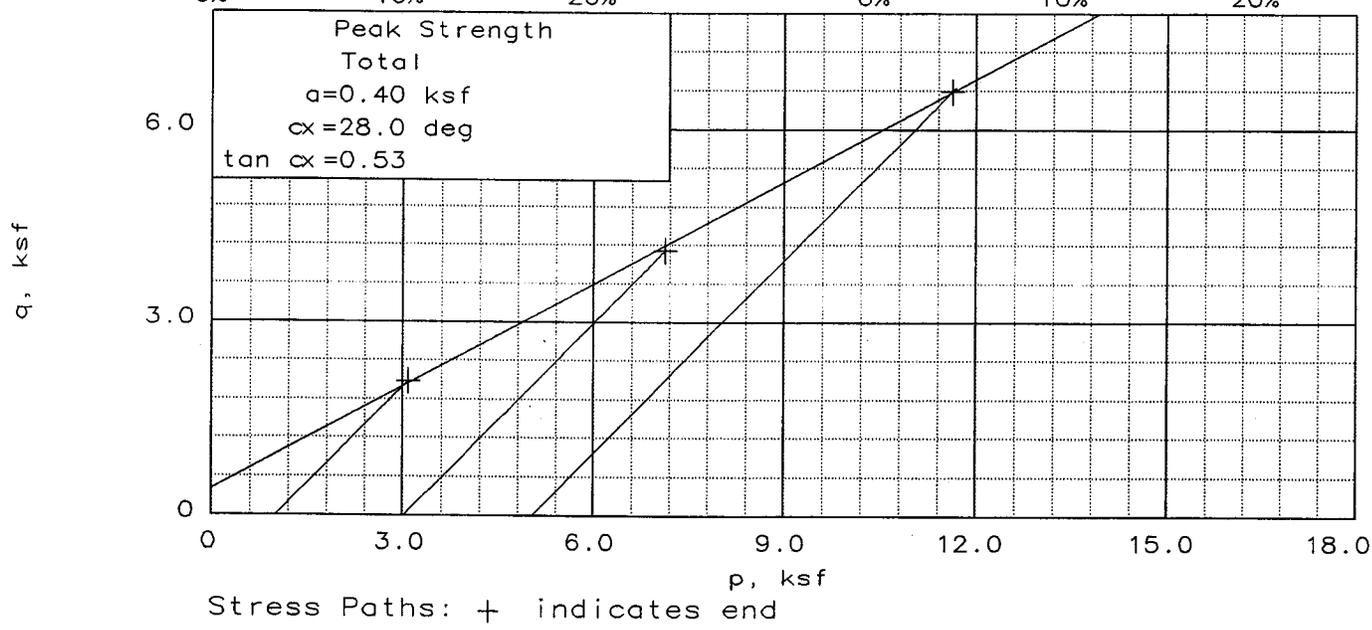
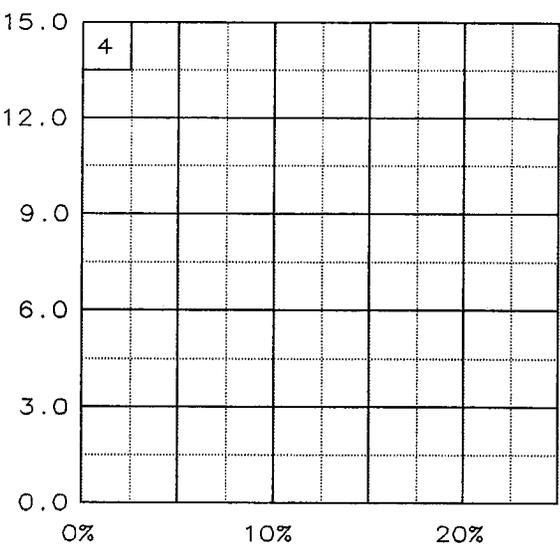
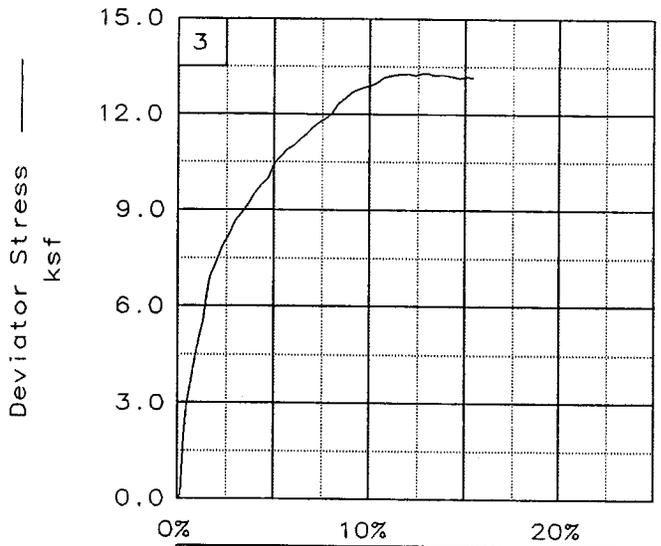
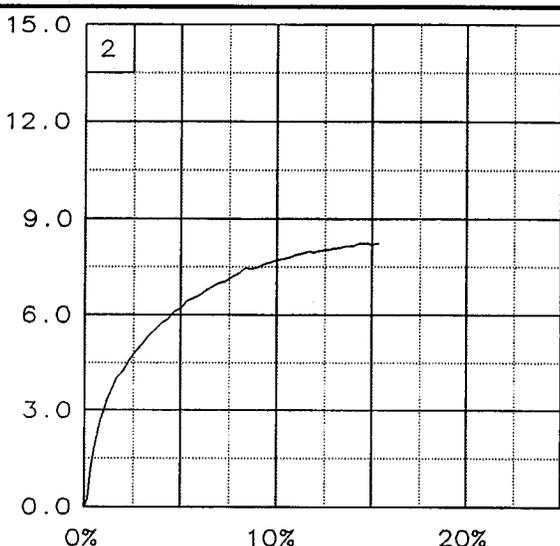
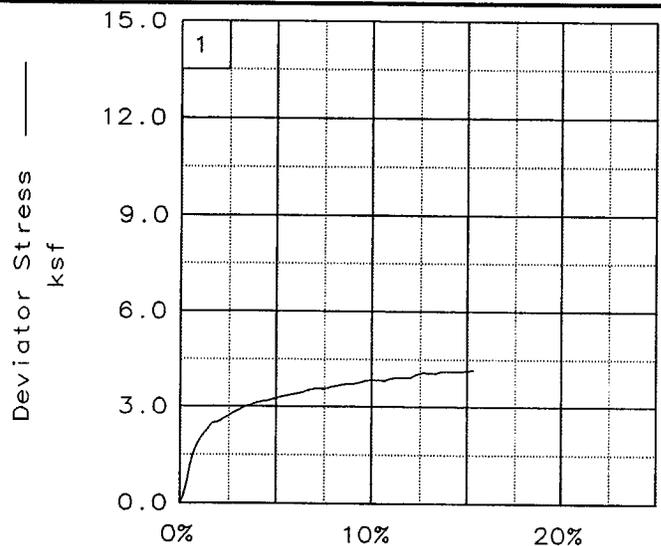
TYPE OF TEST:  
 Unconsolidated Undrained  
 SAMPLE TYPE: REMOLDED  
 DESCRIPTION: FGD SCRUB. SLUDGE  
 LL= 27      PL= 26      PI= 1  
 SPECIFIC GRAVITY= 2.35  
 REMARKS: BULK-92% @ 25%

CLIENT: DUKE ENERGY  
 PROJECT: FGD SCRUBBER WASTE TESTING  
 SAMPLE LOCATION: CONFIDENTIAL POWERPLANT  
 PROJ. NO.: 1264-03-057      DATE: 3-27-03

Fig. No.: BULK-92%

TRIAxIAL SHEAR TEST REPORT

S & ME, INC.



Client: DUKE ENERGY  
 Project: FGD SCRUBBER WASTE TESTING  
 Location: CONFIDENTIAL POWERPLANT  
 File: BULK 92%

Project No.: 1264-03-057

Fig. No.: \_\_\_\_\_

TRIAxIAL COMPRESSION TEST  
Unconsolidated Undrained

4-22-2003  
11:09 am

Project and Sample Data

Date: 4/16/03  
Client: DUKE ENERGY  
Project: FGD SCRUBBER WASTE TESTING  
Sample location: CONFIDENTIAL POWERPLANT  
Sample description: FGD SCRUB. SLUDGE  
Remarks: BULK-95% @ 19%

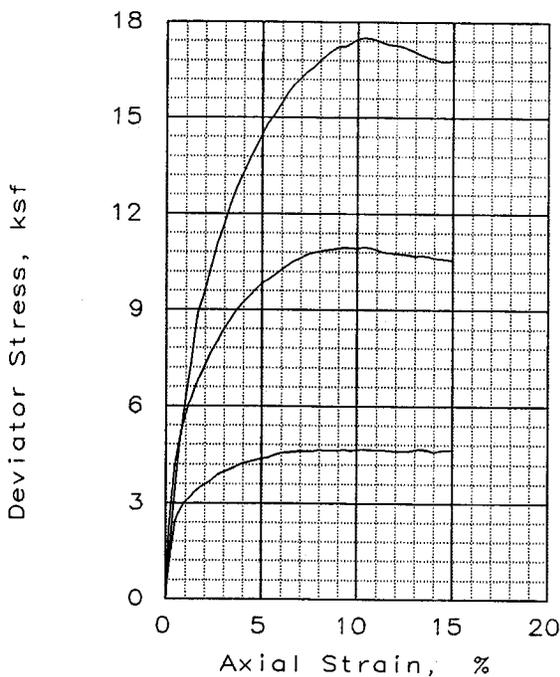
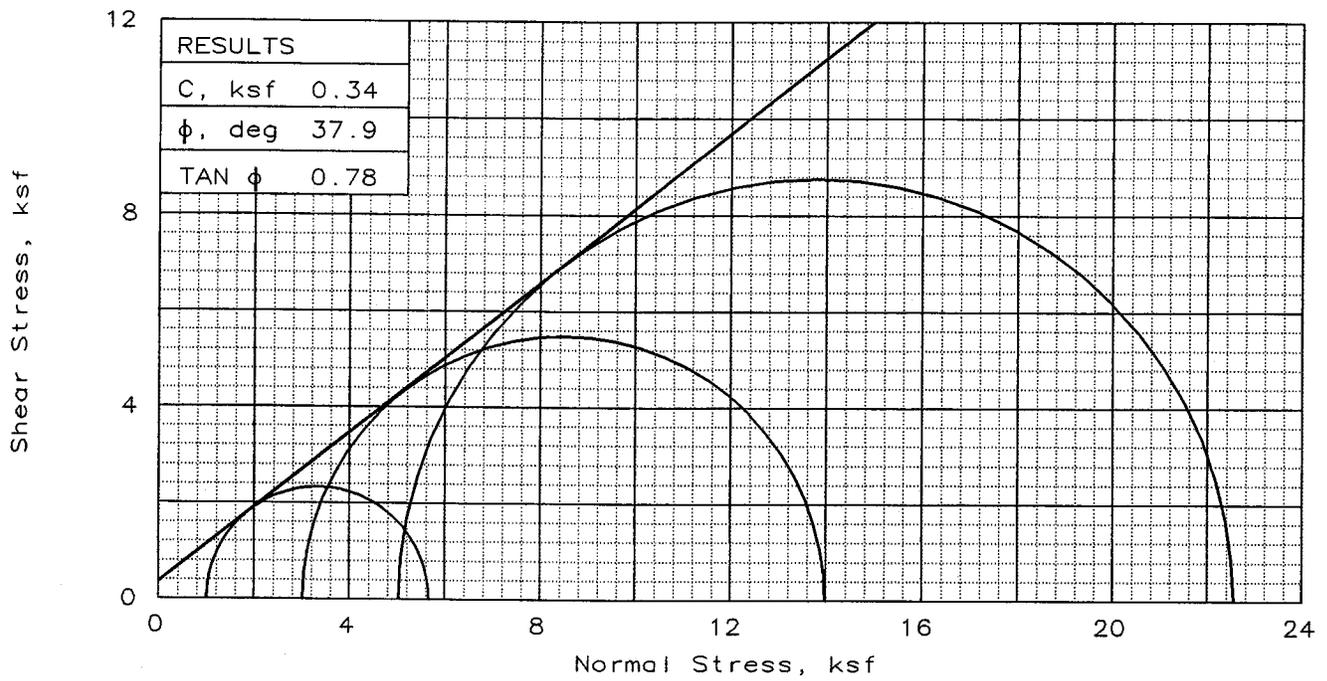
Fig no.: BULK-95% 2nd page Fig no. (if applicable):  
Type of sample: REMOLDED  
Specific gravity= 2.35 LL= 27 PL= 26 PI= 1  
Test method: ASTM - Method A

Specimen Parameters for Specimen No. 1

Specimen Parameter	Initial	Saturated	Final
Wt. moist soil and tare:	255.000		669.800
Wt. dry soil and tare:	226.510		574.300
Wt. of tare:	81.290		73.210
Weight, gms:	1015.3		
Diameter, in:	2.873	2.873	
Area, in <sup>2</sup> :	6.483	6.483	
Height, in:	6.000	6.000	
Net decrease in height, in:		0.000	
% Moisture:	19.6	19.1	19.1
Wet density, pcf:	99.4	99.0	
Dry density, pcf:	83.1	83.1	
Void ratio:	0.7648	0.7648	
% Saturation:	60.3	58.6	

Test Readings Data for Specimen No. 1

Deformation dial constant= 0.001 in per input unit  
Primary load ring constant= 1 lbs per input unit  
Secondary load ring constant= 1 lbs per input unit  
Crossover reading for secondary load ring= 45 input units  
Cell pressure = 7.00 psi = 1.01 ksf  
Back pressure = 0.00 psi = 0.00 ksf  
Effective confining stress = 1.01 ksf  
Strain rate, in/min = 0.0040  
FAIL. STRESS = 4.66 ksf at reading no. 36  
ULT. STRESS = not selected



SAMPLE NO.:		1	2	3
INITIAL	WATER CONTENT, %	19.6	19.6	19.2
	DRY DENSITY, pcf	83.1	83.2	83.6
	SATURATION, %	60.3	60.4	59.6
	VOID RATIO	0.765	0.763	0.755
	DIAMETER, in	2.87	2.87	2.87
	HEIGHT, in	6.00	6.00	6.00
AT TEST	WATER CONTENT, %	19.1	18.6	18.3
	DRY DENSITY, pcf	83.1	83.2	83.6
	SATURATION, %	58.6	57.1	57.1
	VOID RATIO	0.765	0.763	0.755
	DIAMETER, in	2.87	2.87	2.87
	HEIGHT, in	6.00	6.00	6.00
Strain rate, in/min	0.0040	0.0040	0.0040	
BACK PRESSURE, ksf	0.0	0.0	0.0	
CELL PRESSURE, ksf	1.0	3.0	5.0	
FAIL. STRESS, ksf	4.7	11.0	17.5	
STRAIN, %	10.3	10.3	10.3	
ULT. STRESS, ksf				
STRAIN, %				
$\sigma_1$ FAILURE, ksf	5.7	14.0	22.6	
$\sigma_3$ FAILURE, ksf	1.0	3.0	5.0	

TYPE OF TEST:  
Unconsolidated Undrained

SAMPLE TYPE: REMOLDED

DESCRIPTION: FGD SCRUB. SLUDGE

LL= 27      PL= 26      PI= 1

SPECIFIC GRAVITY= 2.35

REMARKS: BULK-95% @ 19%

CLIENT: DUKE ENERGY

PROJECT: FGD SCRUBBER WASTE TESTING

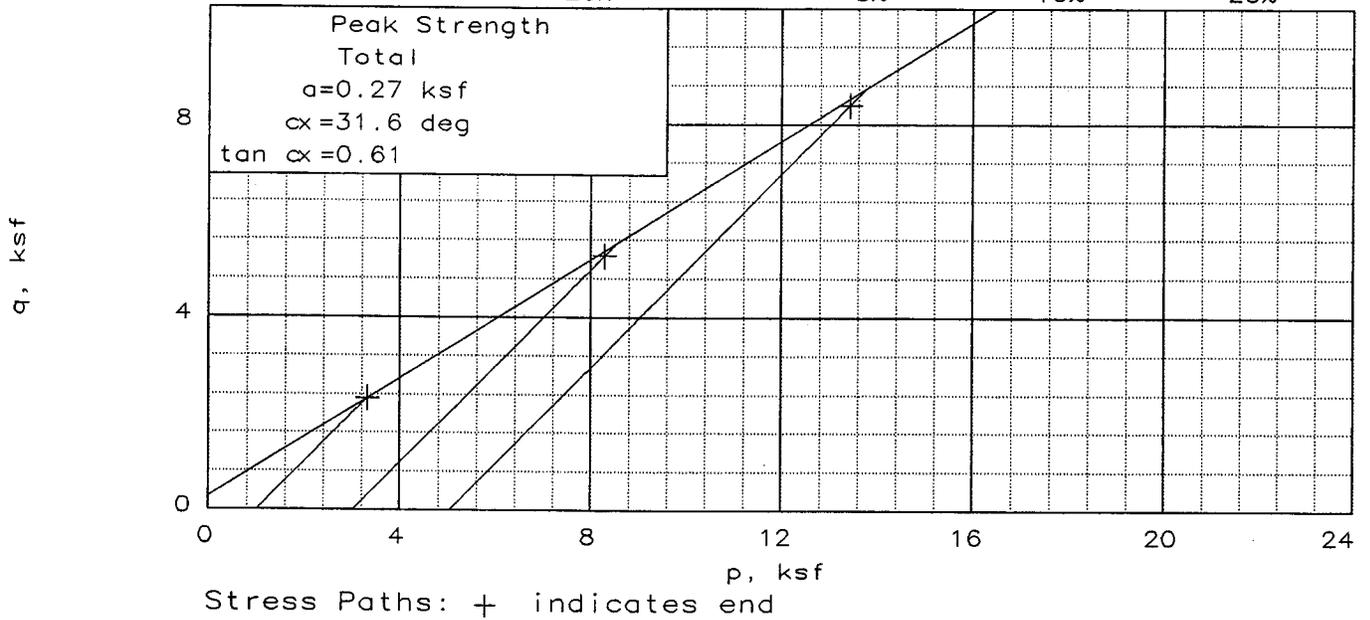
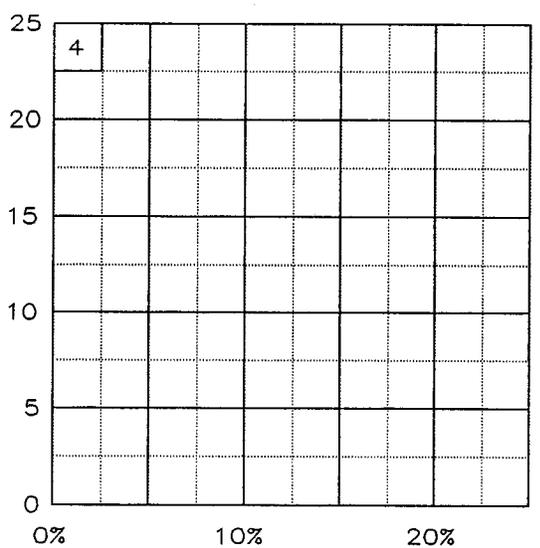
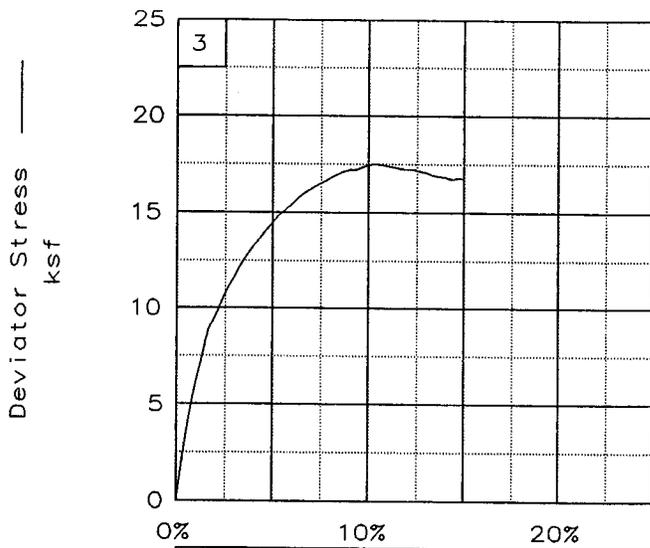
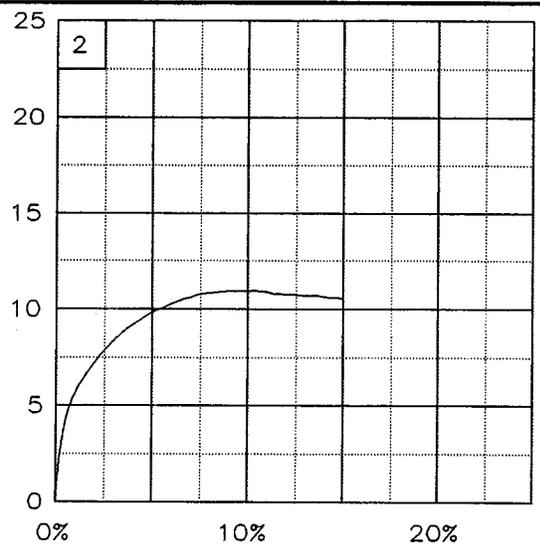
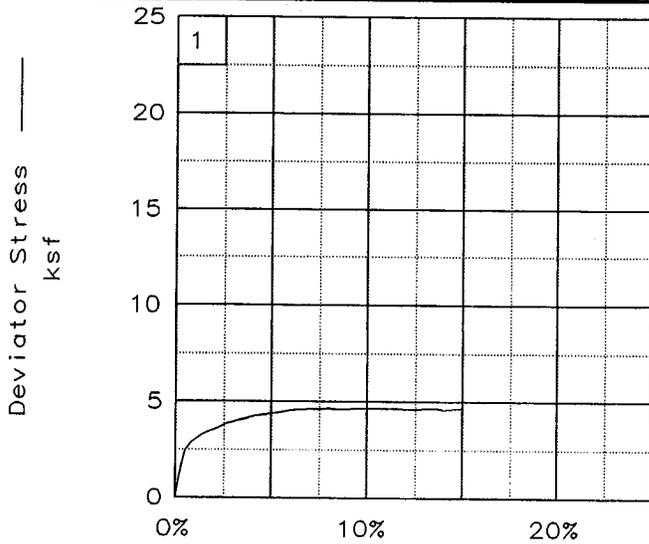
SAMPLE LOCATION: CONFIDENTIAL POWERPLANT

PROJ. NO.: 1264-03-057      DATE: 4/16/03

TRIAxIAL SHEAR TEST REPORT

S & ME, INC.

Fig. No.: BULK-95%



Client: DUKE ENERGY

Project: FGD SCRUBBER WASTE TESTING

Location: CONFIDENTIAL POWERPLANT

File: FGD95

Project No.: 1264-03-057

Fig. No.: \_\_\_\_\_

TRIAXIAL COMPRESSION TEST  
CU with Pore Pressures

4-22-2003  
10:04 am

Project and Sample Data

Date: 3/18/03  
Client: DUKE ENERGY  
Project: FGD SCRUBBER WASTE TESTING  
Sample location: CONFIDENTIAL POWERPLANT  
Sample description: FGD SCRUB. SLUDGE  
Remarks: BULK-90% @ 12%

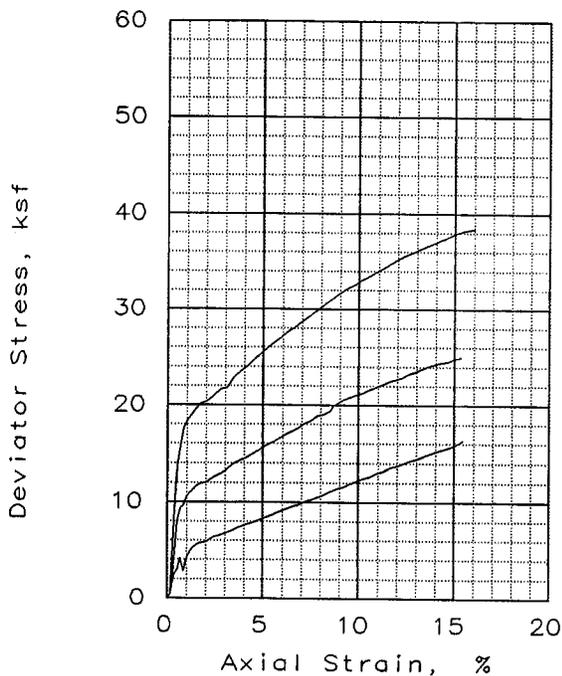
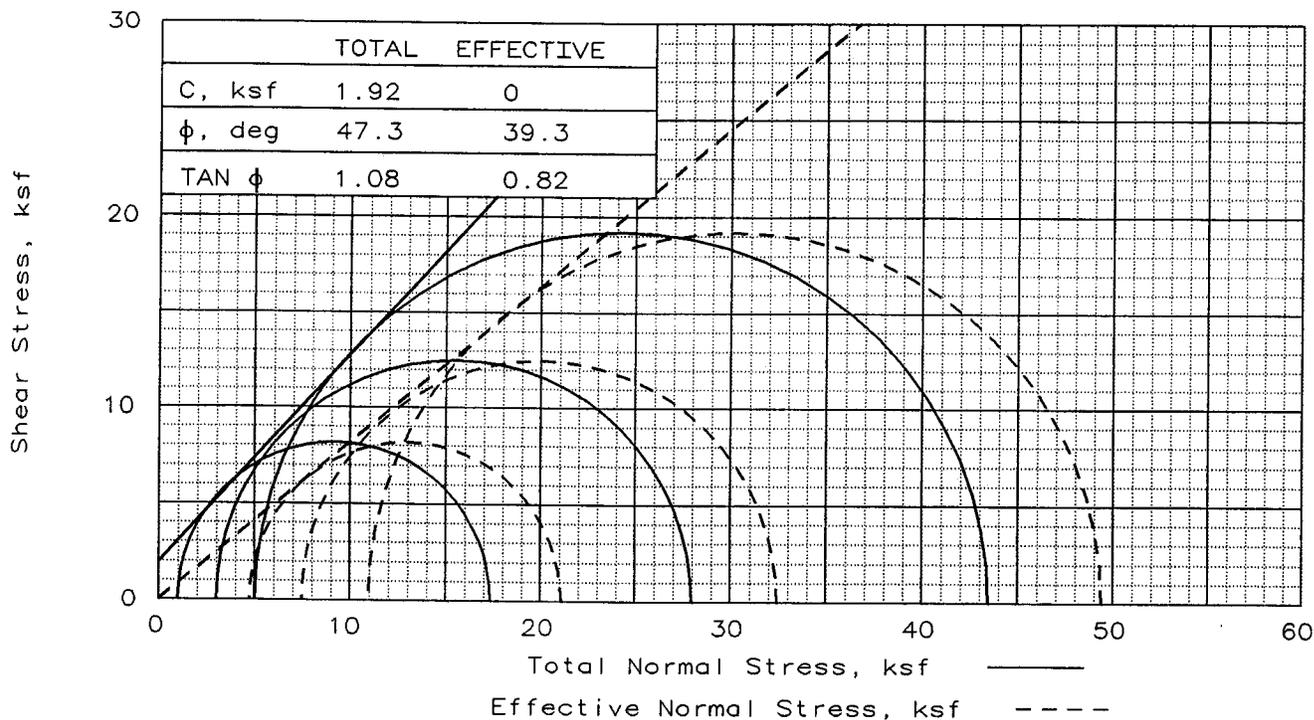
Fig no.: BULK-90% 2nd page Fig no. (if applicable):  
Type of sample: REMOLDED  
Specific gravity= 2.35 LL= 27 PL= 26 PI= 1  
Test method: Corps of Eng. - uniform strain

Specimen Parameters for Specimen No. 1

Specimen Parameter	Initial	Saturated	Consolidated	Final
Wt. moist soil and tare:	284.150			656.600
Wt. dry soil and tare:	262.070			518.400
Wt. of tare:	81.210			81.540
Weight, gms:	905.9			
Diameter, in:	2.874	2.874	2.795	
Area, in <sup>2</sup> :	6.487	6.487	6.135	
Height, in:	6.000	6.000	5.837	
Net decrease in height, in:		0.000	0.163	
Net decrease in water volume, cc:				
Moisture:	12.2	36.5	30.1	31.6
Wet density, pcf:	88.7	107.8	111.8	
Dry density, pcf:	79.0	79.0	85.9	
Void ratio:	0.8566	0.8566	0.7083	
% Saturation:	33.5	100.0	100.0	

Test Readings Data for Specimen No. 1

Deformation dial constant= 0.001 in per input unit  
Primary load ring constant= 1 lbs per input unit  
Secondary load ring constant= 1 lbs per input unit  
Crossover reading for secondary load ring= 45 input units  
Consolidation cell pressure = 87.00 psi = 12.53 ksf  
Consolidation back pressure = 80.00 psi = 11.52 ksf  
Consolidation effective confining stress = 1.01 ksf  
Strain rate, in/min = 0.0040  
FAIL. STRESS = 16.36 ksf at reading no. 50  
ULT. STRESS = not selected



SAMPLE NO.:		1	2	3
INITIAL	WATER CONTENT, %	12.2	12.2	12.3
	DRY DENSITY, pcf	79.0	78.8	79.4
	SATURATION, %	33.5	33.3	34.0
	VOID RATIO	0.857	0.862	0.847
	DIAMETER, in	2.87	2.87	2.87
	HEIGHT, in	6.00	6.03	5.97
AT TEST	WATER CONTENT, %	30.1	30.6	27.2
	DRY DENSITY, pcf	85.9	85.4	89.4
	SATURATION, %	100.0	100.0	100.0
	VOID RATIO	0.708	0.719	0.640
	DIAMETER, in	2.79	2.80	2.76
	HEIGHT, in	5.84	5.87	5.74
Strain rate, in/min		0.0040	0.0040	0.0040
EFF CELL PRESSURE, ksf		1.0	3.0	5.0
FAIL. STRESS, ksf		16.4	25.0	38.4
TOTAL PORE PR., ksf		7.8	7.1	5.6
STRAIN, %		15.4	15.3	16.0
ULT. STRESS, ksf				
TOTAL PORE PR., ksf				
STRAIN, %				
$\sigma_1$ FAILURE, ksf		21.1	32.5	49.4
$\sigma_3$ FAILURE, ksf		4.8	7.5	11.0

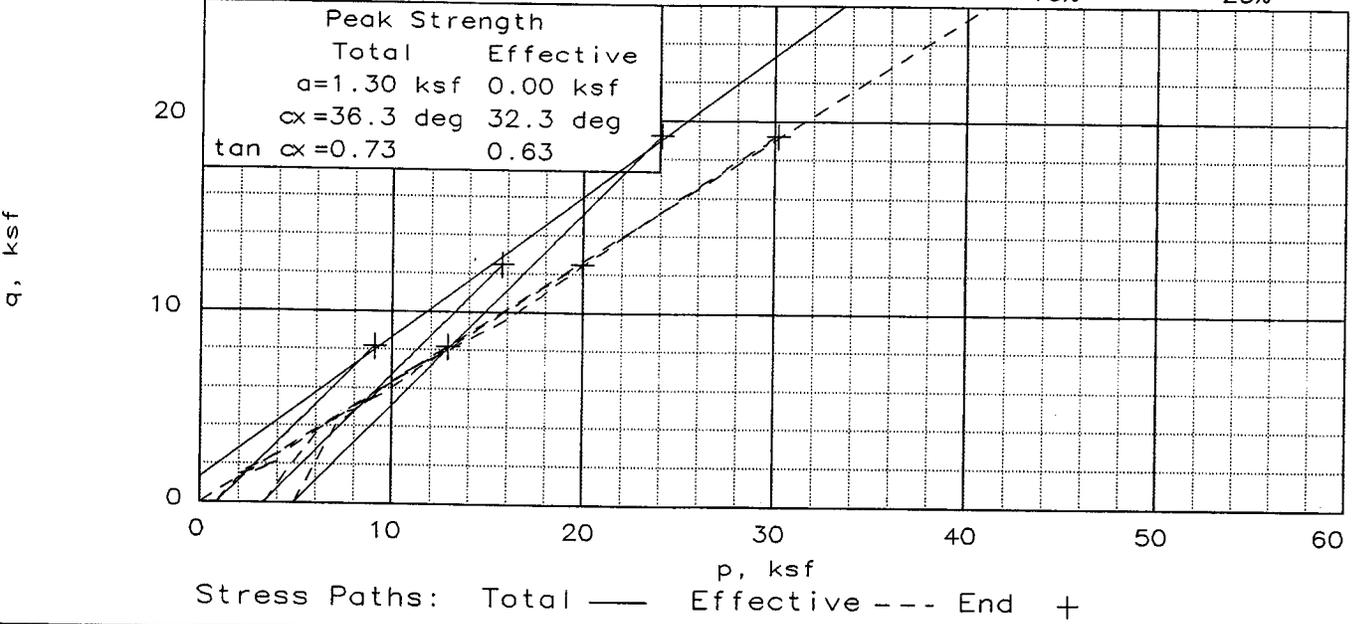
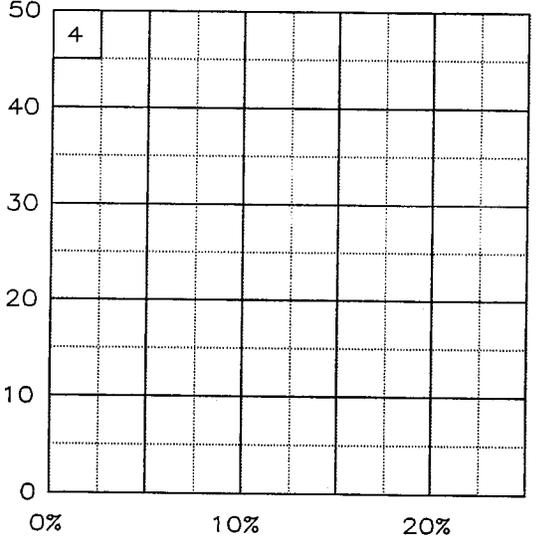
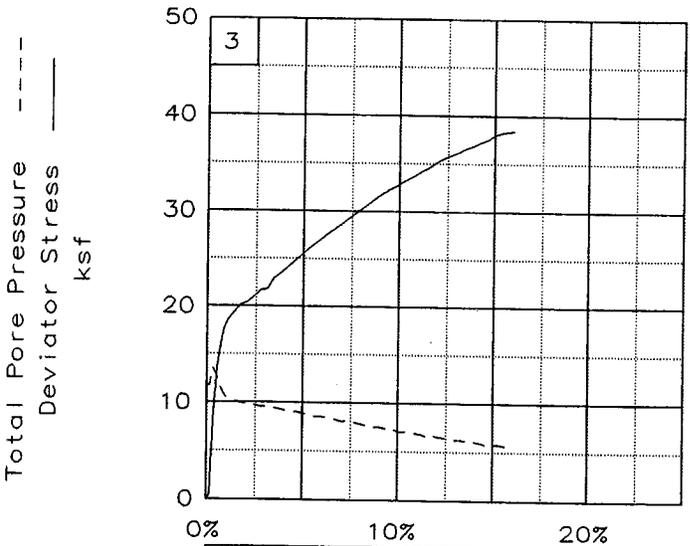
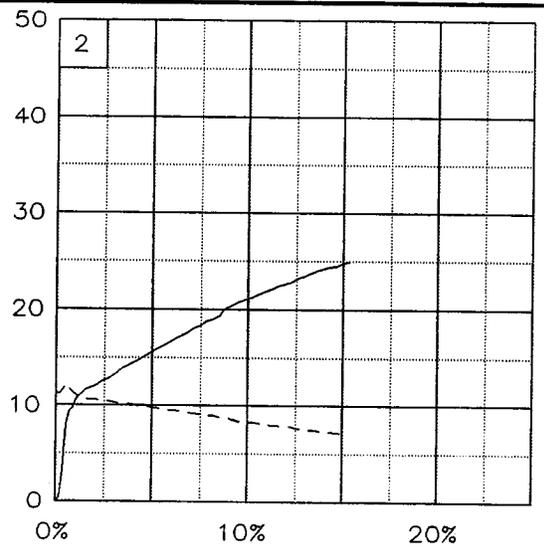
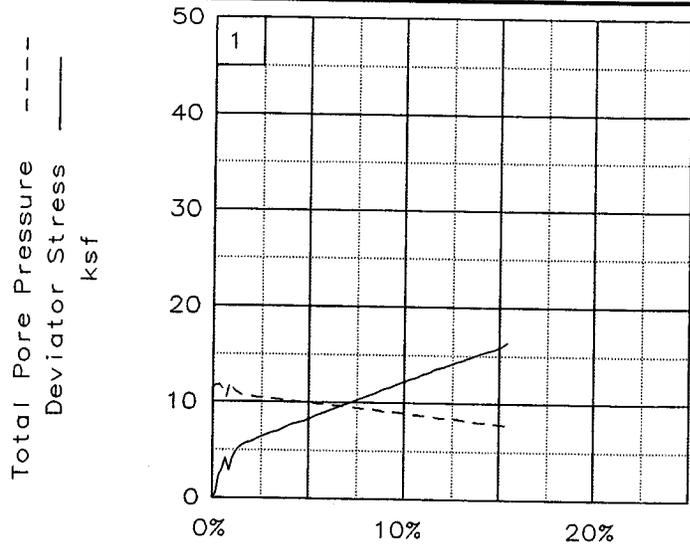
TYPE OF TEST:  
 CU with Pore Pressures  
 SAMPLE TYPE: REMOLDED  
 DESCRIPTION: FGD SCRUB. SLUDGE  
 LL= 27      PL= 26      PI= 1  
 SPECIFIC GRAVITY= 2.35  
 REMARKS: BULK-90% @ 12%

CLIENT: DUKE ENERGY  
 PROJECT: FGD SCRUBBER WASTE TESTING  
 SAMPLE LOCATION: CONFIDENTIAL POWERPLANT  
 PROJ. NO.: 1264-03-057      DATE: 3/18/03

Fig. No.: BULK-90%

TRIAXIAL SHEAR TEST REPORT

S & ME, INC.



Client: DUKE ENERGY  
 Project: FGD SCRUBBER WASTE TESTING  
 Location: CONFIDENTIAL POWERPLANT  
 File: BULK-90% Project No.: 1264-03-057 Fig. No.: \_\_\_\_\_

TRIAXIAL COMPRESSION TEST  
CU with Pore Pressures

4-22-2003  
10:11 am

Project and Sample Data

Date: 3-25-03  
Client: DUKE ENERGY  
Project: FGD SCRUBBER WASTE TESTING  
Sample location: CONFIDENTIAL POWERPLANT  
Sample description: FGD SCRUB. SLUDGE  
Remarks: BULK 95% @ 19%

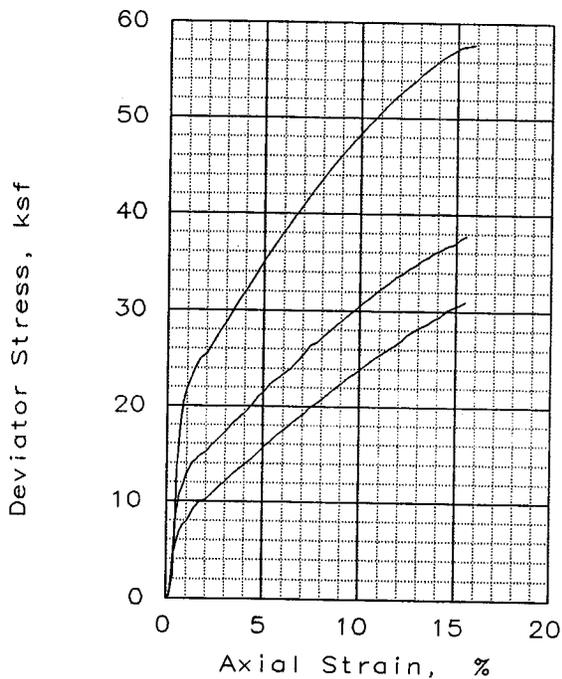
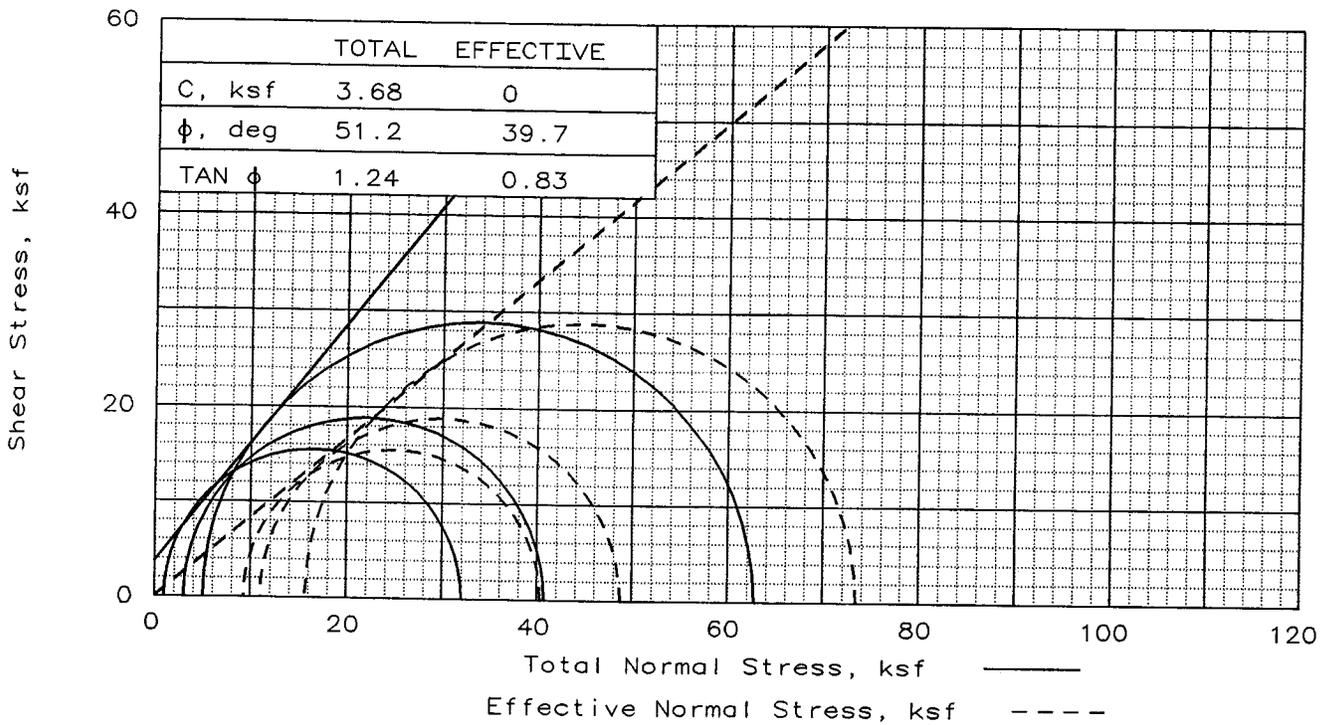
Fig no.: BULK-95% 2nd page Fig no. (if applicable):  
Type of sample: REMOLDED  
Specific gravity= 2.35 LL= 27 PL= 26 PI= 1  
Test method: Corps of Eng. - uniform strain

Specimen Parameters for Specimen No. 1

Specimen Parameter	Initial	Saturated	Consolidated	Final
Wt. moist soil and tare:	350.000			638.500
Wt. dry soil and tare:	306.540			532.100
Wt. of tare:	81.790			152.860
Weight, gms:	1016.6			
Diameter, in:	2.873	2.873	2.841	
Area, in <sup>2</sup> :	6.483	6.483	6.338	
Height, in:	6.000	6.000	5.933	
Net decrease in height, in:		0.000	0.067	
Net decrease in water volume, cc:				
Moisture:	19.3	32.3	29.8	28.1
Wet density, pcf:	99.6	110.4	112.0	
Dry density, pcf:	83.4	83.4	86.3	
Void ratio:	0.7584	0.7584	0.7001	
% Saturation:	59.9	100.0	100.0	

Test Readings Data for Specimen No. 1

Deformation dial constant= 0.001 in per input unit  
Primary load ring constant= 1 lbs per input unit  
Secondary load ring constant= 1 lbs per input unit  
Crossover reading for secondary load ring= 45 input units  
Consolidation cell pressure = 87.00 psi = 12.53 ksf  
Consolidation back pressure = 80.00 psi = 11.52 ksf  
Consolidation effective confining stress = 1.01 ksf  
Strain rate, in/min = 0.0040  
FAIL. STRESS = 31.02 ksf at reading no. 51  
ULT. STRESS = not selected



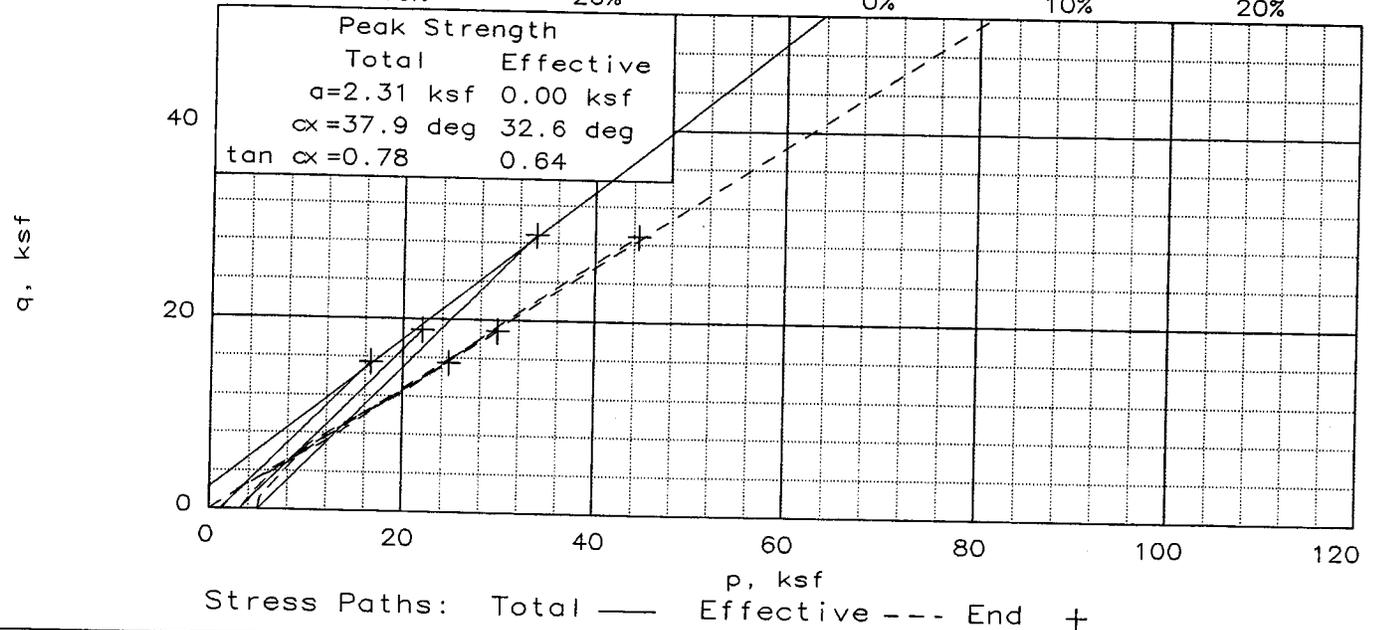
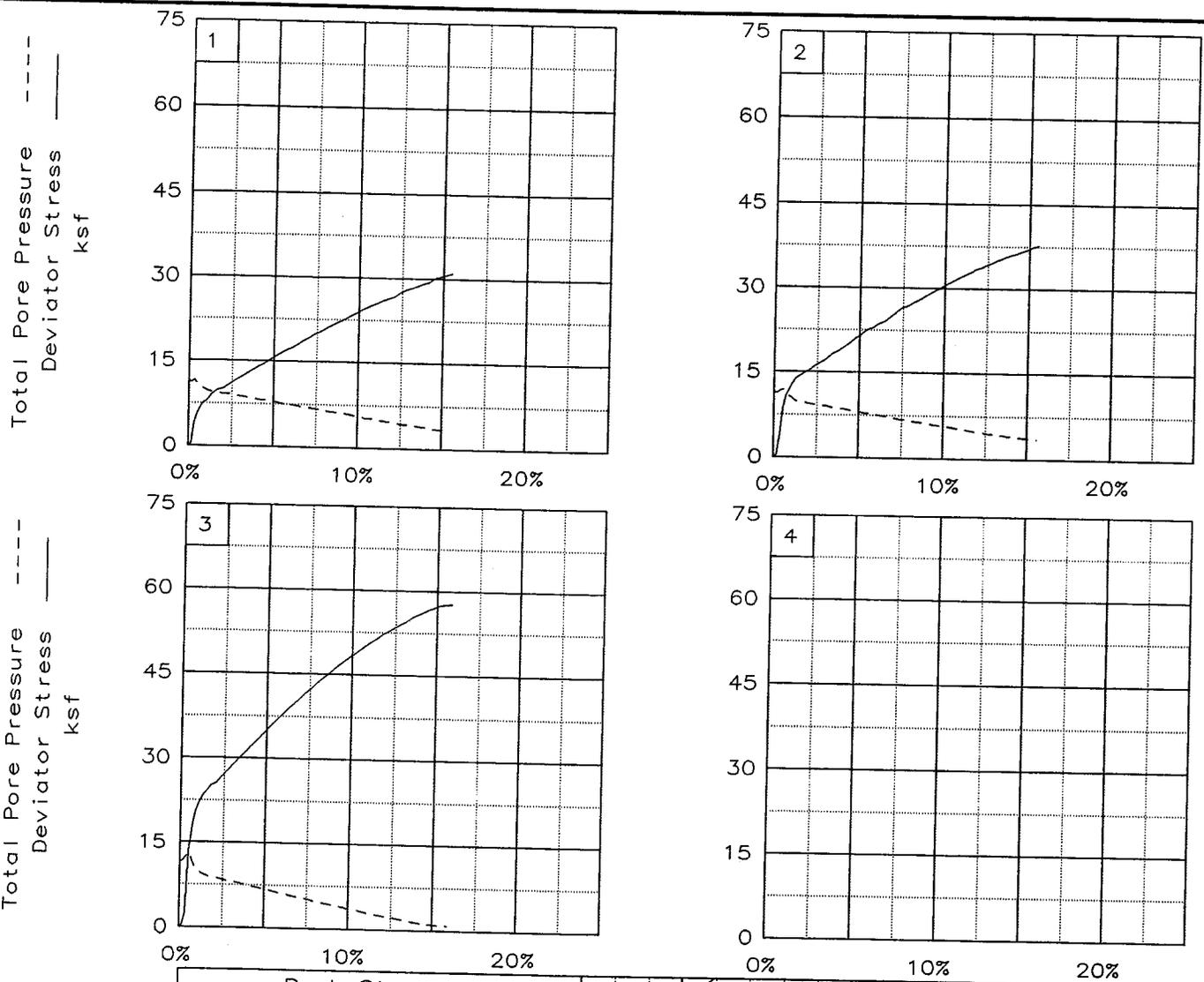
SAMPLE NO.:		1	2	3
INITIAL	WATER CONTENT, %	19.3	19.6	19.3
	DRY DENSITY, pcf	83.4	83.2	83.8
	SATURATION, %	59.9	60.3	60.5
	VOID RATIO	0.758	0.763	0.751
	DIAMETER, in	2.87	2.87	2.87
	HEIGHT, in	6.00	6.00	5.97
AT TEST	WATER CONTENT, %	29.8	29.6	25.3
	DRY DENSITY, pcf	86.3	86.5	92.0
	SATURATION, %	100.0	100.0	100.0
	VOID RATIO	0.700	0.695	0.595
	DIAMETER, in	2.84	2.84	2.78
	HEIGHT, in	5.93	5.92	5.79
Strain rate, in/min		0.0040	0.0040	0.0040
EFF CELL PRESSURE, ksf		1.0	3.0	5.0
FAIL. STRESS, ksf		31.0	37.7	57.7
TOTAL PORE PR., ksf		3.2	3.5	0.8
STRAIN, %		15.5	15.5	15.9
ULT. STRESS, ksf				
TOTAL PORE PR., ksf				
STRAIN, %				
$\bar{\sigma}_1$ FAILURE, ksf		40.3	48.8	73.5
$\bar{\sigma}_3$ FAILURE, ksf		9.3	11.0	15.7

TYPE OF TEST:  
 CU with Pore Pressures  
 SAMPLE TYPE: REMOLDED  
 DESCRIPTION: FGD SCRUB. SLUDGE  
 LL= 27      PL= 26      PI= 1  
 SPECIFIC GRAVITY= 2.35  
 REMARKS: BULK 95% @ 19%

CLIENT: DUKE ENERGY  
 PROJECT: FGD SCRUBBER WASTE TESTING  
 SAMPLE LOCATION: CONFIDENTIAL POWERPLANT  
 PROJ. NO.: 1264-03-057      DATE: 3-25-03

TRIAXIAL SHEAR TEST REPORT

S & ME, INC.

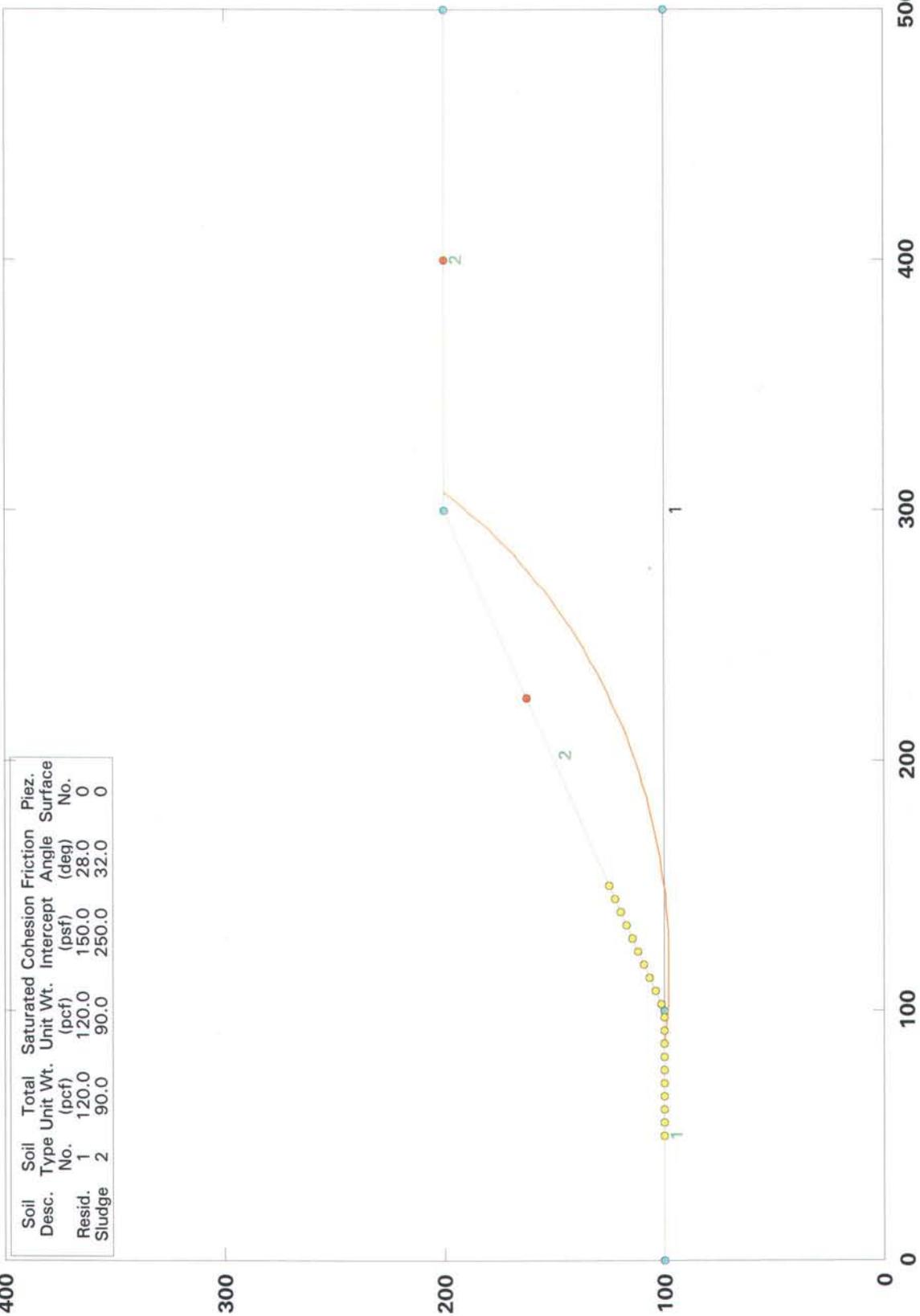


Client: DUKE ENERGY  
 Project: FGD SCRUBBER WASTE TESTING  
 Location: CONFIDENTIAL POWERPLANT  
 File: SCRUBBER Project No.: 1264-03-057 Fig. No.: \_\_\_\_\_

# Appendix B

# Duke FGD Scrubber Sludge Testing 100' / 2:1 Slope (Total Stresses w/o EQ)

C:\PROGRA ~1\STEDWIN\DATA\FGD2T.PL2 Run By: Username 4/29/2003 3:18PM



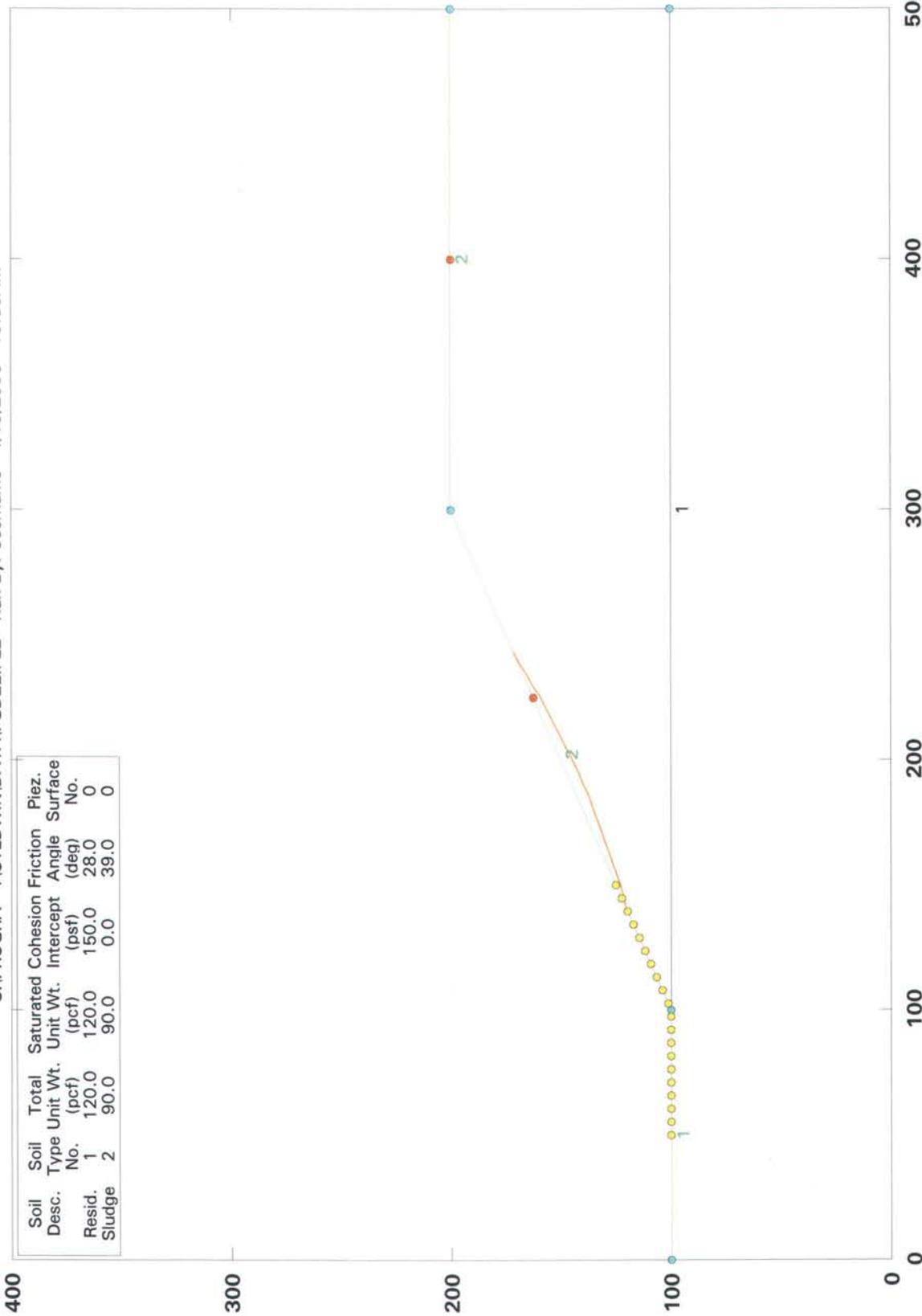
Soil Desc.	Soil Type No.	Total Unit Wt. (pcf)	Saturated Unit Wt. (pcf)	Cohesion (psf)	Friction Intercept (psf)	Friction Angle (deg)	Piez. Surface No.
Resid.	1	90.0	120.0	90.0	150.0	28.0	0
Sludge	2	90.0	90.0	250.0	250.0	32.0	0

STABL6H FSmin = 1.72  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 2:1 Slope (Eff. Stresses w/o EO)

C:\PROGRA ~1\STEDWIN\DATA\FGD2E.PL2 Run By: Username 4/10/2003 10:50AM

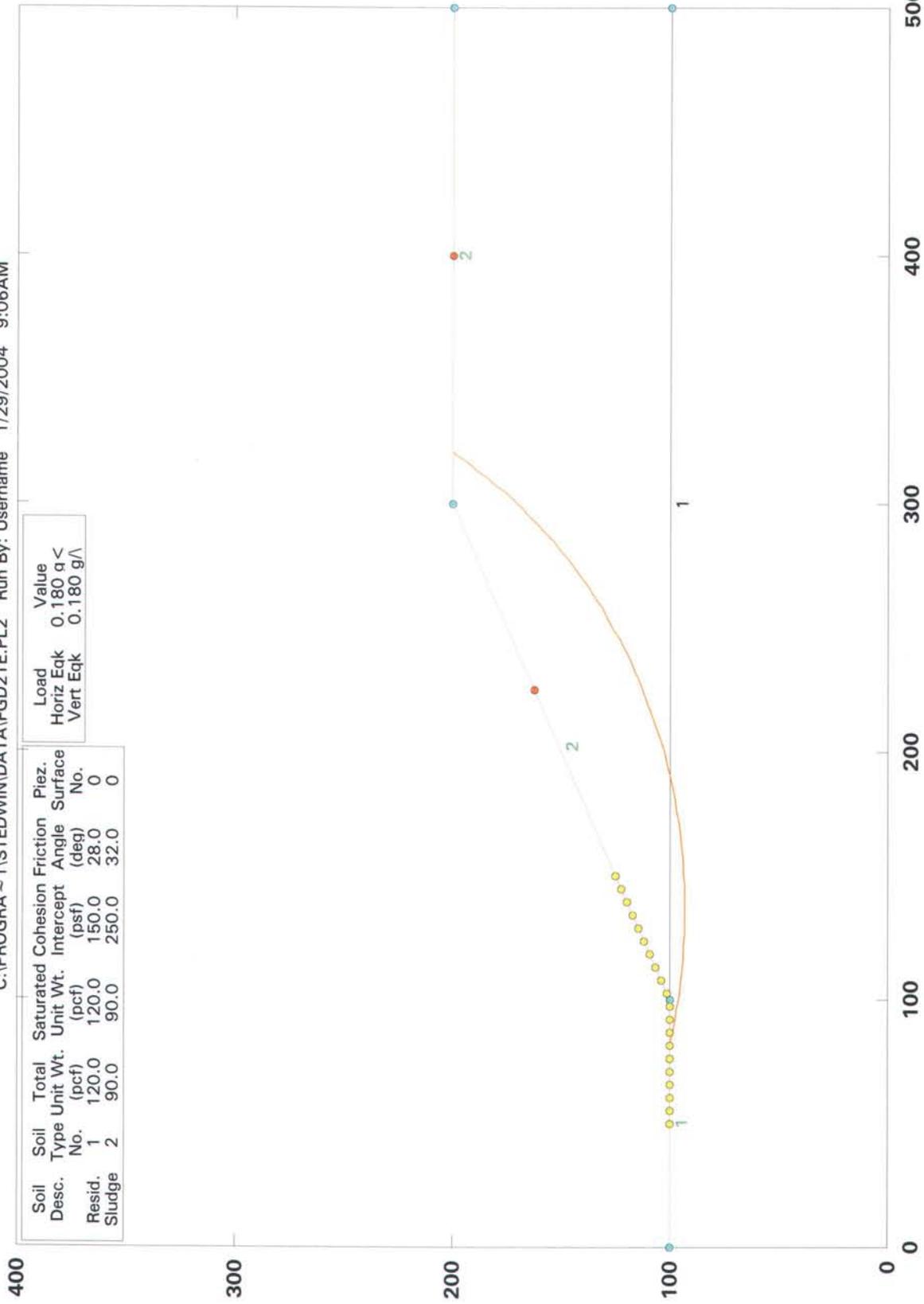


STABL6H FSmin = 1.64  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 2:1 Slope (Total Stresses w/ EQ)

C:\PROGRAMS\1\STEDWIN\DATA\FGD2TE.PL2 Run By: Username 1/29/2004 9:06AM



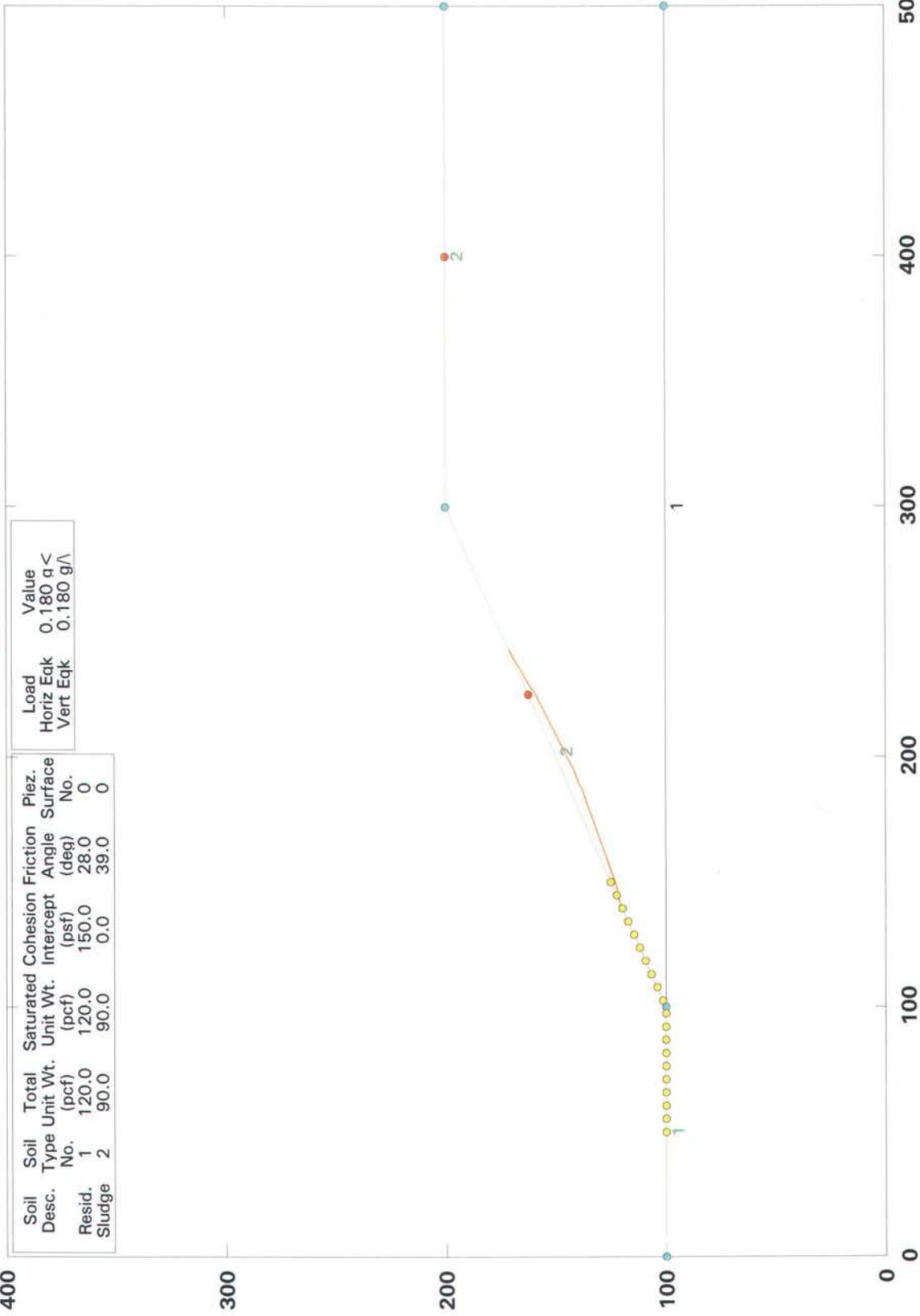
STABL6H FSmin = 1.14

Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 2:1 Slope (Eff Stresses w/ EQ)

C:\PROGRA ~1\STEDWIN\DATA\FGD2EE.PL2 Run By: Username 1/29/2004 9:07AM

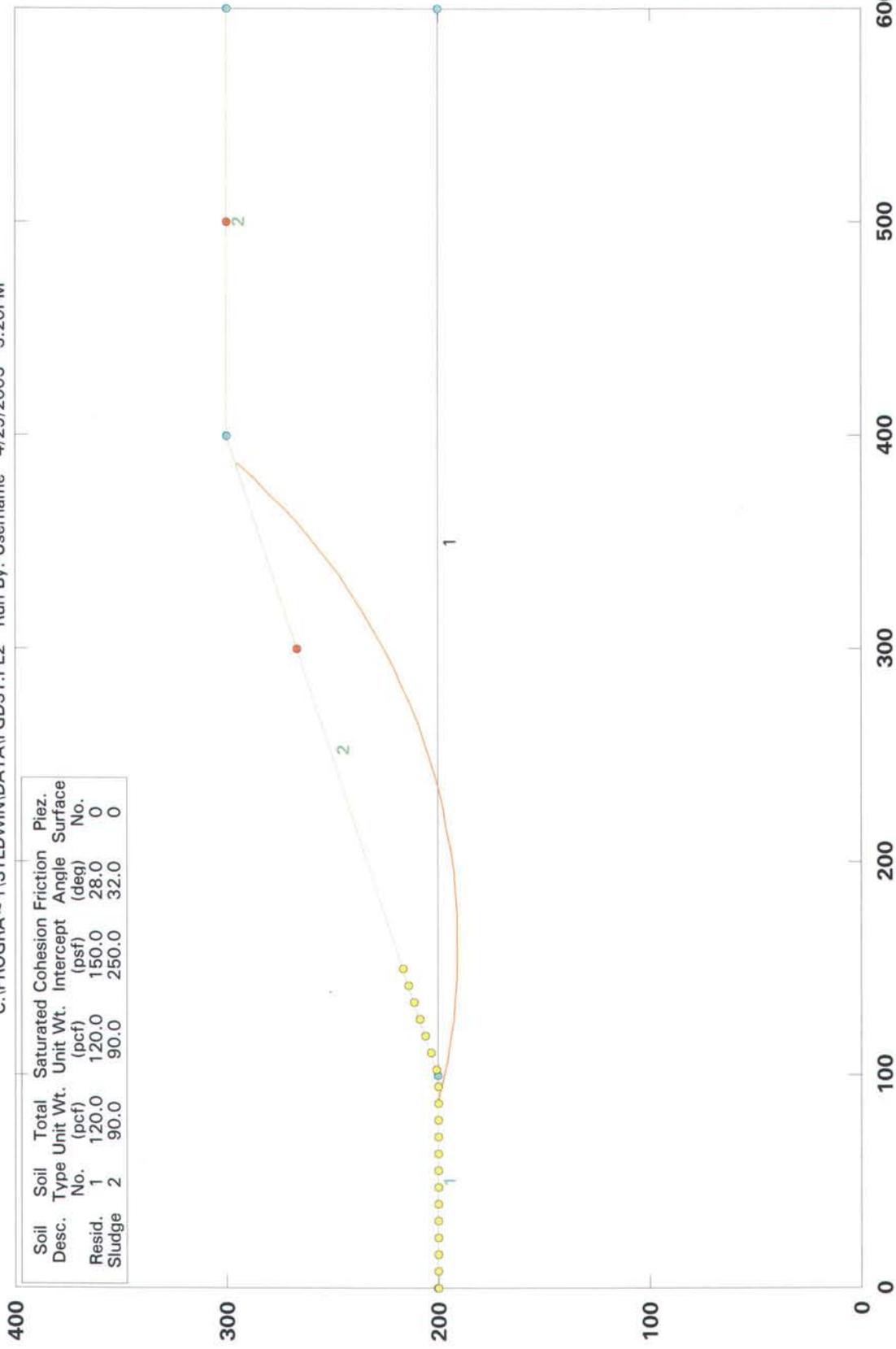


STABL6H FSmin = 1.02  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 3:1 Slope (Total Stresses w/o EQ)

C:\PROGRA ~1\STEDWIN\DATA\FGD3T.PL2 Run By: Username 4/29/2003 3:20PM

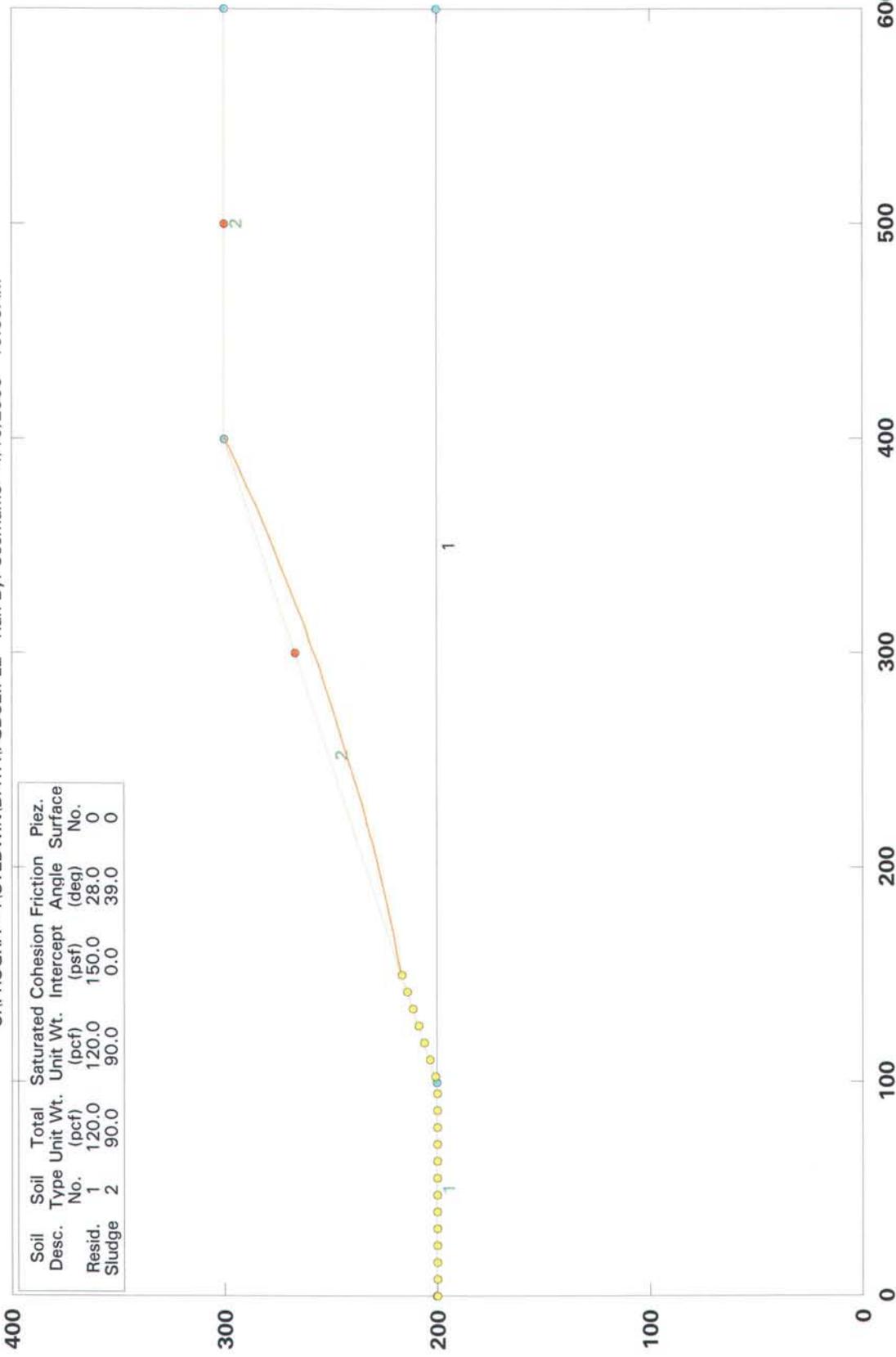


STABL6H FSmin = 2.35  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 3:1 Slope (Eff Stresses w/o EQ)

C:\PROGRA~1\STEDWIN\DATA\FGD3E.PL2 Run By: Username 4/10/2003 10:59AM

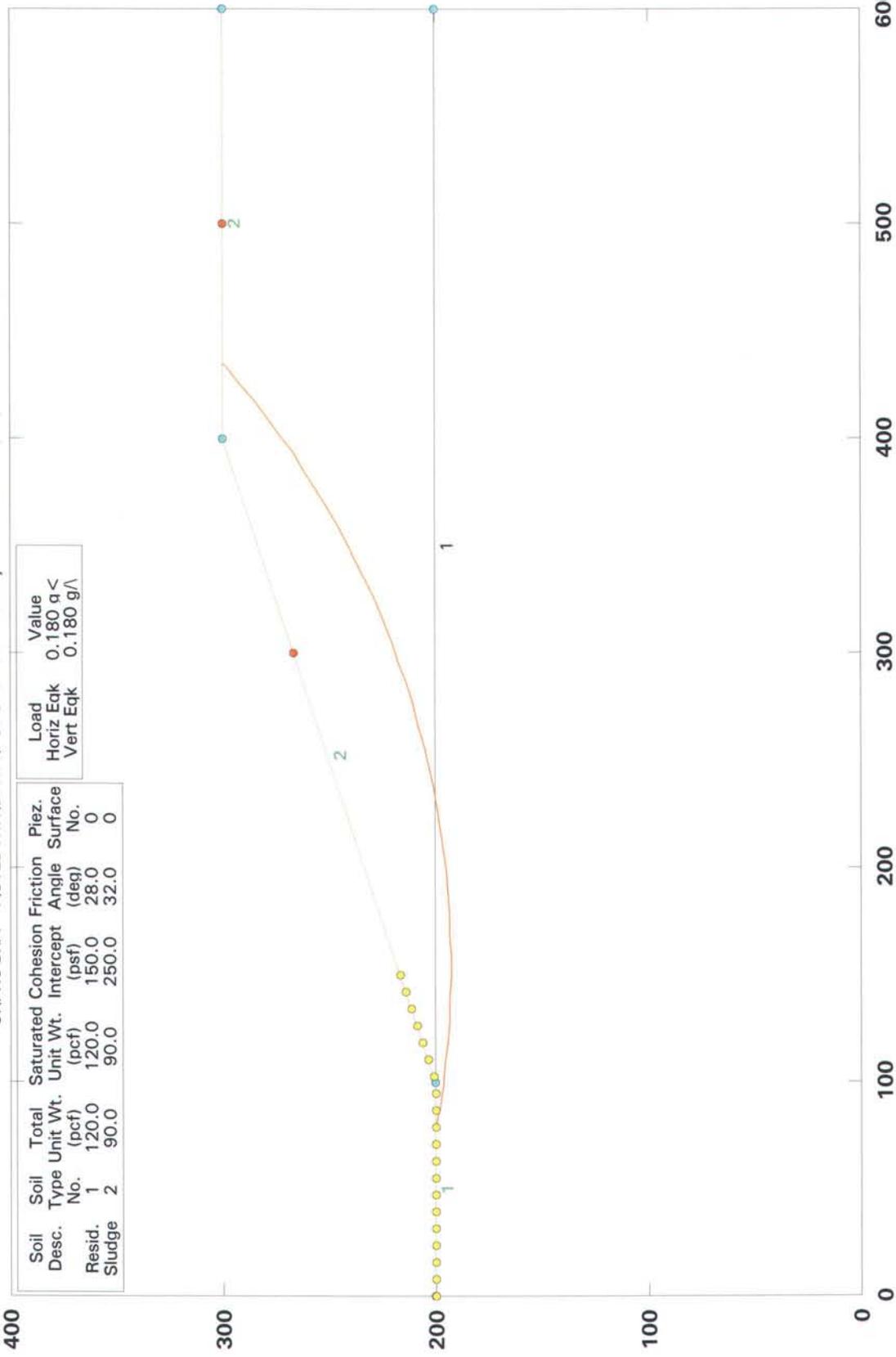


STABL6H FSmin = 2.45  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 3:1 Slope (Total Stresses w/ EQ)

C:\PROGRA~1\STEDWIN\DATA\FGD3TE.PL2 Run By: Username 4/29/2003 3:20PM



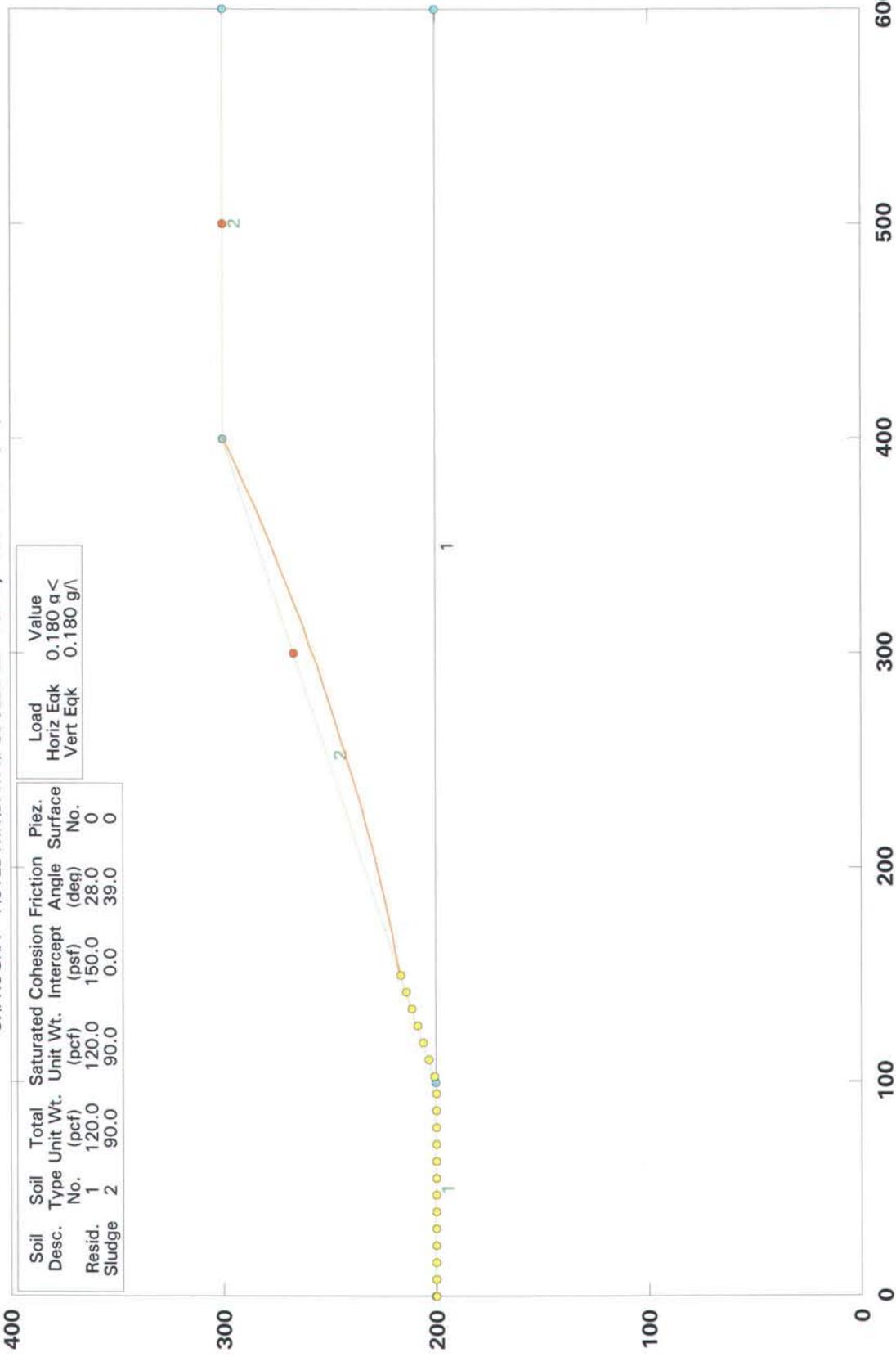
STABL6H FSmin = 1.34

Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 3:1 Slope (Eff Stresses w/ EQ)

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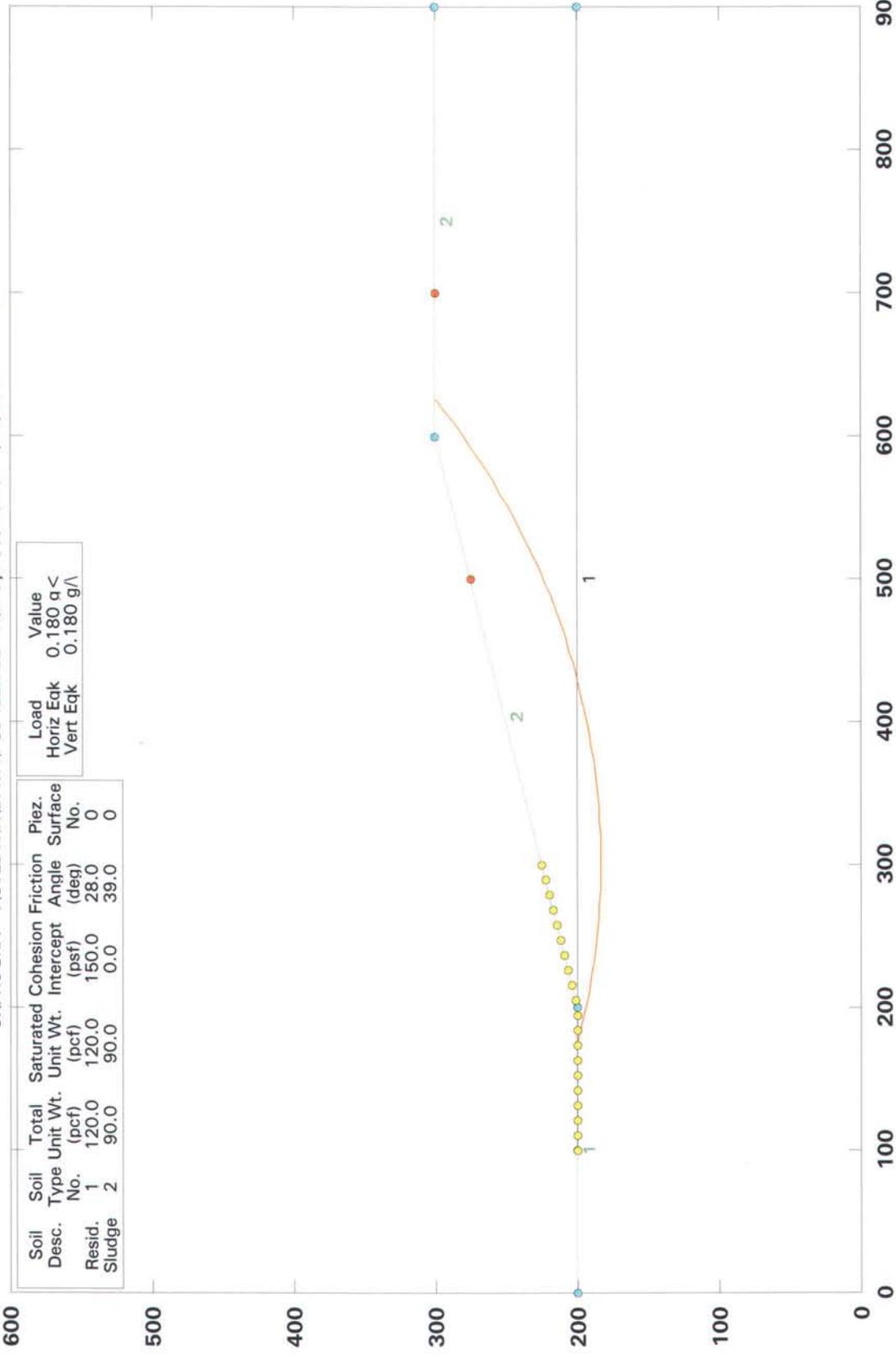


STABL6H FSmin = 1.37  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 4:1 Slope (Eff Stresses w/ EQ)

C:\PROGRA ~1\STEDWIN\DATA\FGD4EE.PL2 Run By: Username 4/10/2003 11:13AM

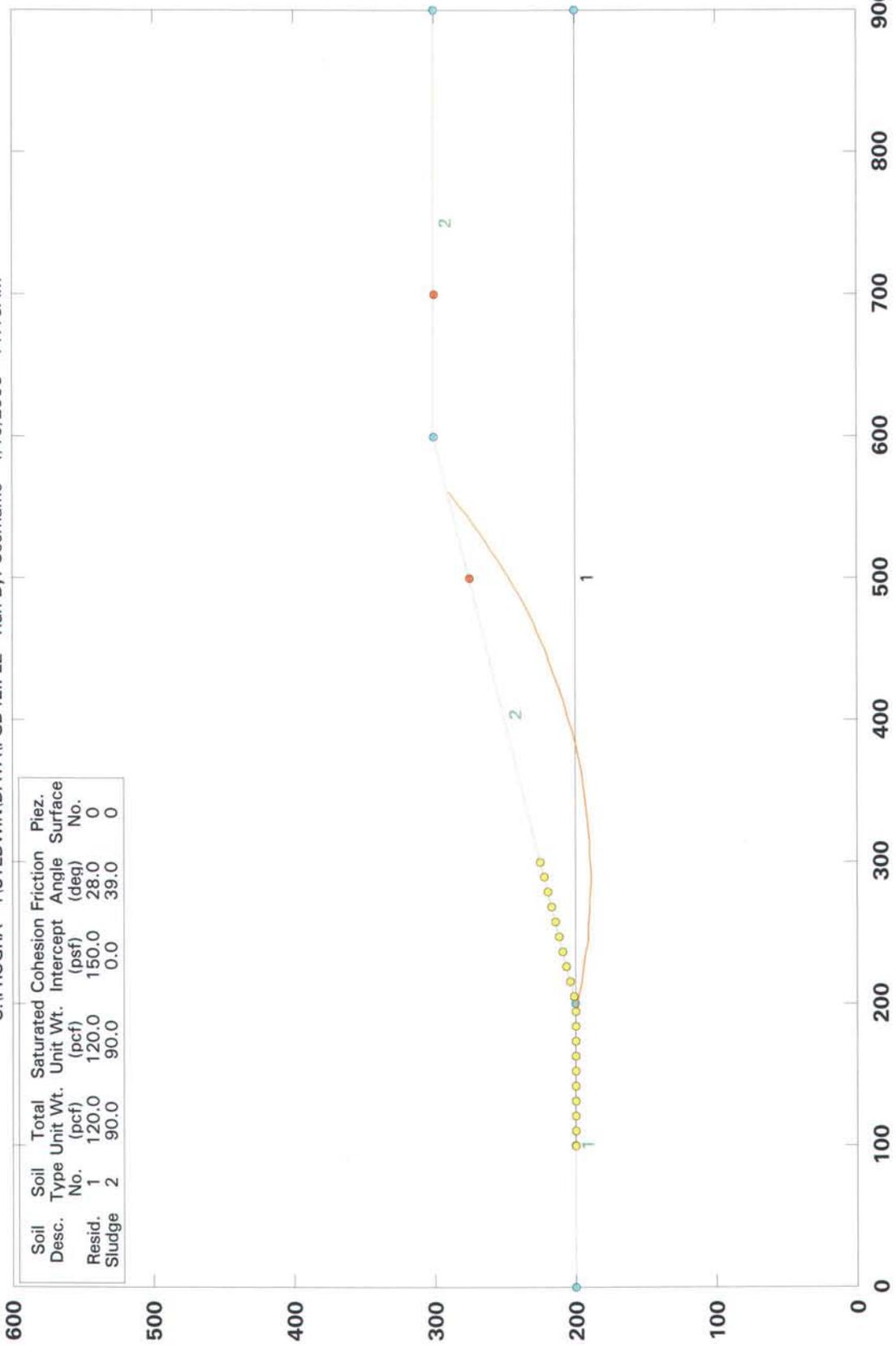


STABL6H FSmin = 1.56  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 4:1 Slope (Eff Stresses w/o EQ)

C:\PROGRA~1\STEDWIN\DATA\IFGD4E.PL2 Run By: Username 4/10/2003 11:13AM



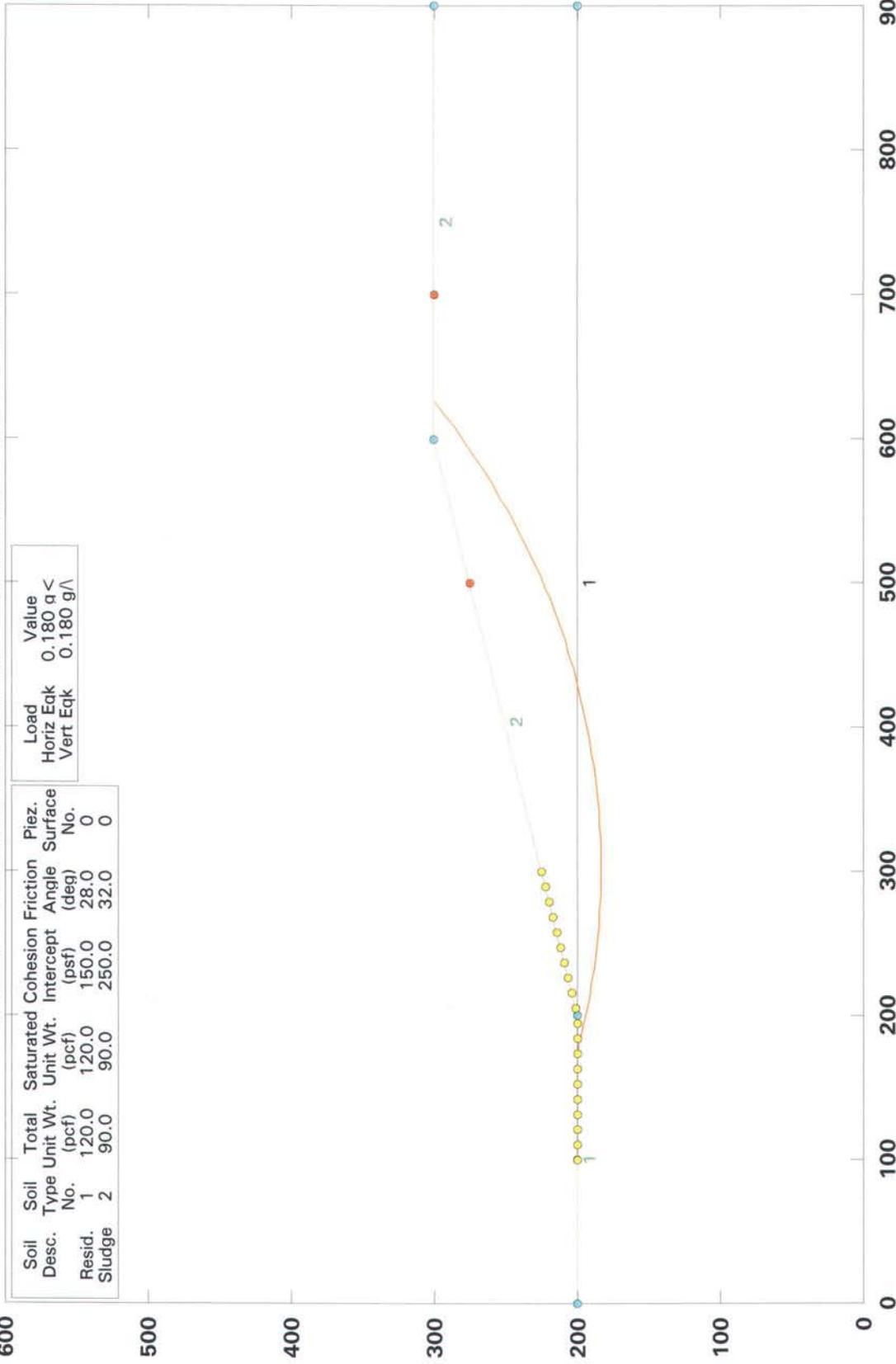
STABL6H FSmin = 3.16

Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 4:1 Slope (Total Stresses w/ EQ)

C:\PROGRA~1\STEDWIN\DATA\FGD4TE.PL2 Run By: Username 4/29/2003 3:22PM

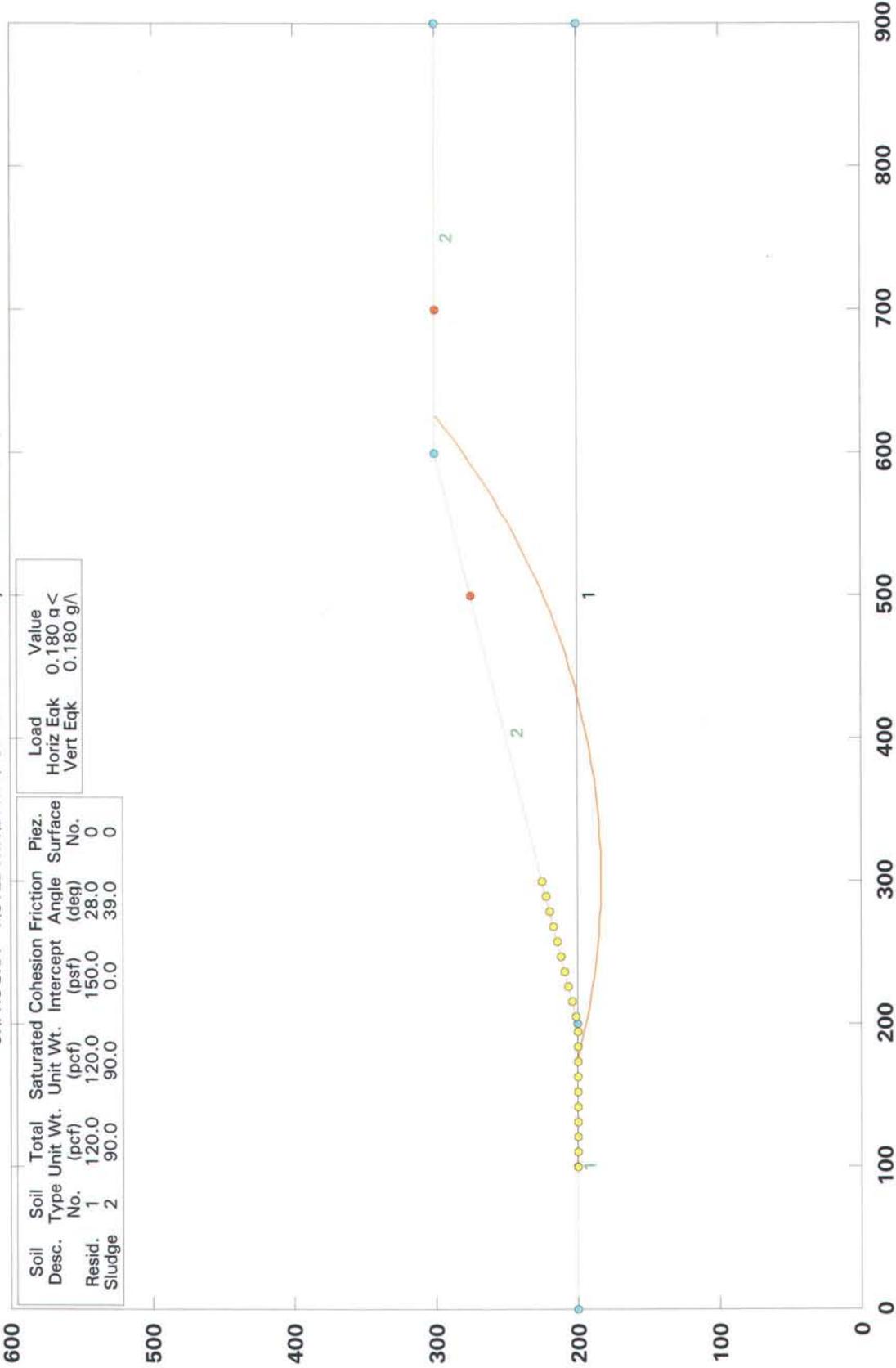


STABL6H FSmin = 1.49  
Safety Factors Are Calculated By The Modified Bishop Method



# Duke FGD Scrubber Sludge Testing 100' / 4:1 Slope (Eff Stresses w/ EQ)

C:\PROGRA~1\STEDWIN\DATA\FGD4EE.PL2 Run By: Username 4/10/2003 11:13AM



STABL6H FSmin = 1.56

Safety Factors Are Calculated By The Modified Bishop Method

### GROUND MOTION VALUES

SITE: **CLIFFSIDE**  
LATITUDE: 35.21367  
LONGITUDE: 81.76253

#### PROBABILISTIC GROUND MOTION VALUES, %g

	10% PE in 50 years	5% PE in 50 years	2% PE in 50 years
<b>PGA</b>	6.475299	10.02965	17.87137
<b>0.2 sec SA</b>	14.83405	22.97971	38.22041
<b>0.3 sec SA</b>	12.08536	18.49899	30.39903
<b>1.0 sec SA</b>	5.282979	8.438171	13.71333

SITE: **MARSHALL**  
LATITUDE: 35.60267  
LONGITUDE: 80.97572

#### PROBABILISTIC GROUND MOTION VALUES, %g

	10% PE in 50 years	5% PE in 50 years	2% PE in 50 years
<b>PGA</b>	5.351426	8.719715	14.61557
<b>0.2 sec SA</b>	12.54198	19.22603	33.45272
<b>0.3 sec SA</b>	10.93671	17.00028	27.52791
<b>1.0 sec SA</b>	4.851488	7.907398	13.09891

SITE: **BELEWS CREEK**  
LATITUDE: 36.27578  
LONGITUDE: 80.05647

#### PROBABILISTIC GROUND MOTION VALUES, %g

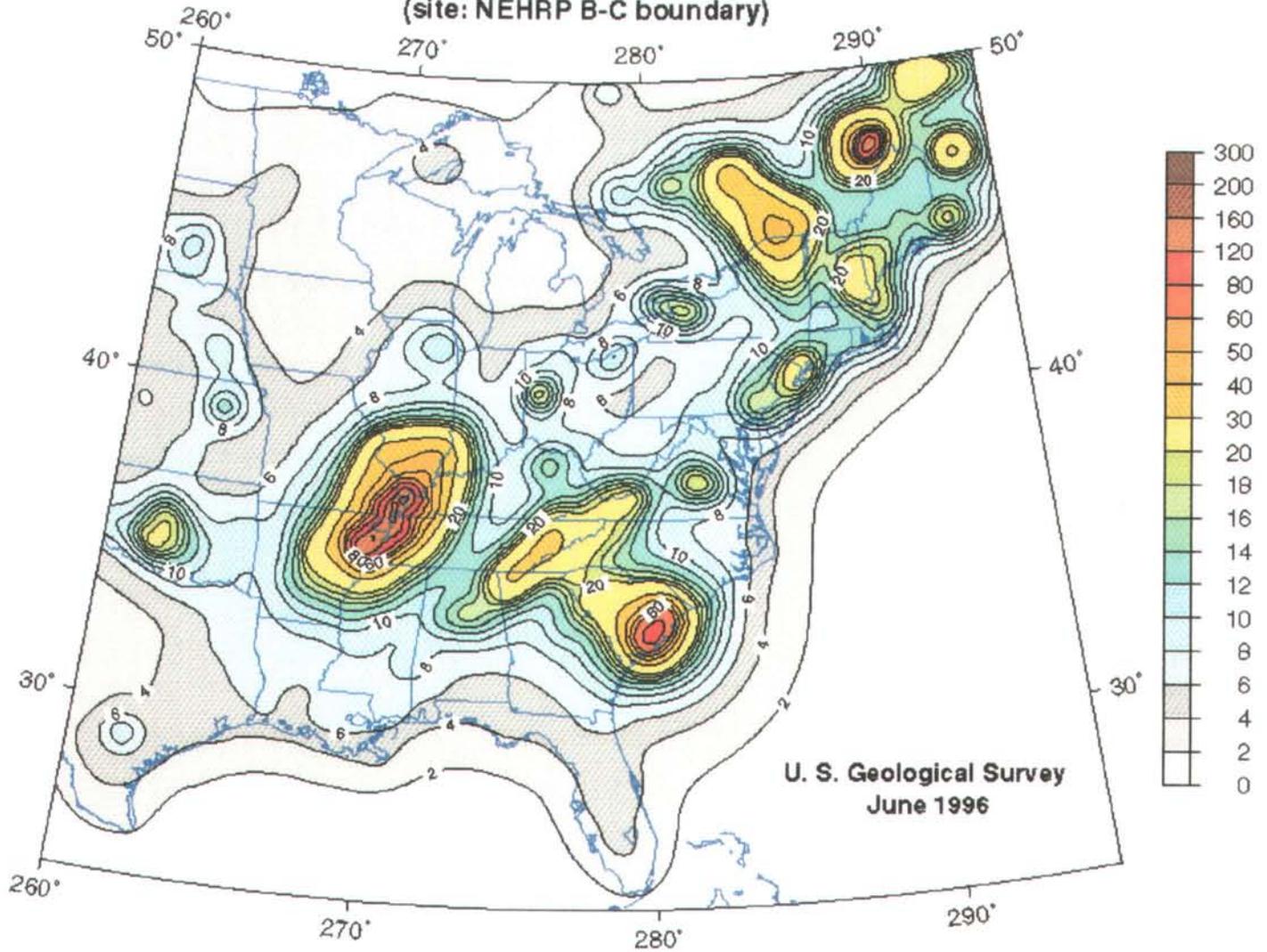
	10% PE in 50 years	5% PE in 50 years	2% PE in 50 years
<b>PGA</b>	4.357762	6.874004	12.07349
<b>0.2 sec SA</b>	10.41264	16.23185	26.81065
<b>0.3 sec SA</b>	8.516776	13.45018	23.06256
<b>1.0 sec SA</b>	4.067841	6.413146	11.15028

Notes:

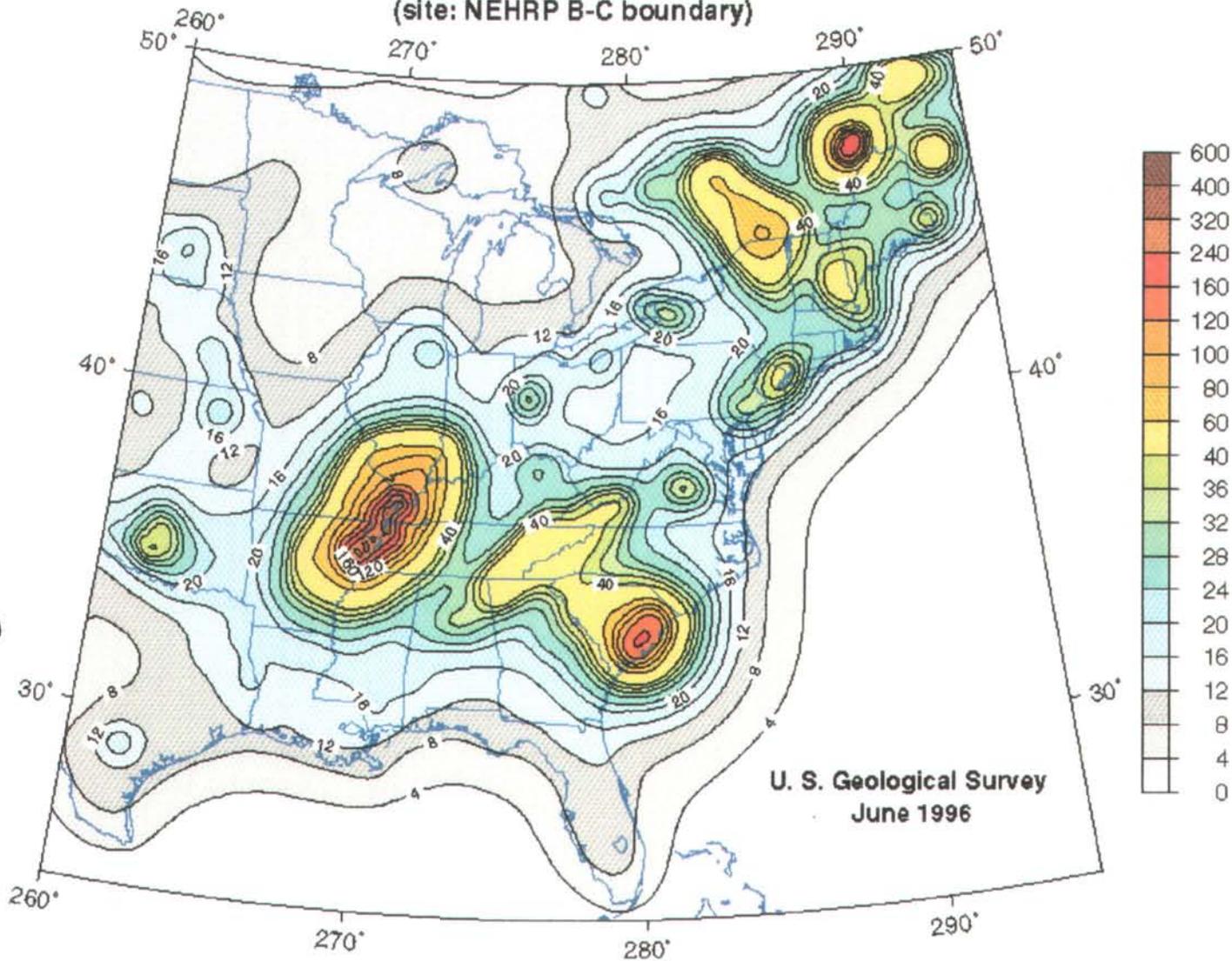
1. PE – Probability of Exceedance
2. PGA – Peak Ground Acceleration
3. SA – Spectral Acceleration

Reference: USGS Seismic Hazard Maps, 1996

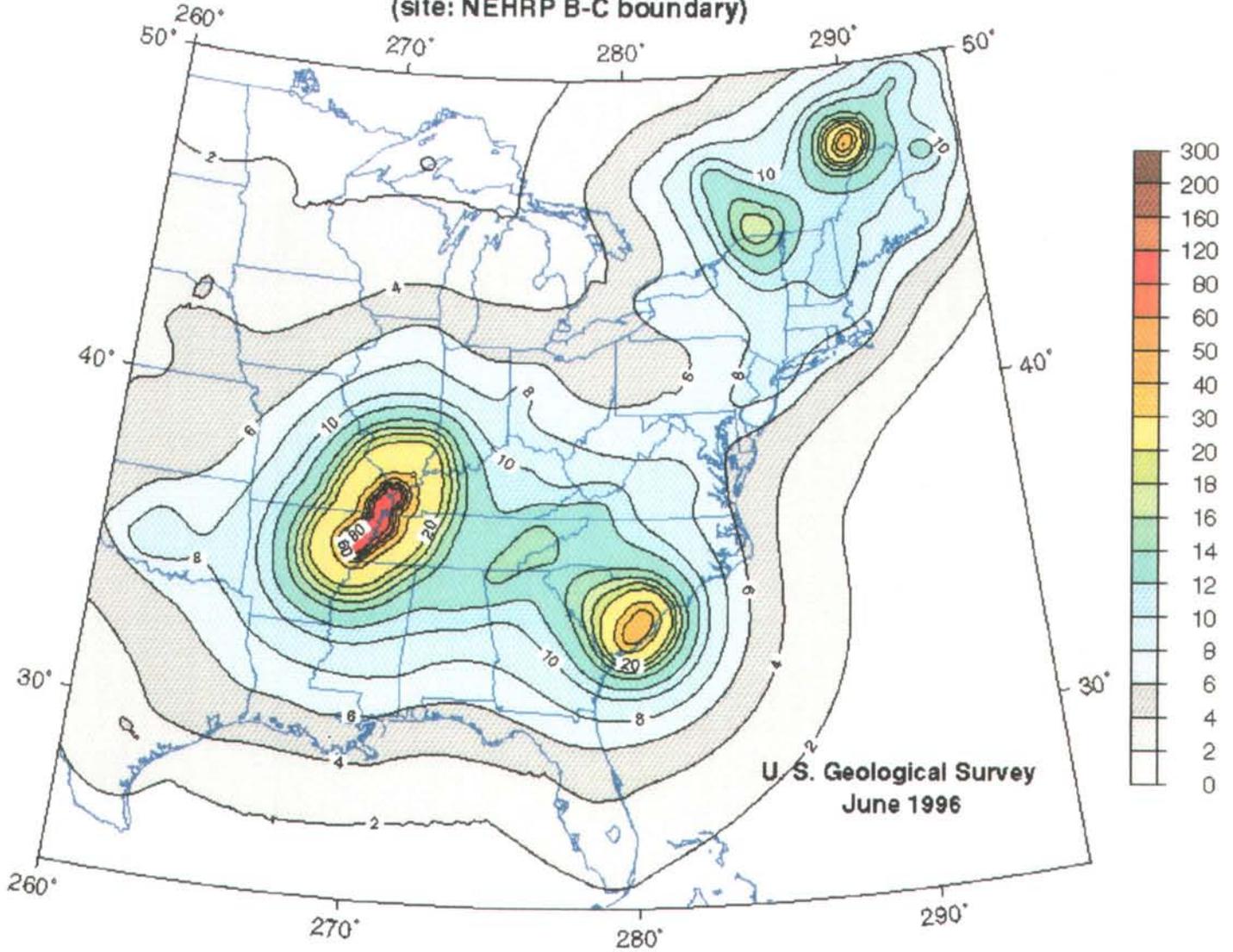
**Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years  
(site: NEHRP B-C boundary)**



0.2 sec Spectral Acceleration (%g) with 2% Probability of Exceedance in 50 Years  
(site: NEHRP B-C boundary)



1.0 sec Spectral Acceleration (%g) with 2% Probability of Exceedance in 50 Years  
(site: NEHRP B-C boundary)



Attachment 2

**Attachment 2**

**Geochemical Evaluation of  
Flue Gas Desulfurization Scrubber Waste,**  
**letter from William J, Deutsch, Senior Geochemist,  
Battelle Pacific Northwest Laboratory**  
**to**  
**Bill Miller, Duke Energy,**  
**dated June 23, 2003**

June 23, 2003



Duke Energy  
PO Box 1006  
Attn: Bill Miller, Mail Code EC 12 ZB  
Charlotte, NC 28201-1006

Dear Bill:

### **GEOCHEMICAL EVALUATION OF FLUE GAS DESULFURIZATION SCRUBBER WASTE**

This project was conducted by Battelle for Duke Energy to measure potential contaminant concentrations in solution from five consecutive leaches of Flue Gas Desulfurization (FGD) scrubber waste. These concentrations were compared to the 15A NCAC 2L groundwater standards to determine if any of the standards were exceeded in the leachate. In addition to the leaching studies, the solid samples were analyzed by x-ray diffraction (XRD) to identify the primary minerals in the waste material, and saturation indices were calculated for the solution analyses to identify minerals in equilibrium with the solution phase. This letter report describes the testing methods, analytical results and the conclusions that can be made from evaluation of the data. The results are summarized in the following paragraph.

The total dissolved solids and sulfate concentrations exceeded the 2L standards for both types of waste in all leachates by factors of about 4 and 6, respectively. The initial leaches of both waste types exceeded the fluoride 2L standard by a factor of about 2; however, the fluoride concentrations decreased with subsequent leaches and either dropped below or were very close to the standard of 2 mg/L by the fifth leach. The arsenic concentrations in all leachates started below the 2L standard of 0.01 mg/L, but the concentrations increased with subsequent leaches and exceeded the standard by a small amount in all cases after the second or third leach. XRD analysis showed that the dominant mineral in the waste was gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). Saturation index calculations confirm that gypsum is controlling the calcium and sulfate concentrations in the leachate and producing the major ions in solution.

### **Test Materials and Methods**

Two samples of FGD scrubber waste were provided by Duke Energy to Battelle. These samples were labeled as HC Plant and Co Plant. The EPA Synthetic Precipitation Leaching Procedure (SPLP, EPA SW846 1312) was used to determine the water soluble constituents in the waste. In this procedure, 100 grams of the solid is tumbled with two liters of extraction fluid for a period of 18 hours. Because the site is east of the Mississippi River, the extraction fluid is a 60/40 weight percent mixture of sulfuric and nitric acids added to reagent water until the pH is 4.2. After each step of leaching was completed, the solid and solution were separated by filtering. The SPLP testing was conducted for Battelle by SVL Analytical Inc., Kellogg, Idaho.

The wastes were consecutively leached with the extraction fluid a total of five times using the SPLP. After each leach procedure, the filtered solution was analyzed for potential contaminants and common major cations and anions. A duplicate, 5-stage leach of the Co Plant waste material was performed to evaluate the reproducibility of the results. A flow diagram for the leaching process is shown in Figure 1. A list of the solution analytes and the 2L standards are provided in Table 1. The analytical reporting limits were equal to or less than the 2L standards.

X-ray diffraction analysis allows for the identification of crystalline solids (minerals) in the waste material. The identification of these minerals is important because their solubilities in water provide an upper limit on potential dissolved concentrations of the components of the minerals. XRD analysis was performed using Battelle procedure PNNL/RPL-PIP-4. In this procedure, approximately 200-mg samples of the waste material are ground to a powder in a tungsten carbide ball mill for 10 minutes. Samples are analyzed on a Scintag XRD unit equipped with a Pelter thermoelectrically-cooled detector and a copper x-ray tube. Randomly oriented whole waste samples were scanned from 2 to 65° 2θ with a dwell time of 1 to 16 seconds. Scans were collected electronically and processed using the JADE® XRD pattern processing software. Identification of the mineral phases was based on mineral powder diffraction files published by the JCPDS International Center for Diffraction Data. Typically, minerals must be present at a concentration of at least 5% (depending on crystallinity) to be identified by this method.

The solution data from each of the leaching tests were entered into an aqueous speciation/mineral equilibrium code to calculate the saturation indices for minerals that might be in equilibrium with the solution. Minerals that calculate to have a saturation index close to zero have the correct concentrations of their constituents in the solution to be in equilibrium with the solution (a negative value indicates undersaturation and a positive value indicates oversaturation). Saturation index calculations help identify the minerals that might be controlling the solution composition. The U.S. Geological Survey computer code PHREEQCv2 (Parkhurst and Appelo 1999) was used to calculate saturation indices.

## Results and Conclusions

Tables 2 through 6 provide a summary of the analytical results of the SPLP tests for each of the five leaching steps. Tables 7 through 9 compile the data for each of the three wastes leached. The complete laboratory data package may be found in Appendix A. The calculated cation/anion balances for the analyses shown in these tables range from 0.21% to -4.33%. It is generally accepted that a balance less than 5% is good, and that the results represent all of the major ions in solution. Most of the analyses for this project are well under 5%, and are considered representative of the major leachable constituents from the tested waste samples.

Sulfate is the major anion in solution. Its concentration ranges from 1,450 to 1,510 mg/L, and is very consistent for all leaches and waste types. These concentrations exceed the 2L groundwater standard of 250 mg/L by a factor of 6. Calcium is the major cation in solution with a range of 579 to 622 mg/L. There is no 2L standard for calcium. The uniformity of the sulfate and calcium concentrations between waste materials and throughout the leaching

procedures suggests that gypsum is controlling the dissolved concentrations of these constituents. The combination of dissolved sulfate and calcium provides most of the total dissolved solids (TDS) in the leachate. The TDS ranges from 2,090 to 2,200 mg/L, which is slightly greater than 4 times the 2L standard. Note that approximately 4% (4 grams) of the total 100 gram solid sample is dissolved in the two liters of water used in each leaching step. After five steps, 80% of the starting solid remains.

The only other parameters that exceed the 2L groundwater standards in some of the leachates are fluoride and arsenic. As shown in Table 7, the fluoride concentration in the first Co Plant leachate is 4.45 mg/L, which exceeds the standard of 2 mg/L. Subsequent leaches of this material show that the fluoride concentration uniformly decreases in the sequence 4.45, 3.98, 3.86, 3.06, and 2.02. This decrease is also shown in the results for the Co Plant Duplicate (Table 8) and HC Plant (Table 9) analyses. In fact, the latter leaches for these two samples decrease below the 2 mg/L standard. This decrease in fluoride concentration with leaching suggests that fluoride is controlled not by mineral solubility but by a limited source that is decreasing with each leach event.

The arsenic concentrations in leachates from the three materials start out below the 2L standard of 0.01 mg/L, and then increase with subsequent leaches. For the Co Plant, the concentration exceeds the standard for the third through fifth leaches, and for the Co Plant Duplicate and the HC Plant, exceedances occur for the second through fifth leaches. The range of arsenic concentrations that exceed the 2L standard is 0.011 to 0.018 mg/L. This effect of increasing dissolved arsenic with subsequent leaches suggests its release to solution may either be rate limited or do to enhanced exposure as other solids are dissolved and removed.

Trends in concentrations for other measurable constituents that are all below the 2L standards can be summarized as:

- pH – circumneutral in the range 6.8 to 7.35
- $\text{HCO}_3^-$  - stable level in the range 7.2 to 10.2 as mg/L  $\text{CaCO}_3$
- Chloride – 1<sup>st</sup> leach: 3.67 to 4.45 mg/L, then < 0.4 mg/L in all cases
- Magnesium – 1<sup>st</sup> leach: 1.23 to 1.6 mg/L, then drop by factor of 10 in second leaches, followed by continuous slow decrease
- Sodium – 1<sup>st</sup> leach: 0.93 to 2.83 mg/L, then continuous decrease
- Boron – relatively uniform in the range of 0.059 to 0.163 mg/L
- Barium – uniform in the range of 0.0411 to 0.0589 mg/L
- Copper – 3 measurements close to detection limit of 0.003 mg/L, all others less than the detection limit
- Manganese – decreasing concentrations in Co Plant and Co Plant Duplicate leaches from 0.029 to 0.009 mg/L; more uniform concentrations for HC Plant starting at 0.0187 mg/L and decreasing to 0.0109 mg/L
- Zinc – relatively uniform measurements in the range 0.0097 to 0.0206 mg/L

XRD analyses of the solids show the predominance of gypsum in the waste material (Figures 2 and 3). It is estimated that at least 90% of the solid waste is gypsum. Minor minerals and

amorphous compounds may be present at individual concentrations of less than 5%, but they were not identifiable on the XRD pattern.

The results of the saturation index (S.I.) calculations for minerals that have an index close to zero are shown in Tables 7 through 9. Gypsum is at saturation with S.I.s in the range of -0.01 to -0.03. (Saturation is generally concluded if the S.I. is  $0.0 \pm 0.5$ .) Mineral equilibrium with gypsum is expected because it is the predominant mineral in the waste material and it is a reactive mineral that typically equilibrates with water in a short period of time. Barite ( $\text{BaSO}_4$ ) calculates to be oversaturated with S.I.s ranging from 0.50 to 0.56. Barite is also a reactive mineral, and is unlikely to be oversaturated. These results call into question the calculation method or analytical data for the components of barite. Fluorite ( $\text{CaF}_2$ ), which commonly limits the fluoride concentration in water, is highly oversaturated (S.I. = 0.51 to 0.94) in all of the first two leaches and then its S.I. decreases to close to zero with subsequent leaches. This oversaturation and variable S.I. suggest that fluorite, if present, is not limiting the dissolved fluoride concentration in the leachates. Calcite ( $\text{CaCO}_3$ ) is undersaturated for the leachate compositions (S.I. = -0.61 to -1.28), meaning that this mineral is not limiting the carbonate concentration in solution.

These results show that FGD scrubber waste has the potential to produce a water leachate that will contain sulfate and, perhaps, arsenic and fluoride at concentrations greater than the 2L groundwater standards. It is expected that the arsenic concentration will be close to its standard throughout the leaching process and that fluoride may only exceed its standard during the early stages of leaching. Sulfate, on the other hand, will exceed its standard by a factor of about six throughout the leaching process until almost all of the solid waste has been dissolved. The reason for this is that the primary component of the waste is the moderately soluble sulfate mineral gypsum. Using the SPLP method, as many as 25 consecutive leaches would be required to dissolve all of the gypsum.

## References

Parkhurst, D.L. and C.A.J. Appelo. User's Guide to PHREEQC (Version 2) – A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations. Water-Resources Investigations Report 99-4259. U.S. Geological Survey.

Sincerely,



William J. Deutsch  
Senior Geochemist

WJD:sls

Attachments

Figure 1

Flow Chart for Scrubber Waste SPLP Testing and Solution Analyses

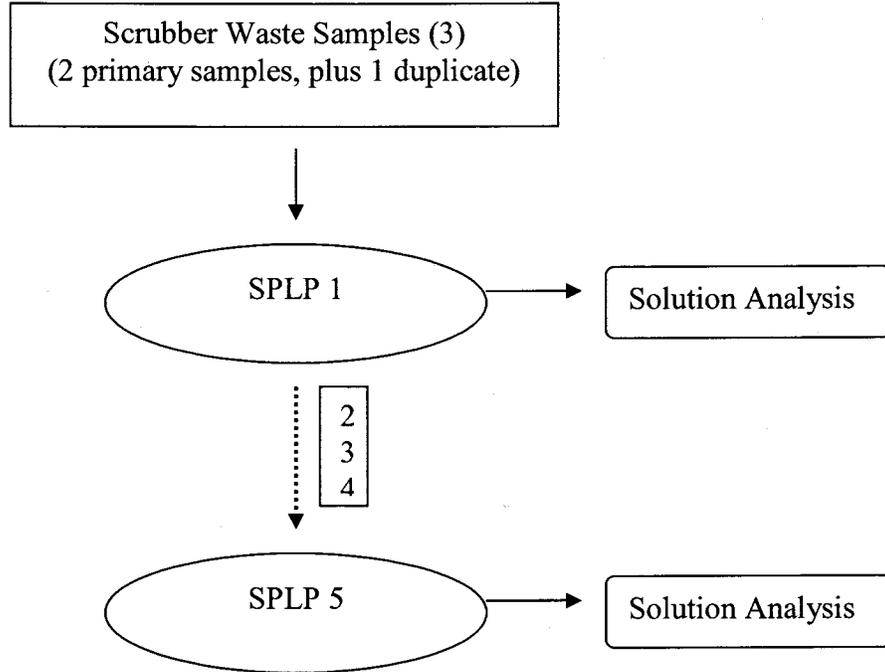


Figure 2  
X-Ray Diffraction Pattern – Co Plant Scrubber Waste

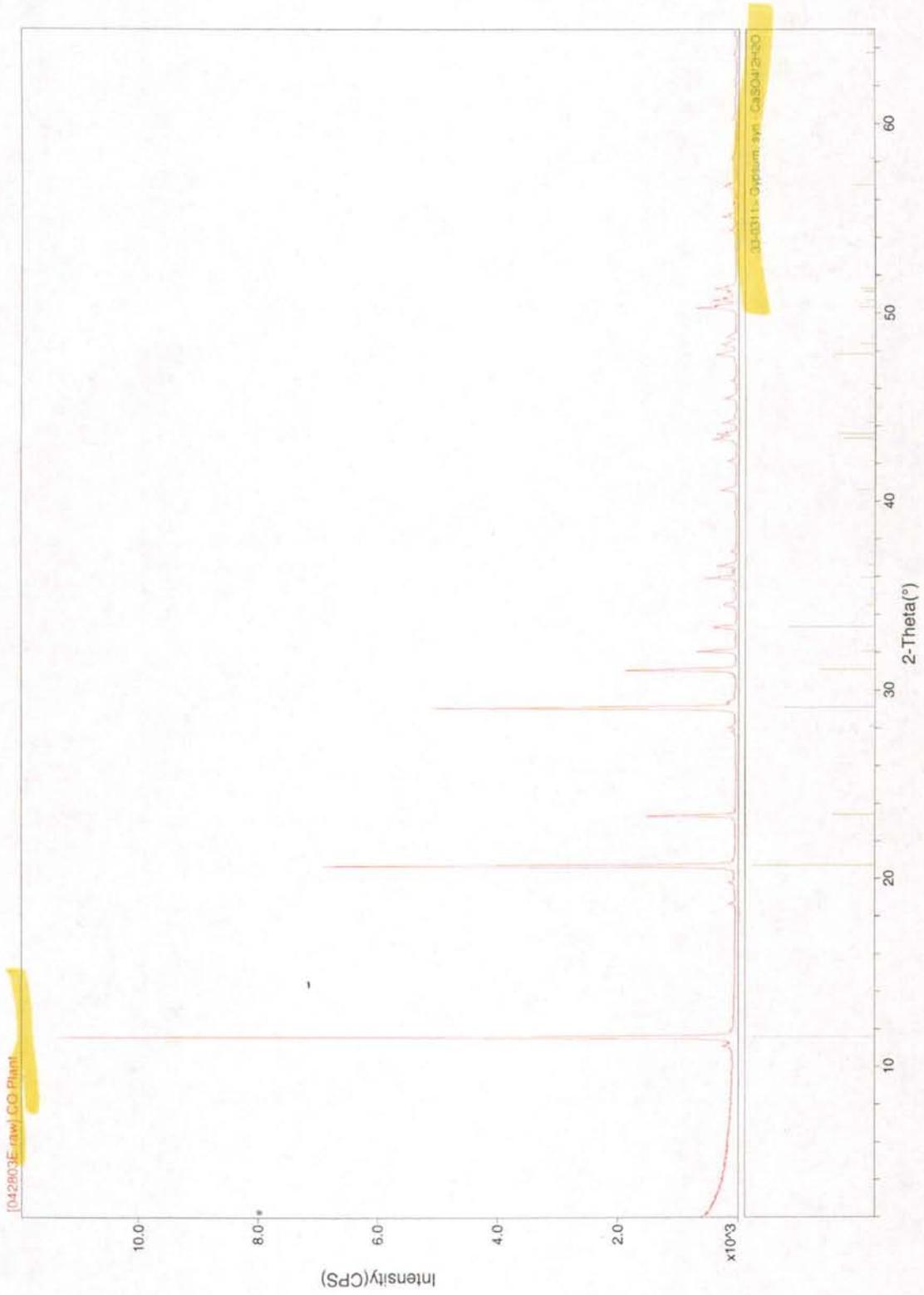


Figure 3  
X-Ray Diffraction Pattern – HC Plant Scrubber Waste

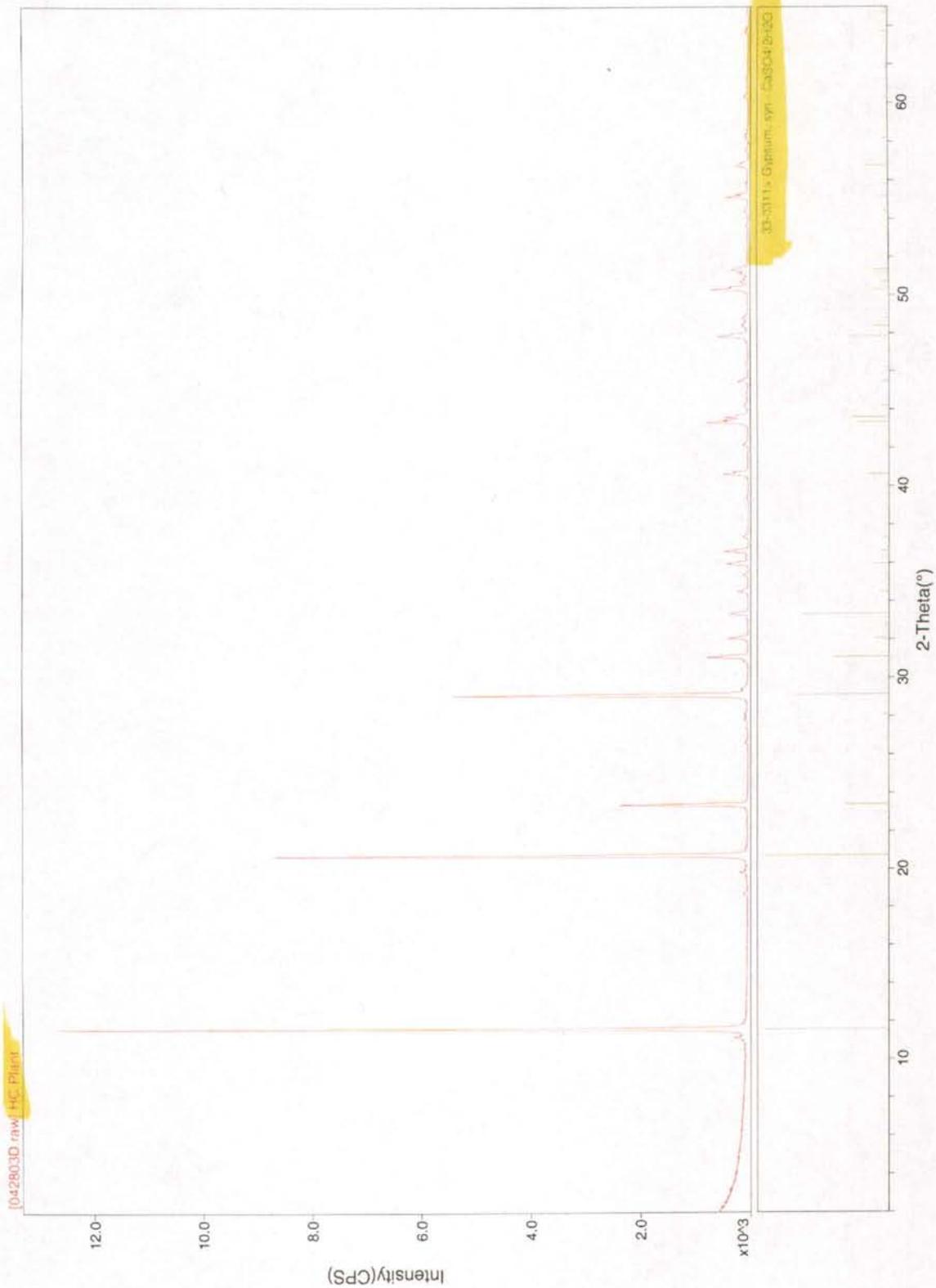


Table 1. Analytes of Interest and the 15A NCAC 2L Groundwater Standards (mg/L)

Parameters	North Carolina 15A NCAC 2L Groundwater Standards (mg/L)
arsenic:	0.01
barium:	2.0
boron:	0.32
cadmium:	0.005
chloride:	250.0
chromium:	0.05
copper:	1.0
dissolved solids (total):	500
fluoride:	2.0
iron:	0.3
lead:	0.015
manganese:	0.05
mercury:	0.0011
nickel:	0.1
pH:	6.5 to 8.5
selenium:	0.05
silver:	0.018
sulfate:	250.0
zinc:	2.1
<i>Additional parameters</i>	
Calcium	NA
Magnesium	NA
Sodium	NA
Potassium	NA
Carbonate/bicarbonate	NA

**Table 2. Scrubber Waste SPLP Results - First Leach**

Analyte	Units	CO Plant	CO Plant Dup	HC Plant
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	10.2	9.9	9.5
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	10.2	9.9	9.5
pH	std units	7.35	7.31	7.14
TDS	mg/L Ext	2,160	2,180	2,200
Calcium	mg/L Ext	597	614	612
Chloride	mg/L Ext	5.33	4.98	3.67
Fluoride	mg/L Ext	4.45	4.02	3.05
Potassium	mg/L Ext	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	1.6	1.73	1.23
Sodium	mg/L Ext	0.93	0.94	2.83
Sulfate, SO <sub>4</sub>	mg/L Ext	1,490	1,500	1,510
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	<0.010	<0.010	<0.010
Boron	mg/L Ext	0.149	0.162	0.13
Barium	mg/L Ext	0.0411	0.0429	0.0507
Cadmium	mg/L Ext	<0.0020	<0.00020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	0.0031	0.0035	<0.0030
Iron	mg/L Ext	<0.020	0.051	0.026
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0286	0.0292	0.0187
Nickel	mg/L Ext	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.012	0.0133	0.0157

Calculated TDS		2,107	2,128	2,136
TDS/CalcTDS:		1.0	1.0	1.0
Cation/Anion Balance		-2.73%	-1.41%	-1.71%

Red denotes concentrations greater than NCAC 2L groundwater standards

**Table 3. Scrubber Waste SPLP Results - Second Leach**

Analyte	Units	CO Plant	CO Plant Dup	HC Plant
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	7.6	7.7	7.2
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	7.6	7.7	7.2
pH	std units	6.8	7.07	7.1
TDS	mg/L Ext	2,090	2,190	2,150
Calcium	mg/L Ext	603	579	580
Chloride	mg/L Ext	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	3.98	3.88	3.18
Potassium	mg/L Ext	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	0.237	0.215	0.155
Sodium	mg/L Ext	0.58	0.70	1.08
Sulfate, SO <sub>4</sub>	mg/L Ext	1,500	1,500	1,470
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	<0.010	0.02	0.012
Boron	mg/L Ext	0.065	0.059	0.163
Barium	mg/L Ext	0.0461	0.0476	0.0443
Cadmium	mg/L Ext	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	<0.0030	<0.0030	<0.0030
Iron	mg/L Ext	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0107	0.0108	0.0125
Nickel	mg/L Ext	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.0097	0.0091	<0.0050

Calculated TDS		2,114	2,087	2,063
TDS/CalcTDS:		1.0	1.0	1.0
Cation/Anion Balance		-2.41%	-4.33%	-3.33%

Red denotes concentrations greater than NCAC 2L groundwater standards

**Table 4. Scrubber Waste SPLP Results - Third Leach**

Analyte	Units	CO Plant	CO Plant Dup	HC Plant
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	9.5	8.5	7.8
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	9.5	8.5	7.8
pH	std units	6.89	6.99	7.3
TDS	mg/L Ext	2,130	2,190	2,200
Calcium	mg/L Ext	605	607	622
Chloride	mg/L Ext	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	3.86	3.73	2.61
Potassium	mg/L Ext	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	0.228	0.20	0.138
Sodium	mg/L Ext	<0.50	0.59	0.76
Sulfate, SO <sub>4</sub>	mg/L Ext	1,510	1,510	1,470
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	0.013	0.013	0.018
Boron	mg/L Ext	<0.040	0.069	0.147
Barium	mg/L Ext	0.0473	0.0418	0.0536
Cadmium	mg/L Ext	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	0.0043	<0.0030	<0.0030
Iron	mg/L Ext	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0133	0.0107	0.0127
Nickel	mg/L Ext	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.0134	0.0111	0.0098

Calculated TDS		2,129	2,122	2,102
TDS/CalcTDS:		1.0	1.0	1.0
Cation/Anion Balance		-2.74%	-2.19%	0.21%

Red denotes concentrations greater than NCAC 2L groundwater standards

**Table 5. Scrubber Waste SPLP Results - Fourth Leach**

Analyte	Units	CO Plant	CO Plant Dup	HC Plant
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	8.4	8.4	7.4
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	8.4	8.4	7.4
pH	std units	7.11	7.08	6.97
TDS	mg/L Ext	2,140	2,150	2,110
Calcium	mg/L Ext	599	595	589
Chloride	mg/L Ext	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	3.06	3.03	1.77
Potassium	mg/L Ext	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	0.184	0.197	0.127
Sodium	mg/L Ext	<0.50	0.87	0.70
Sulfate, SO <sub>4</sub>	mg/L Ext	1,460	1,460	1,450
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	0.011	0.018	0.017
Boron	mg/L Ext	0.061	0.081	0.136
Barium	mg/L Ext	0.0437	0.0417	0.0513
Cadmium	mg/L Ext	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	<0.0030	<0.0030	<0.0030
Iron	mg/L Ext	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0111	0.0105	0.0121
Nickel	mg/L Ext	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.0133	0.0148	0.0138
Calculated TDS		2,067	2,065	2,042
TDS/CalcTDS:		1.0	1.0	1.0
Cation/Anion Balance		-1.35%	-1.65%	-1.54%

Red denotes concentrations greater than NCAC 2L groundwater standards

**Table 6. Scrubber Waste SPLP Results - Fifth Leach**

Analyte	Units	CO Plant	CO Plant Dup	HC Plant
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	8.3	8.4	8
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	8.3	8.4	8
pH	std units	7.04	7.29	7.18
TDS	mg/L Ext	2,140	2,200	2,100
Calcium	mg/L Ext	586	601	591
Chloride	mg/L Ext	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	2.02	1.88	1.21
Potassium	mg/L Ext	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	0.159	0.175	0.131
Sodium	mg/L Ext	0.55	0.51	0.73
Sulfate, SO <sub>4</sub>	mg/L Ext	1,490	1,480	1,500
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	0.013	0.015	0.011
Boron	mg/L Ext	0.073	0.078	0.152
Barium	mg/L Ext	0.0442	0.0459	0.0589
Cadmium	mg/L Ext	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	<0.0030	<0.0030	<0.0030
Iron	mg/L Ext	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0092	0.0094	0.0109
Nickel	mg/L Ext	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.0171	0.0206	0.0164
Calculated TDS		2,081	2,091	2,095
TDS/CalcTDS:		1.0	1.1	1.0
Cation/Anion Balance		-3.26%	-1.82%	-3.05%

Red denotes concentrations greater than NCAC 2L groundwater standards

**Table 7. Scrubber Waste SPLP Results - Co Plant Leaches**

Analyte	Units	CO Plant #1	CO Plant #2	CO Plant #3	CO Plant #4	CO Plant #5
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	10.2	7.6	9.5	8.4	8.3
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	10.2	7.6	9.5	8.4	8.3
pH	std units	7.35	6.8	6.89	7.11	7.04
TDS	mg/L Ext	2,160	2,090	2,130	2,140	2,140
Calcium	mg/L Ext	597	603	605	599	586
Chloride	mg/L Ext	5.33	<0.4	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	4.45	3.98	3.86	3.06	2.02
Potassium	mg/L Ext	<1.0	<1.0	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	1.6	0.237	0.228	0.184	0.159
Sodium	mg/L Ext	0.93	0.58	<0.50	<0.50	0.55
Sulfate, SO <sub>4</sub>	mg/L Ext	1,490	1,500	1,510	1,460	1,490
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	<0.010	<0.010	0.013	0.011	0.013
Boron	mg/L Ext	0.149	0.065	<0.040	0.061	0.073
Barium	mg/L Ext	0.0411	0.0461	0.0473	0.0437	0.0442
Cadmium	mg/L Ext	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	0.0031	<0.0030	0.0043	<0.0030	<0.0030
Iron	mg/L Ext	<0.020	<0.020	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0286	0.0107	0.0133	0.0111	0.0092
Nickel	mg/L Ext	<0.010	<0.010	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.012	0.0097	0.0134	0.0133	0.0171
Calculated TDS		2,107	2,114	2,129	2,067	2,081
TDS/CalcTDS:		1.0	1.0	1.0	1.0	1.0
Cation/Anion Balance		-2.73%	-2.41%	-2.74%	-1.35%	-3.26%

Red denotes concentrations greater than NCAC 2L groundwater standards

*Saturation Indices*

Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	-0.02	-0.01	-0.01	-0.02	-0.02
Fluorite	CaF <sub>2</sub>	0.83	0.74	0.71	0.51	0.14
Barite	BaSO <sub>4</sub>	0.50	0.55	0.56	0.52	0.53
Calcite	CaCO <sub>3</sub>	-0.61	-1.28	-1.09	-0.92	-1.01

**Table 8. Scrubber Waste SPLP Results - Co Plant Duplicate Leaches**

Analyte	Units	CO Plant Dup #1	CO Plant Dup #2	CO Plant Dup #3	CO Plant Dup #4	CO Plant Dup #5
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	9.9	7.7	8.5	8.4	8.4
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	9.9	7.7	8.5	8.4	8.4
pH	std units	7.31	7.07	6.99	7.08	7.29
TDS	mg/L Ext	2,180	2,190	2,190	2,150	2,200
Calcium	mg/L Ext	614	579	607	595	601
Chloride	mg/L Ext	4.98	<0.4	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	4.02	3.88	3.73	3.03	1.88
Potassium	mg/L Ext	<1.0	<1.0	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	1.73	0.215	0.20	0.197	0.175
Sodium	mg/L Ext	0.94	0.70	0.59	0.87	0.51
Sulfate, SO <sub>4</sub>	mg/L Ext	1,500	1,500	1,510	1,460	1,480
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	<0.010	0.015	0.013	0.018	0.015
Boron	mg/L Ext	0.162	0.059	0.069	0.081	0.078
Barium	mg/L Ext	0.0429	0.0476	0.0418	0.0417	0.0459
Cadmium	mg/L Ext	<0.00020	<0.0020	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	0.0035	<0.0030	<0.0030	<0.0030	<0.0030
Iron	mg/L Ext	0.051	<0.020	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0292	0.0108	0.0107	0.0105	0.0094
Nickel	mg/L Ext	<0.010	<0.010	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.0133	0.0091	0.0111	0.0148	0.0206

Calculated TDS		2,128	2,087	2,122	2,065	2,091
TDS/CalcTDS:		1.0	1.0	1.0	1.0	1.1
Cation/Anion Balance		-1.41%	-4.33%	-2.19%	-1.65%	-1.82%

Red denotes concentrations greater than NCAC 2L groundwater standards

*Saturation Indices*

Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	-0.01	-0.02	-0.01	-0.02	-0.02
Fluorite	CaF <sub>2</sub>	0.94	0.70	0.68	0.50	0.09
Barite	BaSO <sub>4</sub>	0.51	0.56	0.50	0.50	0.54
Calcite	CaCO <sub>3</sub>	-0.65	-1.02	-1.04	-0.96	-0.75

**Table 9. Scrubber Waste SPLP Results - HC Plant Leaches**

Analyte	Units	HC Plant #1	HC Plant #2	HC Plant #3	HC Plant #4	HC Plant #5
Alkalinity, CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	9.5	7.2	7.8	7.4	8
CO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	<1.0	<1.0	<1.0	<1.0	<1.0
HCO <sub>3</sub> , CaCO <sub>3</sub>	mg CaCO <sub>3</sub> /L	9.5	7.2	7.8	7.4	8
pH	std units	7.14	7.1	7.3	6.97	7.18
TDS	mg/L Ext	2,200	2,150	2,200	2,110	2,100
Calcium	mg/L Ext	612	580	622	589	591
Chloride	mg/L Ext	3.67	<0.4	<0.4	<0.4	<0.4
Fluoride	mg/L Ext	3.05	3.18	2.61	1.77	1.21
Potassium	mg/L Ext	<1.0	<1.0	<1.0	<1.0	<1.0
Magnesium	mg/L Ext	1.23	0.155	0.138	0.127	0.131
Sodium	mg/L Ext	2.83	1.08	0.76	0.70	0.73
Sulfate, SO <sub>4</sub>	mg/L Ext	1,510	1,470	1,470	1,450	1,500
Silver	mg/L Ext	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Arsenic	mg/L Ext	<0.010	0.012	0.018	0.017	0.011
Boron	mg/L Ext	0.13	0.163	0.147	0.136	0.152
Barium	mg/L Ext	0.0507	0.0443	0.0536	0.0513	0.0589
Cadmium	mg/L Ext	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020
Chromium	mg/L Ext	<0.0060	<0.0060	<0.0060	<0.0060	<0.0060
Copper	mg/L Ext	<0.0030	<0.0030	<0.0030	<0.0030	<0.0030
Iron	mg/L Ext	0.026	<0.020	<0.020	<0.020	<0.020
Mercury	mg/L Ext	<0.00020	<0.00020	<0.00020	<0.00020	<0.00020
Manganese	mg/L Ext	0.0187	0.0125	0.0127	0.0121	0.0109
Nickel	mg/L Ext	<0.010	<0.010	<0.010	<0.010	<0.010
Lead	mg/L Ext	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Selenium	mg/L Ext	<0.010	<0.010	<0.010	<0.010	<0.010
Zinc	mg/L Ext	0.0157	<0.0050	0.0098	0.0138	0.0164

Calculated TDS		2,136	2,063	2,102	2,042	2,095
TDS/CalcTDS:		1.0	1.0	1.0	1.0	1.0
Cation/Anion Balance		-1.71%	-3.33%	0.21%	-1.54%	-3.05%

Red denotes concentrations greater than NCAC 2L groundwater standards

*Saturation Indices*

Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	-0.01	-0.03	-0.01	-0.03	-0.02
Fluorite	CaF <sub>2</sub>	0.51	0.53	0.39	0.03	-0.31
Barite	BaSO <sub>4</sub>	0.59	0.53	0.60	0.59	0.65
Calcite	CaCO <sub>3</sub>	-0.84	-1.01	-0.75	-0.70	-0.89

Appendix A

SPLP Laboratory Data Package

**SVL ANALYTICAL, INC.**

One Government Gulch ■ P.O. Box 929 ■ Kellogg, Idaho 83837-0929 ■ Phone: (208)784-1258 ■ Fax: (208)783-0891

Certificate: WA DOE NO. C074; DOH NO. 050

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: CO PLANT #1  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327955

Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	10.2	mg CaCO3/L		2320	4/01/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/01/03
HCO3, CaCO3	10.2	mg CaCO3/L		2320	4/01/03
pH	7.35			150.1	4/01/03
TDS	2160	mg/L Ext		160.1	3/31/03
Calcium	597	mg/L Ext		6010B	4/01/03
Chloride	5.33	mg/L Ext	2	300.0	3/31/03
Fluoride	4.45	mg/L Ext	2	300.0	3/31/03
Potassium	<1.0	mg/L Ext		6010B	4/01/03
Magnesium	1.60	mg/L Ext		6010B	4/01/03
Sodium	0.93	mg/L Ext		6010B	4/01/03
Sulfate, SO4	1490	mg/L Ext	100	300.0	3/31/03
Silver	<0.0050	mg/L Ext		6010B	4/01/03
Arsenic	<0.010	mg/L Ext		6010B	4/01/03
Boron	0.149	mg/L Ext		6010B	4/01/03
Barium	0.0411	mg/L Ext		6010B	4/01/03
Cadmium	<0.0020	mg/L Ext		6010B	4/01/03
Chromium	<0.0060	mg/L Ext		6010B	4/01/03
Copper	0.0031	mg/L Ext		6010B	4/01/03
Iron	<0.020	mg/L Ext		6010B	4/01/03
Mercury	<0.00020	mg/L Ext		245.1	4/01/03
Manganese	0.0286	mg/L Ext		6010B	4/01/03
Nickel	<0.010	mg/L Ext		6010B	4/01/03
Lead	<0.0050	mg/L Ext		6010B	4/01/03
Selenium	<0.010	mg/L Ext		6010B	4/01/03
Zinc	0.0120	mg/L Ext		6010B	4/01/03
CalcTDS: 2107.4		TDS/Cond:	CATION SUM: 29.96meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.64meq/L		-2.73%

P.O. #7080

Reviewed By: Blake Johnson

Date 4/10/03  
 4/10/03 10:07

**SVL ANALYTICAL, INC.**

One Government Gulch ■ P.O. Box 929 ■ Kellogg, Idaho 83837-0929 ■ Phone: (208)784-1258 ■ Fax: (208)783-0891

Certificate: WA DOE NO. C074; DOH NO. 050

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: CO PLANT #2  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327956

Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	7.6	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	7.6	mg CaCO3/L		2320	4/04/03
pH	6.80			150.1	4/04/03
TDS	2090	mg/L Ext		160.1	3/31/03
Calcium	603	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext		300.0	4/09/03
Fluoride	3.98	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.237	mg/L Ext		6010B	4/07/03
Sodium	0.58	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1500	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	<0.010	mg/L Ext		6010B	4/07/03
Boron	0.065	mg/L Ext		6010B	4/07/03
Barium	0.0461	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0107	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0097	mg/L Ext		6010B	4/07/03
CalcTDS: 2114.4		TDS/Cond:	CATION SUM: 30.14meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.63meq/L		-2.41%

\*Elevated detection limit due to matrix interference.  
 P.O. #7080

Reviewed By: Blake Johnson Date 4/10/03  
 4/10/03 10:07

**SVL ANALYTICAL, INC.**

One Government Gulch

P.O. Box 929

Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
 Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: CO PLANT #3  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327957  
 Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	9.5	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	9.5	mg CaCO3/L		2320	4/04/03
pH	6.89			150.1	4/04/03
TDS	2130	mg/L Ext		160.1	3/31/03
Calcium	605	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext		300.0	4/09/03
Fluoride	3.86	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.228	mg/L Ext		6010B	4/07/03
Sodium	<0.50	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1510	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.013	mg/L Ext		6010B	4/07/03
Boron	<0.040	mg/L Ext		6010B	4/07/03
Barium	0.0473	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	0.0043	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0133	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0134	mg/L Ext		6010B	4/07/03
CalcTDS: 2128.8		TDS/Cond:	CATION SUM: 30.21meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.91meq/L		-2.74%

\*Elevated detection limit due to matrix interference.  
 P.O. #7080

Reviewed By: Blake Johnson

Date 4/10/03  
 4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch ■ P.O. Box 929 ■ Kellogg, Idaho 83837-0929 ■ Certificate: WA DOE NO. C074; DOH NO. 050  
 Phone: (208)784-1258 ■ Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB	SVL JOB: 105348
PROJECT: 7080	SAMPLE: 327958
CLIENT SAMPLE ID: CO PLANT #4	
Sample Collected:	
Sample Receipt : 3/26/03	Matrix: ESOIL
Date of Report : 4/10/03	Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	8.4	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	8.4	mg CaCO3/L		2320	4/04/03
pH	7.11			150.1	4/04/03
TDS	2140	mg/L Ext		160.1	3/31/03
Calcium	599	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext		300.0	4/09/03
Fluoride	3.06	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.184	mg/L Ext		6010B	4/07/03
Sodium	<0.50	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1460	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.011	mg/L Ext		6010B	4/07/03
Boron	0.061	mg/L Ext		6010B	4/07/03
Barium	0.0437	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0111	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0133	mg/L Ext		6010B	4/07/03
CalcTDS: 2067.4	TDS/Cond:	CATION SUM: 29.91meq/L		BALANCE	
TDS/CalcTDS: 1.0	CalcTDS/Cond:	ANION SUM: 30.73meq/L		-1.35%	

\*Elevated detection limit due to matrix interference.  
 P.O. #7080

Reviewed By: Blake Johnson Date 4/10/03  
 4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch ■ P.O. Box 929 ■ Kellogg, Idaho 83837-0929 ■ Phone: (208)784-1258 ■ Fax: (208)783-0891

Certificate: WA DOE NO. C074; DOH NO. 050

CLIENT : BATTELLE/PNN LAB	SVL JOB: 105348
PROJECT: 7080	SAMPLE: 327959
CLIENT SAMPLE ID: CO PLANT #5	
Sample Collected:	
Sample Receipt : 3/26/03	Matrix: ESOIL
Date of Report : 4/10/03	Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	8.3	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	8.3	mg CaCO3/L		2320	4/04/03
pH	7.04			150.1	4/04/03
TDS	2140	mg/L Ext		160.1	3/31/03
Calcium	586	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext		300.0	4/09/03
Fluoride	2.02	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.159	mg/L Ext		6010B	4/07/03
Sodium	0.55	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1490	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.013	mg/L Ext		6010B	4/07/03
Boron	0.073	mg/L Ext		6010B	4/07/03
Barium	0.0442	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0092	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0171	mg/L Ext		6010B	4/07/03
CalcTDS: 2080.8	TDS/Cond:	CATION SUM: 29.27meq/L		BALANCE	
TDS/CalcTDS: 1.0	CalcTDS/Cond:	ANION SUM: 31.24meq/L		-3.26%	

\*Elevated detection limit due to matrix interference.  
P.O. #7080

Reviewed By: Blebe Johnson Date 4/10/03  
4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch

P.O. Box 929

Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
PROJECT: 7080  
CLIENT SAMPLE ID: CO PLANT DUP #1  
Sample Collected:  
Sample Receipt : 3/26/03  
Date of Report : 4/10/03

SVL JOB: 105348  
SAMPLE: 327960

Matrix: ESOIL  
Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	9.9	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/01/03
HCO3, CaCO3	9.9	mg CaCO3/L		2320	4/01/03
pH	7.31			150.1	4/01/03
TDS	2180	mg/L Ext		160.1	3/31/03
Calcium	614	mg/L Ext		6010B	4/01/03
Chloride	4.98	mg/L Ext	2	300.0	3/31/03
Fluoride	4.02	mg/L Ext	2	300.0	3/31/03
Potassium	<1.0	mg/L Ext		6010B	4/01/03
Magnesium	1.73	mg/L Ext		6010B	4/01/03
Sodium	0.94	mg/L Ext		6010B	4/01/03
Sulfate, SO4	1500	mg/L Ext	100	300.0	3/31/03
Silver	<0.0050	mg/L Ext		6010B	4/01/03
Arsenic	<0.010	mg/L Ext		6010B	4/01/03
Boron	0.162	mg/L Ext		6010B	4/01/03
Barium	0.0429	mg/L Ext		6010B	4/01/03
Cadmium	<0.0020	mg/L Ext		6010B	4/01/03
Chromium	<0.0060	mg/L Ext		6010B	4/01/03
Copper	0.0035	mg/L Ext		6010B	4/01/03
Iron	0.051	mg/L Ext		6010B	4/01/03
Mercury	<0.00020	mg/L Ext		245.1	4/01/03
Manganese	0.0292	mg/L Ext		6010B	4/01/03
Nickel	<0.010	mg/L Ext		6010B	4/01/03
Lead	<0.0050	mg/L Ext		6010B	4/01/03
Selenium	<0.010	mg/L Ext		6010B	4/01/03
Zinc	0.0133	mg/L Ext		6010B	4/01/03
CalcTDS: 2127.6		TDS/Cond:	CATION SUM:	30.82meq/L	BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM:	31.70meq/L	-1.41%

P.O. #7080

Reviewed By: Bleche Johnson

Date 4/10/03  
4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch ■ P.O. Box 929 ■ Kellogg, Idaho 83837-0929 ■ Phone: (208)784-1258 ■ Fax: (208)783-0891

Certificate: WA DOE NO. C074; DOH NO. 050

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: CO PLANT DUP #2  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327961

Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	7.7	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	7.7	mg CaCO3/L		2320	4/04/03
pH	7.07			150.1	4/04/03
TDS	2190	mg/L Ext		160.1	3/31/03
Calcium	579	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	3.88	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.215	mg/L Ext		6010B	4/07/03
Sodium	0.70	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1500	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.015	mg/L Ext		6010B	4/07/03
Boron	0.059	mg/L Ext		6010B	4/07/03
Barium	0.0476	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0108	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0091	mg/L Ext		6010B	4/07/03
CalcTDS: 2087.4		TDS/Cond:	CATION SUM: 28.94meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.56meq/L		-4.33%

\*Elevated detection limit due to matrix interference.

P.O. #7080

Reviewed By: Blake Johnson

Date 4/10/03  
 4/10/03 10:08

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One Government Gulch

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Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
PROJECT: 7080  
CLIENT SAMPLE ID: CO PLANT DUP #3  
Sample Collected:  
Sample Receipt : 3/26/03  
Date of Report : 4/10/03

SVL JOB: 105348  
SAMPLE: 327962

Matrix: ESOIL  
Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	8.5	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	8.5	mg CaCO3/L		2320	4/04/03
pH	6.99			150.1	4/04/03
TDS	2190	mg/L Ext		160.1	3/31/03
Calcium	607	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	3.73	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.200	mg/L Ext		6010B	4/07/03
Sodium	0.59	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1510	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.013	mg/L Ext		6010B	4/07/03
Boron	0.069	mg/L Ext		6010B	4/07/03
Barium	0.0418	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0107	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0111	mg/L Ext		6010B	4/07/03
CalcTDS: 2121.6		TDS/Cond:	CATION SUM: 30.34meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.70meq/L		-2.19%

\*Elevated detection limit due to matrix interference.  
P.O. #7080

Reviewed By: Blake Johnson Date 4/10/03  
4/10/03 10:08

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Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
PROJECT: 7080  
CLIENT SAMPLE ID: CO PLANT DUP #4  
Sample Collected:  
Sample Receipt : 3/26/03  
Date of Report : 4/10/03

SVL JOB: 105348  
SAMPLE: 327963

Matrix: ESOIL  
Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	8.4	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	8.4	mg CaCO3/L		2320	4/04/03
pH	7.08			150.1	4/04/03
TDS	2150	mg/L Ext		160.1	3/31/03
Calcium	595	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	3.03	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.197	mg/L Ext		6010B	4/07/03
Sodium	0.87	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1460	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.018	mg/L Ext		6010B	4/07/03
Boron	0.081	mg/L Ext		6010B	4/07/03
Barium	0.0417	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0105	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0148	mg/L Ext		6010B	4/07/03
CalcTDS: 2065.1		TDS/Cond:	CATION SUM: 29.75meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 30.75meq/L		-1.65%

\*Elevated detection limit due to matrix interference.  
P.O. #7080

Reviewed By: Bleche Johnson

Date 4/10/03  
4/10/03 10:08

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One Government Gulch

P.O. Box 929

Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
 Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: CO PLANT DUP #5  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327964

Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	8.4	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	8.4	mg CaCO3/L		2320	4/04/03
pH	7.29			150.1	4/04/03
TDS	2200	mg/L Ext		160.1	3/31/03
Calcium	601	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	1.88	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.175	mg/L Ext		6010B	4/07/03
Sodium	0.51	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1480	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.015	mg/L Ext		6010B	4/07/03
Boron	0.078	mg/L Ext		6010B	4/07/03
Barium	0.0459	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0094	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0206	mg/L Ext		6010B	4/07/03
CalcTDS: 2090.6		TDS/Cond:	CATION SUM: 30.02meq/L		BALANCE
TDS/CalcTDS: 1.1		CalcTDS/Cond:	ANION SUM: 31.13meq/L		-1.82%

\*Elevated detection limit due to matrix interference.  
 P.O. #7080

Reviewed By: Beth Johnson Date 4/10/03  
 4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch

P.O. Box 929

Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
 Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB	SVL JOB: 105348
PROJECT: 7080	SAMPLE: 327965
CLIENT SAMPLE ID: HC PLANT #1	
Sample Collected:	
Sample Receipt : 3/26/03	Matrix: ESOIL
Date of Report : 4/10/03	Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	9.5	mg CaCO3/L		2320	4/01/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/01/03
HCO3, CaCO3	9.5	mg CaCO3/L		2320	4/01/03
pH	7.14			150.1	4/01/03
TDS	2200	mg/L Ext		160.1	3/31/03
Calcium	612	mg/L Ext		6010B	4/01/03
Chloride	3.67	mg/L Ext	2	300.0	3/31/03
Fluoride	3.05	mg/L Ext	2	300.0	3/31/03
Potassium	<1.0	mg/L Ext		6010B	4/01/03
Magnesium	1.23	mg/L Ext		6010B	4/01/03
Sodium	2.83	mg/L Ext		6010B	4/01/03
Sulfate, SO4	1510	mg/L Ext	100	300.0	3/31/03
Silver	<0.0050	mg/L Ext		6010B	4/01/03
Arsenic	<0.010	mg/L Ext		6010B	4/01/03
Boron	0.130	mg/L Ext		6010B	4/01/03
Barium	0.0507	mg/L Ext		6010B	4/01/03
Cadmium	<0.0020	mg/L Ext		6010B	4/01/03
Chromium	<0.0060	mg/L Ext		6010B	4/01/03
Copper	<0.0030	mg/L Ext		6010B	4/01/03
Iron	0.026	mg/L Ext		6010B	4/01/03
Mercury	<0.00020	mg/L Ext		245.1	4/01/03
Manganese	0.0187	mg/L Ext		6010B	4/01/03
Nickel	<0.010	mg/L Ext		6010B	4/01/03
Lead	<0.0050	mg/L Ext		6010B	4/01/03
Selenium	<0.010	mg/L Ext		6010B	4/01/03
Zinc	0.0157	mg/L Ext		6010B	4/01/03
CalcTDS: 2135.5		TDS/Cond:	CATION SUM: 30.76meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.83meq/L		-1.71%

P.O. #7080

Reviewed By: Blahe Johnson Date 4/10/03  
 4/10/03 10:08

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Certificate: WA DOE NO. C074; DOH NO. 050

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: HC PLANT #2  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327966

Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	7.2	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	7.2	mg CaCO3/L		2320	4/04/03
pH	7.10			150.1	4/04/03
TDS	2150	mg/L Ext		160.1	3/31/03
Calcium	580	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	3.18	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.155	mg/L Ext		6010B	4/07/03
Sodium	1.08	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1470	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.012	mg/L Ext		6010B	4/07/03
Boron	0.163	mg/L Ext		6010B	4/07/03
Barium	0.0443	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0125	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	<0.0050	mg/L Ext		6010B	4/07/03
CalcTDS: 2062.8		TDS/Cond:	CATION SUM: 29.00meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 31.00meq/L		-3.33%

\*Elevated detection limit due to matrix interference.

P.O. #7080

Reviewed By: Blake Johnson Date 4/10/03  
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Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
PROJECT: 7080  
CLIENT SAMPLE ID: HC PLANT #3  
Sample Collected:  
Sample Receipt : 3/26/03  
Date of Report : 4/10/03

SVL JOB: 105348  
SAMPLE: 327967

Matrix: ESOIL  
Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	7.8	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	7.8	mg CaCO3/L		2320	4/04/03
pH	7.30			150.1	4/04/03
TDS	2200	mg/L Ext		160.1	3/31/03
Calcium	622	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	2.61	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.138	mg/L Ext		6010B	4/07/03
Sodium	0.76	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1470	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.018	mg/L Ext		6010B	4/07/03
Boron	0.147	mg/L Ext		6010B	4/07/03
Barium	0.0536	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0127	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0098	mg/L Ext		6010B	4/07/03
CalcTDS: 2102.2		TDS/Cond:	CATION SUM: 31.08meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 30.95meq/L		0.21%

\*Elevated detection limit due to matrix interference.  
P.O. #7080

Reviewed By: Blebe Johnson Date 4/10/03  
4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch

P.O. Box 929

Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
 Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB  
 PROJECT: 7080  
 CLIENT SAMPLE ID: HC PLANT #4  
 Sample Collected:  
 Sample Receipt : 3/26/03  
 Date of Report : 4/10/03

SVL JOB: 105348  
 SAMPLE: 327968

Matrix: ESOIL  
 Extraction: SPLP

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	7.4	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	7.4	mg CaCO3/L		2320	4/04/03
pH	6.97			150.1	4/04/03
TDS	2110	mg/L Ext		160.1	3/31/03
Calcium	589	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	1.77	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.127	mg/L Ext		6010B	4/07/03
Sodium	0.70	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1450	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.017	mg/L Ext		6010B	4/07/03
Boron	0.136	mg/L Ext		6010B	4/07/03
Barium	0.0513	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0121	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0138	mg/L Ext		6010B	4/07/03
CalcTDS: 2042.0		TDS/Cond:	CATION SUM: 29.43meq/L		BALANCE
TDS/CalcTDS: 1.0		CalcTDS/Cond:	ANION SUM: 30.35meq/L		-1.54%

\*Elevated detection limit due to matrix interference.  
 P.O. #7080

Reviewed By: Blake Johnson Date 4/10/03  
 4/10/03 10:08

**SVL ANALYTICAL, INC.**

One Government Gulch

P.O. Box 929

Kellogg, Idaho

83837-0929

Certificate: WA DOE NO. C074; DOH NO. 050  
Phone: (208)784-1258 Fax: (208)783-0891

CLIENT : BATTELLE/PNN LAB PROJECT: 7080 CLIENT SAMPLE ID: HC PLANT #5 Sample Collected: Sample Receipt : 3/26/03 Date of Report : 4/10/03	SVL JOB: 105348 SAMPLE: 327969  Matrix: ESOIL Extraction: SPLP
--	--

Determination	Result	Units	Dilution	Method	Analyzed
Alkalinity, CaCO3	8.0	mg CaCO3/L		2320	4/04/03
CO3, CaCO3	<1.0	mg CaCO3/L		2320	4/04/03
HCO3, CaCO3	8.0	mg CaCO3/L		2320	4/04/03
pH	7.18			150.1	4/04/03
TDS	2100	mg/L Ext		160.1	3/31/03
Calcium	591	mg/L Ext		6010B	4/07/03
Chloride	<0.4*	mg/L Ext	2	300.0	4/09/03
Fluoride	1.21	mg/L Ext	2	300.0	4/09/03
Potassium	<1.0	mg/L Ext		6010B	4/07/03
Magnesium	0.131	mg/L Ext		6010B	4/07/03
Sodium	0.73	mg/L Ext		6010B	4/07/03
Sulfate, SO4	1500	mg/L Ext	100	300.0	4/09/03
Silver	<0.0050	mg/L Ext		6010B	4/07/03
Arsenic	0.011	mg/L Ext		6010B	4/07/03
Boron	0.152	mg/L Ext		6010B	4/07/03
Barium	0.0589	mg/L Ext		6010B	4/07/03
Cadmium	<0.0020	mg/L Ext		6010B	4/07/03
Chromium	<0.0060	mg/L Ext		6010B	4/07/03
Copper	<0.0030	mg/L Ext		6010B	4/07/03
Iron	<0.020	mg/L Ext		6010B	4/07/03
Mercury	<0.00020	mg/L Ext		245.1	4/04/03
Manganese	0.0109	mg/L Ext		6010B	4/07/03
Nickel	<0.010	mg/L Ext		6010B	4/07/03
Lead	<0.0050	mg/L Ext		6010B	4/07/03
Selenium	<0.010	mg/L Ext		6010B	4/07/03
Zinc	0.0164	mg/L Ext		6010B	4/07/03
CalcTDS: 2094.8	TDS/Cond:		CATION SUM:	29.53meq/L	BALANCE
TDS/CalcTDS: 1.0	CalcTDS/Cond:		ANION SUM:	31.39meq/L	-3.05%

\*Elevated detection limit due to matrix interference.  
P.O. #7080

Reviewed By: Blanche Johnson Date 4/10/03  
4/10/03 10:08

Client :BATTELLE/PNN LAB PO 7080					SVL JOB No: 105348			Analysis
Analyte	Method	Matrix	Units	Prep Blank	True—LCS—Found	LCS %R	Date	
Silver	6010B	ESOIL	mg/L Ext	<0.0050	1.00 1.10	110.0	4/07/03	
Arsenic	6010B	ESOIL	mg/L Ext	<0.010	1.00 1.13	113.0	4/07/03	
Boron	6010B	ESOIL	mg/L Ext	<0.040	1.00 1.03	103.0	4/07/03	
Barium	6010B	ESOIL	mg/L Ext	<0.0020	1.00 1.07	107.0	4/07/03	
Calcium	6010B	ESOIL	mg/L Ext	<0.040	20.0 19.2	96.0	4/07/03	
Cadmium	6010B	ESOIL	mg/L Ext	<0.0020	1.00 1.07	107.0	4/07/03	
Chromium	6010B	ESOIL	mg/L Ext	<0.0060	1.00 1.08	108.0	4/07/03	
Copper	6010B	ESOIL	mg/L Ext	<0.0030	1.00 1.07	107.0	4/07/03	
Iron	6010B	ESOIL	mg/L Ext	<0.020	10.0 10.3	103.0	4/07/03	
Potassium	6010B	ESOIL	mg/L Ext	<1.0	30.0 29.9	99.7	4/07/03	
Magnesium	6010B	ESOIL	mg/L Ext	<0.040	20.0 21.0	105.0	4/07/03	
Manganese	6010B	ESOIL	mg/L Ext	<0.0020	1.00 1.03	103.0	4/07/03	
Sodium	6010B	ESOIL	mg/L Ext	<0.50	20.0 19.3	96.5	4/07/03	
Nickel	6010B	ESOIL	mg/L Ext	<0.010	1.00 0.976	97.6	4/07/03	
Lead	6010B	ESOIL	mg/L Ext	<0.0050	1.00 1.06	106.0	4/07/03	
Selenium	6010B	ESOIL	mg/L Ext	<0.010	1.00 1.08	108.0	4/07/03	
Zinc	6010B	ESOIL	mg/L Ext	<0.0050	1.00 1.05	105.0	4/07/03	
Mercury	245.1	ESOIL	mg/L Ext	<0.0002	0.0050 0.0050	100.0	4/04/03	
Chloride	300.0	ESOIL	mg/L Ext	<0.20	5.00 5.10	102.0	3/31/03	
Fluoride	300.0	ESOIL	mg/L Ext	<0.10	2.50 2.58	103.2	3/31/03	
Sulfate, SO4	300.0	ESOIL	mg/L Ext	<0.30	10.0 10.2	102.0	3/31/03	
Alkalinity, CaCO3	2320	ESOIL	mg/L Ext	<1.0	71.0 74.3	104.6	4/01/03	
pH	150.1	ESOIL		5.46	6.80 6.78	99.7	4/01/03	
TDS	160.1	ESOIL	mg/L Ext	<10	315 284	90.2	3/31/03	

REND:

LCS = Laboratory Control Sample

LCS %R = LCS Percent Recovery

N/A = Not Applicable

Client :BATTELLE/PNN LAB PO 7080

Element	Method	Matrix	QC SAMPLE ID		Duplicate or MSD		Matrix Spike			Analysis Date
			Units	Result	Found	RPD%	Result	SPK ADD	%R	
Ag	6010B	ESOIL	1 mg/L Ex	<0.0050	<0.0050	UDL	1.09	1.00	109.0	4/01/03
Ag	6010B	ESOIL	2 mg/L Ex	<0.0050	<0.0050	UDL	1.16	1.00	116.0	4/07/03
Ag	6010B	ESOIL	3 mg/L Ex	<0.0050	N/A	N/A	1.14	1.00	114.0	4/07/03
As	6010B	ESOIL	1 mg/L Ex	<0.010	<0.010	UDL	1.08	1.00	108.0	4/01/03
As	6010B	ESOIL	2 mg/L Ex	<0.010	0.022	200.0	1.18	1.00	118.0	4/07/03
As	6010B	ESOIL	3 mg/L Ex	0.012	N/A	N/A	1.17	1.00	115.8	4/07/03
B	6010B	ESOIL	1 mg/L Ex	0.149	0.149	0.0	1.18	1.00	103.1	4/01/03
B	6010B	ESOIL	2 mg/L Ex	0.065	0.062	4.7	1.18	1.00	111.5	4/07/03
B	6010B	ESOIL	3 mg/L Ex	0.163	N/A	N/A	1.14	1.00	97.7	4/07/03
Ba	6010B	ESOIL	1 mg/L Ex	0.0411	0.0410	0.2	1.04	1.00	99.9	4/01/03
Ba	6010B	ESOIL	2 mg/L Ex	0.0461	0.0528	13.5	1.13	1.00	108.4	4/07/03
Ba	6010B	ESOIL	3 mg/L Ex	0.0443	N/A	N/A	1.08	1.00	103.6	4/07/03
Ca	6010B	ESOIL	1 mg/L Ex	597	609	2.0	628	20.0	R >4S	4/01/03
Ca	6010B	ESOIL	2 mg/L Ex	603	606	0.5	663	20.0	R >4S	4/07/03
Ca	6010B	ESOIL	3 mg/L Ex	580	N/A	N/A	588	20.0	R >4S	4/07/03
Cd	6010B	ESOIL	1 mg/L Ex	<0.0020	<0.0020	UDL	0.971	1.00	97.1	4/01/03
Cd	6010B	ESOIL	2 mg/L Ex	<0.0020	<0.0020	UDL	1.05	1.00	105.0	4/07/03
Cd	6010B	ESOIL	3 mg/L Ex	<0.0020	N/A	N/A	1.01	1.00	101.0	4/07/03
Cr	6010B	ESOIL	1 mg/L Ex	<0.0060	<0.0060	UDL	1.01	1.00	101.0	4/01/03
Cr	6010B	ESOIL	2 mg/L Ex	<0.0060	<0.0060	UDL	1.09	1.00	109.0	4/07/03
Cr	6010B	ESOIL	3 mg/L Ex	<0.0060	N/A	N/A	1.05	1.00	105.0	4/07/03
Cu	6010B	ESOIL	1 mg/L Ex	0.0031	0.0030	3.3	1.11	1.00	110.7	4/01/03
Cu	6010B	ESOIL	2 mg/L Ex	<0.0030	<0.0030	UDL	1.10	1.00	110.0	4/07/03
Cu	6010B	ESOIL	3 mg/L Ex	<0.0030	N/A	N/A	1.15	1.00	115.0	4/07/03
Fe	6010B	ESOIL	1 mg/L Ex	<0.020	<0.020	UDL	9.83	10.0	98.3	4/01/03
Fe	6010B	ESOIL	2 mg/L Ex	<0.020	<0.020	UDL	10.9	10.0	109.0	4/07/03
Fe	6010B	ESOIL	3 mg/L Ex	<0.020	N/A	N/A	9.59	10.0	95.9	4/07/03
K	6010B	ESOIL	1 mg/L Ex	<1.0	<1.0	UDL	31.8	30.0	106.0	4/01/03
K	6010B	ESOIL	2 mg/L Ex	<1.0	<1.0	UDL	32.5	30.0	108.3	4/07/03
K	6010B	ESOIL	3 mg/L Ex	<1.0	N/A	N/A	29.7	30.0	99.0	4/07/03
Mg	6010B	ESOIL	1 mg/L Ex	1.60	1.62	1.2	21.9	20.0	101.5	4/01/03
Mg	6010B	ESOIL	2 mg/L Ex	0.237	0.248	4.5	22.4	20.0	110.8	4/07/03
Mg	6010B	ESOIL	3 mg/L Ex	0.155	N/A	N/A	19.6	20.0	97.2	4/07/03
Mn	6010B	ESOIL	1 mg/L Ex	0.0286	0.0289	1.0	1.02	1.00	99.1	4/01/03
Mn	6010B	ESOIL	2 mg/L Ex	0.0107	0.0110	2.8	1.11	1.00	109.9	4/07/03
Mn	6010B	ESOIL	3 mg/L Ex	0.0125	N/A	N/A	0.975	1.00	96.3	4/07/03
Na	6010B	ESOIL	1 mg/L Ex	0.93	0.94	1.1	21.7	20.0	103.9	4/01/03
Na	6010B	ESOIL	2 mg/L Ex	0.58	0.58	0.0	21.3	20.0	103.6	4/07/03
Na	6010B	ESOIL	3 mg/L Ex	1.08	N/A	N/A	20.0	20.0	94.6	4/07/03
Ni	6010B	ESOIL	1 mg/L Ex	<0.010	<0.010	UDL	0.989	1.00	98.9	4/01/03
Ni	6010B	ESOIL	2 mg/L Ex	<0.010	<0.010	UDL	1.03	1.00	103.0	4/07/03
Ni	6010B	ESOIL	3 mg/L Ex	<0.010	N/A	N/A	0.998	1.00	99.8	4/07/03
Pb	6010B	ESOIL	1 mg/L Ex	<0.0050	<0.0050	UDL	1.02	1.00	102.0	4/01/03
Pb	6010B	ESOIL	2 mg/L Ex	<0.0050	<0.0050	UDL	0.996	1.00	99.6	4/07/03

LEGEND:

RPD% =  $(|SAM - DUP| / ((SAM + DUP) / 2)) * 100$  UDL = Both SAM & DUP not detected. \*Result or \*Found: Interference required dilution.

RPD% =  $(|SPK - MSD| / ((SPK + MSD) / 2)) * 100$  M in Duplicate/MSD column indicates MSD.

SPIKE ADD column, A = Post Digest Spike; %R = Percent Recovery N/A = Not Analyzed; R > 4S = Result more than 4X the Spike Added

QC Sample 1: SVL SAM No.: 327955 Client Sample ID: CO PLANT #1

QC Sample 2: SVL SAM No.: 327956 Client Sample ID: CO PLANT #2

QC Sample 3: SVL SAM No.: 327966 Client Sample ID: HC PLANT #2

Client :BATTELLE/PNN LAB PO 7080

Element	Method	Matrix	QC SAMPLE ID		Duplicate or MSD		Matrix Spike		Analysis Date	
			Units	Result	Found	RPD%	Result	SPK ADD		%R
Pb	6010B	ESOIL	3 mg/L Ex	<0.0050	N/A	N/A	0.996	1.00	99.6	4/07/03
Se	6010B	ESOIL	1 mg/L Ex	<0.010	<0.010	UDL	1.12	1.00	112.0	4/01/03
Se	6010B	ESOIL	2 mg/L Ex	<0.010	<0.010	UDL	1.12	1.00	112.0	4/07/03
Se	6010B	ESOIL	3 mg/L Ex	<0.010	N/A	N/A	1.09	1.00	109.0	4/07/03
Zn	6010B	ESOIL	1 mg/L Ex	0.0120	0.0125	4.1	0.962	1.00	95.0	4/01/03
Zn	6010B	ESOIL	2 mg/L Ex	0.0097	0.0119	20.4	1.05	1.00	104.0	4/07/03
Zn	6010B	ESOIL	3 mg/L Ex	<0.0050	N/A	N/A	1.00	1.00	100.0	4/07/03
Hg	245.1	ESOIL	1 mg/L Ex	<0.0002	<0.0002	UDL	0.0009	0.0010	90.0	4/01/03
Hg	245.1	ESOIL	3 mg/L Ex	<0.0002	N/A	N/A	0.0009	0.0010	90.0	4/04/03
Cl	300.0	ESOIL	1 mg/L Ex	5.33	4.86	9.2	8.89	4.00	89.0	3/31/03
F	300.0	ESOIL	1 mg/L Ex	4.45	4.06	9.2	7.87	4.00	85.5	3/31/03
SO4	300.0	ESOIL	1 mg/L Ex	1490	1510	1.3	2030	500	108.0	3/31/03
ALK	2320	ESOIL	1 mg/L Ex	10.2	10.0	2.0	N/A	N/A	N/A	4/01/03
CO3	2320	ESOIL	1 mg/L Ex	<1.0	<1.0	UDL	N/A	N/A	N/A	4/01/03
HCO3	2320	ESOIL	1 mg/L Ex	10.2	10.0	2.0	N/A	N/A	N/A	4/01/03
pH	150.1	ESOIL	1	7.35	7.35	0.0	N/A	N/A	N/A	4/01/03
TDS	160.1	ESOIL	1 mg/L Ex	2160	2170	0.5	N/A	N/A	N/A	3/31/03

LEGEND:

RPD% =  $(|SAM - DUP| / ((SAM + DUP) / 2)) * 100$  UDL = Both SAM & DUP not detected. \*Result or \*Found: Interference required dilution.

RPD% =  $(|SPK - MSD| / ((SPK + MSD) / 2)) * 100$  M in Duplicate/MSD column indicates MSD.

SPIKE ADD column, A = Post Digest Spike; %R = Percent Recovery N/A = Not Analyzed; R > 4S = Result more than 4X the Spike Added

QC Sample 1: SVL SAM No.: 327955 Client Sample ID: CO PLANT #1  
 QC Sample 2: SVL SAM No.: 327956 Client Sample ID: CO PLANT #2  
 QC Sample 3: SVL SAM No.: 327966 Client Sample ID: HC PLANT #2

SPLP Extraction Log

JOB#: 105348  
SVL ANALYTICAL, INC.

Case #: SAS #: SDG #:

SVL#	M	ClientID	Fluid Type	mls Fluid	Sample Wt.	Tumble Ext. Time	Final pH
		pH 4 Buffer					4.01
		pH 7 Buffer					6.98
127955	ES	CO PLANT #1					
127956	ES	CO PLANT #2	EASTERN FLUID	2000 MIS	100g	18 HR	6.71
127957	ES	CO PLANT #3		2000 MIS	100g	18 HR	6.72
127958	ES	CO PLANT #4	↓	2000 MIS	100g	18 HR	6.83
127959	ES	CO PLANT #5		2000 MIS	100g	18 HR	6.80
127960	ES	CO PLANT DUP #1					
127961	ES	CO PLANT DUP #2	EASTERN FLUID	2000 MIS	100g	18 HR	6.71
127962	ES	CO PLANT DUP #3		2000 MIS	100g	18 HR	6.85
127963	ES	CO PLANT DUP #4	↓	2000 MIS	100g	18 HR	6.84
127964	ES	CO PLANT DUP #5		2000 MIS	100g	18 HR	6.88
127965	ES	HC PLANT #1					
127966	ES	HC PLANT #2	EASTERN FLUID	2000 MIS	100g	18 HR	6.78
127967	ES	HC PLANT #3		2000 MIS	100g	18 HR	6.82
127968	ES	HC PLANT #4	↓	2000 MIS	100g	18 HR	6.77
327969	ES	HC PLANT #5		2000 MIS	100g	18 HR	6.75
327970	ES	EXTRACTION FLUID	↓				4.20

Extraction Started By: Ja Date/Time: 03/31/03 1200

Extraction Completed By: Ja Date/Time: 04/04/03 0600

Client: BATTELLE/PNN LAB  
Received: 3/26/03

Attachment 3

**Attachment 3**  
**HELP Model**  
**Input Data and Results**

**Project : MSS FGD Landfill - Operations- Half Ht**

*Marshall FGD Landfill*

**Model : HELP**

*An US EPA model for predicting landfill hydrologic processes and testing of effectiveness of landfill designs*

**Location : Marshall Scrubber Landfill**

**3/12/2004**

# 1. Profile. FGD Landfill - Half Height - Uncovered

## Model Settings

[HELP] Case Settings

Parameter	Value	Units
Runoff Method	User modified	(-)
Initial Moisture Settings	Model calculated	(-)

[HELP] Surface Water Settings

Parameter	Value	Units
Runoff Curve Number	93	(-)
Runoff Area	100	(%%)

## Profile Structure

Layer	Top ( ft )	Bottom ( ft )	Thickness ( ft )
FGD Residue 1	0.0000	-13.8000	13.8000
FGD Residue 2	-13.8000	-27.6000	13.8000
FGD Residue 3	-27.6000	-40.0000	12.4000
MSS Site Soil - Soil Beneath Waste	-40.0000	-44.0000	4.0000

### 1.1. Layer. FGD Residue 1

Top Slope Length: 0.0000  
 Bottom Slope Length: 0.0000  
 Top Slope: 0.0000  
 Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.2. Layer. FGD Residue 2

Top Slope Length: 0.0000  
 Bottom Slope Length: 0.0000  
 Top Slope: 0.0000  
 Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.3. Layer. FGD Residue 3

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.4. Layer. MSS Site Soil - Soil Beneath Waste

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	.43	(vol/vol)
field capacity	.252	(vol/vol)
wilting point	.115	(vol/vol)
sat.hydr.conductivity	2.2E-04	(cm/sec)
subsurface inflow	0	(mm/year)

```

*****
*****
**                                     **
**                                     **
**      HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE      **
**      HELP MODEL VERSION 3.07 (1 November 1997)          **
**      DEVELOPED BY ENVIRONMENTAL LABORATORY              **
**      USAE WATERWAYS EXPERIMENT STATION                 **
**      FOR USEPA RISK REDUCTION ENGINEERING LABORATORY    **
**      **                                                 **
**      **                                                 **
*****
*****

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PRECIPITATION DATA FILE: C:\WHI\UNSAT22\data\P7114.VHP\weather1.dat
TEMPERATURE DATA FILE:  C:\WHI\UNSAT22\data\P7114.VHP\weather2.dat
SOLAR RADIATION DATA FILE: C:\WHI\UNSAT22\data\P7114.VHP\weather3.dat
EVAPOTRANSPIRATION DATA: C:\WHI\UNSAT22\data\P7114.VHP\weather4.dat
SOIL AND DESIGN DATA FILE: C:\WHI\UNSAT22\data\P7114.VHP\392838.inp
OUTPUT DATA FILE:       C:\WHI\UNSAT22\data\P7114.VHP\O_392838.prt

```

TIME: 7:47 DATE: 3/12/2004

```

*****
TITLE: FGD Landfill - Half Height - Uncovered
*****

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NOTE: INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE  
COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.

LAYER 1

```

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TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 45
THICKNESS      = 420.62 CM
POROSITY       = 0.4100 VOL/VOL
FIELD CAPACITY = 0.1800 VOL/VOL
WILTING POINT  = 0.0550 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.1951 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

```

LAYER 2  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1893 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 3  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 377.95 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1881 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 4  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 49  
THICKNESS = 121.92 CM  
POROSITY = 0.4300 VOL/VOL  
FIELD CAPACITY = 0.2520 VOL/VOL  
WILTING POINT = 0.1150 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.2541 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.220000000000E-03 CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA  
-----

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM A USER-SPECIFIED CURVE NUMBER OF 93.0, A SURFACE SLOPE OF 0.0% AND A SLOPE LENGTH OF 0. METERS.

SCS RUNOFF CURVE NUMBER = 93.00  
FRACTION OF AREA ALLOWING RUNOFF = 100.0 PERCENT  
AREA PROJECTED ON HORIZONTAL PLANE = 0.4047 HECTARES  
EVAPORATIVE ZONE DEPTH = 25.4 CM  
INITIAL WATER IN EVAPORATIVE ZONE = 3.390 CM  
UPPER LIMIT OF EVAPORATIVE STORAGE = 10.414 CM  
LOWER LIMIT OF EVAPORATIVE STORAGE = 1.397 CM  
INITIAL SNOW WATER = 0.000 CM  
INITIAL WATER IN LAYER MATERIALS = 263.766 CM  
TOTAL INITIAL WATER = 263.766 CM  
TOTAL SUBSURFACE INFLOW = 0.00 MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM  
Marshall Scrubber LandfillNC

STATION LATITUDE = 35.60 DEGREES  
 MAXIMUM LEAF AREA INDEX = 0.00  
 START OF GROWING SEASON (JULIAN DATE) = 83  
 END OF GROWING SEASON (JULIAN DATE) = 312  
 EVAPORATIVE ZONE DEPTH = 10.0 INCHES  
 AVERAGE ANNUAL WIND SPEED = 7.50 MPH  
 AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 64.00 %  
 AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 67.00 %  
 AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 74.00 %  
 AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 70.00 %

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber LandfillNC

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
4.10	4.10	4.70	3.80	3.60	3.90
5.00	5.60	3.80	3.40	3.10	4.10

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber LandfillNC

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
41.00	42.00	49.00	59.00	67.00	75.00
77.00	76.00	70.50	60.50	49.00	41.50

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber LandfillNC  
AND STATION LATITUDE = 35.60 DEGREES

\*\*\*\*\*  
AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1 THROUGH 100

	INCHES	CU. FEET	PERCENT
PRECIPITATION	49.24 ( 7.134)	178732.6	100.00
RUNOFF	10.116 ( 2.9615)	36721.32	20.545
EVAPOTRANSPIRATION	29.738 ( 3.3331)	107947.72	60.396
PERCOLATION/LEAKAGE THROUGH LAYER 4	9.34172 (2.25125)	33909.716	18.97232
CHANGE IN WATER STORAGE	0.042 ( 3.2192)	153.83	0.086

\*\*\*\*\*

\*\*\*\*\*

PEAK DAILY VALUES FOR YEARS 1 THROUGH 100 and their dates (DDDDYY)

	(INCHES)	(CU. FT.)		
PRECIPITATION	5.58	20254.95852	2590053	
RUNOFF	3.922	14236.10301	2590053	
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.091918	333.65458	3450018	
SNOW WATER	3.87	14051.2239	320045	
MAXIMUM VEG. SOIL WATER (VOL/VOL)		0.3132		
MINIMUM VEG. SOIL WATER (VOL/VOL)		0.0550		

\*\*\*\*\*

\*\*\*\*\*

FINAL WATER STORAGE AT END OF YEAR 100

LAYER	(INCHES)	(VOL/VOL)
1	31.4577	0.1900
2	32.6707	0.1973
3	30.7138	0.2064
4	13.2404	0.2758
SNOW WATER	0.000	

\*\*\*\*\*  
\*\*\*\*\*

# **Project : MSS FGD Landfill - Operations- Full Ht**

*Marshall FGD Landfill*

## **Model : HELP**

*An US EPA model for predicting landfill hydrologic processes and testing of effectiveness of landfill designs*

**Location : Marshall Scrubber Landfill**

**3/12/2004**

# 1. Profile. FGD Landfill - Max Height - Uncovered

## Model Settings

[HELP] Case Settings

Parameter	Value	Units
Runoff Method	User modified	(-)
Initial Moisture Settings	Model calculated	(-)

[HELP] Surface Water Settings

Parameter	Value	Units
Runoff Curve Number	93	(-)
Runoff Area	100	(%%)

## Profile Structure

Layer	Top (ft)	Bottom (ft)	Thickness (ft)
FGD Residue 1	0.0000	-13.8000	13.8000
FGD Residue 2	-13.8000	-27.6000	13.8000
FGD Residue 3	-27.6000	-41.4000	13.8000
FGD Residue 4	-41.4000	-55.2000	13.8000
FGD Residue 5	-55.2000	-69.0000	13.8000
FGD Residue 61	-69.0000	-80.5000	11.5000
MSS Site Soil - Soil Beneath Waste	-80.5000	-84.5000	4.0000

### 1.1. Layer. FGD Residue 1

Top Slope Length: 0.0000  
 Bottom Slope Length: 0.0000  
 Top Slope: 0.0000  
 Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.2. Layer. FGD Residue 2

Top Slope Length: 0.0000  
 Bottom Slope Length: 0.0000  
 Top Slope: 0.0000  
 Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.3. Layer. FGD Residue 3

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.4. Layer. FGD Residue 4

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.5. Layer. FGD Residue 5

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.6. Layer. FGD Residue 61

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

## 1.7. Layer. MSS Site Soil - Soil Beneath Waste

Top Slope Length: 0.0000  
Bottom Slope Length: 0.0000  
Top Slope: 0.0000  
Bottom Slope : 0.0000

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	.43	(vol/vol)
field capacity	.252	(vol/vol)
wilting point	.115	(vol/vol)
sat.hydr.conductivity	2.2E-04	(cm/sec)
subsurface inflow	0	(mm/year)

```

*****
*****
**                               **
**                               **
**      HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE      **
**      HELP MODEL VERSION 3.07 (1 November 1997)          **
**      DEVELOPED BY ENVIRONMENTAL LABORATORY                **
**      USAE WATERWAYS EXPERIMENT STATION                   **
**      FOR USEPA RISK REDUCTION ENGINEERING LABORATORY     **
**      **                                                    **
**      **                                                    **
*****
*****

```

```

PRECIPITATION DATA FILE: C:\WHI\UNSAT22\data\P7130.VHP\weather1.dat
TEMPERATURE DATA FILE:  C:\WHI\UNSAT22\data\P7130.VHP\weather2.dat
SOLAR RADIATION DATA FILE: C:\WHI\UNSAT22\data\P7130.VHP\weather3.dat
EVAPOTRANSPIRATION DATA: C:\WHI\UNSAT22\data\P7130.VHP\weather4.dat
SOIL AND DESIGN DATA FILE: C:\WHI\UNSAT22\data\P7130.VHP\392857.inp
OUTPUT DATA FILE:       C:\WHI\UNSAT22\data\P7130.VHP\O_392857 prt

```

TIME: 7:41 DATE: 3/12/2004

```

*****
TITLE: FGD Landfill - Max Height - Uncovered
*****

```

NOTE: INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.

LAYER 1

```

-----
TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 45
THICKNESS      = 420.62 CM
POROSITY       = 0.4100 VOL/VOL
FIELD CAPACITY = 0.1800 VOL/VOL
WILTING POINT  = 0.0550 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.1951 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

```

LAYER 2

```

-----
TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 45
THICKNESS      = 420.62 CM
POROSITY       = 0.4100 VOL/VOL
FIELD CAPACITY = 0.1800 VOL/VOL
WILTING POINT  = 0.0550 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.1894 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

```

LAYER 3  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1879 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 4  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1837 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 5  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1807 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 6  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 350.52 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1798 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 7  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER

MATERIAL TEXTURE NUMBER 49

THICKNESS = 121.92 CM  
POROSITY = 0.4300 VOL/VOL  
FIELD CAPACITY = 0.2520 VOL/VOL  
WILTING POINT = 0.1150 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.2517 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.220000000000E-03 CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA  
-----

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM A USER-SPECIFIED CURVE NUMBER OF 93.0, A SURFACE SLOPE OF 0.0% AND A SLOPE LENGTH OF 0. METERS.

SCS RUNOFF CURVE NUMBER = 93.00  
FRACTION OF AREA ALLOWING RUNOFF = 100.0 PERCENT  
AREA PROJECTED ON HORIZONTAL PLANE = 0.4047 HECTARES  
EVAPORATIVE ZONE DEPTH = 25.4 CM  
INITIAL WATER IN EVAPORATIVE ZONE = 3.390 CM  
UPPER LIMIT OF EVAPORATIVE STORAGE = 10.414 CM  
LOWER LIMIT OF EVAPORATIVE STORAGE = 1.397 CM  
INITIAL SNOW WATER = 0.000 CM  
INITIAL WATER IN LAYER MATERIALS = 487.739 CM  
TOTAL INITIAL WATER = 487.739 CM  
TOTAL SUBSURFACE INFLOW = 0.00 MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA  
-----

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM Marshall Scrubber Landfill NC

STATION LATITUDE = 35.60 DEGREES  
MAXIMUM LEAF AREA INDEX = 0.00  
START OF GROWING SEASON (JULIAN DATE) = 83  
END OF GROWING SEASON (JULIAN DATE) = 312  
EVAPORATIVE ZONE DEPTH = 10.0 INCHES  
AVERAGE ANNUAL WIND SPEED = 7.50 MPH  
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 64.00 %  
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 67.00 %  
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 74.00 %  
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 70.00 %

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber Landfill INC

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
4.10	4.10	4.70	3.80	3.60	3.90
5.00	5.60	3.80	3.40	3.10	4.10

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber Landfill INC

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
41.00	42.00	49.00	59.00	67.00	75.00
77.00	76.00	70.50	60.50	49.00	41.50

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber Landfill INC  
AND STATION LATITUDE = 35.60 DEGREES

\*\*\*\*\*

\*\*\*\*\*

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1 THROUGH 100

	<u>INCHES</u>	<u>CU. FEET</u>	<u>PERCENT</u>
PRECIPITATION	49.24 ( 7.134)	178732.6	100.00
RUNOFF	10.116 (2.9615)	36721.32	20.545
EVAPOTRANSPIRATION	29.738 ( 3.3331)	107947.72	60.396
PERCOLATION/LEAKAGE THROUGH LAYER 7	9.22915 (2.21676)	33501.070	18.74368
CHANGE IN WATER STORAGE	0.155 (3.4748)	562.48	0.315

\*\*\*\*\*

# **Project : Marshall Scrubber Landfill - Closed Condition**

*Marshall FGD Landfill*

**Model :**

*Visual HELP, Version 2.2.0.1 August 2000. This version of Visual HELP uses  
HELP Version 3.07.*

*An US EPA model for predicting landfill hydrologic processes and testing of effectiveness of landfill designs*

**3/23/2004**

# 1. Profile. FGD Landfill - Closed Condition

## Model Settings

[HELP] Case Settings

Parameter	Value	Units
Runoff Method	User modified	(-)
Initial Moisture Settings	Model calculated	(-)

[HELP] Surface Water Settings

Parameter	Value	Units
Runoff Area	100	(%%)
Runoff Curve Number	61	(-)

## Profile Structure

Layer	Top ( ft )	Bottom ( ft )	Thickness ( ft )
■ MSS Site Soil - Upper Vegetated Layer	0.0000	-0.7500	0.7500
■ MSS Site Soil - Lower Vegetated Layer	-0.7500	-2.0000	1.2500
▨ Drainage Net (0.5cm)	-2.0000	-2.0164	0.0164
□ Low Density Polyethylene	-2.0164	-2.0197	0.0033
■ MSS Site Soil - Cover Soil	-2.0197	-3.5197	1.5000
■ FGD Residue 1	-3.5197	-13.8197	10.3000
■ FGD Residue 2	-13.8197	-27.6197	13.8000
■ FGD Residue 3	-27.6197	-41.4197	13.8000
■ FGD Residue 4	-41.4197	-55.2197	13.8000
■ FGD Residue 5	-55.2197	-69.0197	13.8000
■ FGD Residue 6	-69.0197	-84.0000	14.9803
■ MSS Site Soil - Soil Beneath Waste	-84.0000	-88.0000	4.0000

### 1.1. Layer. MSS Site Soil - Upper Vegetated Layer

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	.44	(vol/vol)
field capacity	.242	(vol/vol)
wilting point	0.122	(vol/vol)
sat.hydr.conductivity	2.2E-05	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.2. Layer. MSS Site Soil - Lower Vegetated Layer

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	.44	(vol/vol)
field capacity	0.242	(vol/vol)
wilting point	0.122	(vol/vol)
sat.hydr.conductivity	7.4E-6	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.3. Layer. Drainage Net (0.5cm)

[HELP] Geotextiles and Geonets Parameters

Parameter	Value	Units
total porosity	0.85	(vol/vol)
field capacity	0.01	(vol/vol)
wilting point	0.005	(vol/vol)
sat.hydr.conductivity	1	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.4. Layer. Low Density Polyethylene

[HELP] Geomembrane Liner Parameters

Parameter	Value	Units
sat.hydr.conductivity	4E-13	(cm/sec)
pinhole density	1	(#/acre)
installation defects	4	(#/acre)
placement quality	3	(-)
geotextile transmissivity	0	(cm <sup>2</sup> /sec)

### 1.5. Layer. MSS Site Soil - Cover Soil

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	.44	(vol/vol)
field capacity	0.242	(vol/vol)
wilting point	0.122	(vol/vol)
sat.hydr.conductivity	7.4E-6	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.6. Layer. FGD Residue 1

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.7. Layer. FGD Residue 2

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.8. Layer. FGD Residue 3

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.9. Layer. FGD Residue 4

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.10. Layer. FGD Residue 5

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.11. Layer. FGD Residue 6

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	0.41	(vol/vol)
field capacity	0.180	(vol/vol)
wilting point	0.055	(vol/vol)
sat.hydr.conductivity	2.53E-04	(cm/sec)
subsurface inflow	0	(mm/year)

### 1.12. Layer. MSS Site Soil - Soil Beneath Waste

[HELP] Vertical Perc. Layer Parameters

Parameter	Value	Units
total porosity	.43	(vol/vol)
field capacity	.252	(vol/vol)
wilting point	.115	(vol/vol)
sat.hydr.conductivity	2.2E-04	(cm/sec)
subsurface inflow	0	(mm/year)

## Listing from Original HELP Model

```
*****
*****
**                               **
**                               **
**   HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE   **
**   HELP MODEL VERSION 3.07 (1 November 1997)       **
**   DEVELOPED BY ENVIRONMENTAL LABORATORY           **
**   USAE WATERWAYS EXPERIMENT STATION              **
**   FOR USEPA RISK REDUCTION ENGINEERING LABORATORY **
**                               **
**                               **
*****
*****
```

PRECIPITATION DATA FILE: C:\WHI\UNSAT22\data\P4964.VHP\weather1.dat  
TEMPERATURE DATA FILE: C:\WHI\UNSAT22\data\P4964.VHP\weather2.dat  
SOLAR RADIATION DATA FILE: C:\WHI\UNSAT22\data\P4964.VHP\weather3.dat  
EVAPOTRANSPIRATION DATA: C:\WHI\UNSAT22\data\P4964.VHP\weather4.dat  
SOIL AND DESIGN DATA FILE: C:\WHI\UNSAT22\data\P4964.VHP\390456.inp  
OUTPUT DATA FILE: C:\WHI\UNSAT22\data\P4964.VHP\O\_390456.prt

TIME: 11:30 DATE: 3/19/2004

```
*****
TITLE: FGD Landfill - Closed Condition
*****
```

NOTE: INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE  
COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.

### LAYER 1

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 46  
THICKNESS = 22.86 CM  
POROSITY = 0.4400 VOL/VOL  
FIELD CAPACITY = 0.2420 VOL/VOL  
WILTING POINT = 0.1220 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.2737 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.220000000000E-04 CM/SEC

### LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 46  
THICKNESS = 38.10 CM  
POROSITY = 0.4400 VOL/VOL  
FIELD CAPACITY = 0.2420 VOL/VOL  
WILTING POINT = 0.1220 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.3893 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.740000000000E-05 CM/SEC



LAYER 3

-----  
TYPE 2 - LATERAL DRAINAGE LAYER  
MATERIAL TEXTURE NUMBER 20  
THICKNESS = 0.50 CM  
POROSITY = 0.8500 VOL/VOL  
FIELD CAPACITY = 0.0100 VOL/VOL  
WILTING POINT = 0.0050 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.2009 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 1.00000000000 CM/SEC  
SLOPE = 12.50 PERCENT  
DRAINAGE LENGTH = 91.4 METERS

LAYER 4

-----  
TYPE 4 - FLEXIBLE MEMBRANE LINER  
MATERIAL TEXTURE NUMBER 36  
THICKNESS = 0.10 CM  
POROSITY = 0.0000 VOL/VOL  
FIELD CAPACITY = 0.0000 VOL/VOL  
WILTING POINT = 0.0000 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.0000 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.400000000000E-12 CM/SEC  
FML PINHOLE DENSITY = 2.47 HOLES/HECTARE  
FML INSTALLATION DEFECTS = 9.88 HOLES/HECTARE  
FML PLACEMENT QUALITY = 3 - GOOD

LAYER 5

-----  
TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 46  
THICKNESS = 45.72 CM  
POROSITY = 0.4400 VOL/VOL  
FIELD CAPACITY = 0.2420 VOL/VOL  
WILTING POINT = 0.1220 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.2419 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.740000000000E-05 CM/SEC

LAYER 6

-----  
TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 313.94 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1799 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 7  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1799 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 8  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1799 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 9  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1799 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 10  
-----

TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 420.62 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1799 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 11

-----  
TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 45  
THICKNESS = 456.60 CM  
POROSITY = 0.4100 VOL/VOL  
FIELD CAPACITY = 0.1800 VOL/VOL  
WILTING POINT = 0.0550 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.1799 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.253000000000E-03 CM/SEC

LAYER 12

-----  
TYPE 1 - VERTICAL PERCOLATION LAYER  
MATERIAL TEXTURE NUMBER 49  
THICKNESS = 121.92 CM  
POROSITY = 0.4300 VOL/VOL  
FIELD CAPACITY = 0.2520 VOL/VOL  
WILTING POINT = 0.1150 VOL/VOL  
INITIAL SOIL WATER CONTENT = 0.2520 VOL/VOL  
EFFECTIVE SAT. HYD. COND. = 0.220000000000E-03 CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

-----  
NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM A USER-SPECIFIED CURVE NUMBER OF 61.0, A SURFACE SLOPE OF 0.0% AND A SLOPE LENGTH OF 0. METERS.

SCS RUNOFF CURVE NUMBER = 61.00  
FRACTION OF AREA ALLOWING RUNOFF = 100.0 PERCENT  
AREA PROJECTED ON HORIZONTAL PLANE = 0.4047 HECTARES  
EVAPORATIVE ZONE DEPTH = 25.4 CM  
INITIAL WATER IN EVAPORATIVE ZONE = 7.120 CM  
UPPER LIMIT OF EVAPORATIVE STORAGE = 11.176 CM  
LOWER LIMIT OF EVAPORATIVE STORAGE = 3.099 CM  
INITIAL SNOW WATER = 0.000 CM  
INITIAL WATER IN LAYER MATERIALS = 504.228 CM  
TOTAL INITIAL WATER = 504.228 CM  
TOTAL SUBSURFACE INFLOW = 0.00 MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

-----  
NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM Marshall Scrubber Landfill INC

STATION LATITUDE = 35.60 DEGREES  
MAXIMUM LEAF AREA INDEX = 2.00  
START OF GROWING SEASON (JULIAN DATE) = 83  
END OF GROWING SEASON (JULIAN DATE) = 312  
EVAPORATIVE ZONE DEPTH = 10.0 INCHES  
AVERAGE ANNUAL WIND SPEED = 7.50 MPH  
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 64.00 %  
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 67.00 %  
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 74.00 %  
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 70.00 %

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber LandfillNC

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
4.10	4.10	4.70	3.80	3.60	3.90
5.00	5.60	3.80	3.40	3.10	4.10

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber LandfillNC

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
41.00	42.00	49.00	59.00	67.00	75.00
77.00	76.00	70.50	60.50	49.00	41.50

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING  
COEFFICIENTS FOR Marshall Scrubber LandfillNC  
AND STATION LATITUDE = 35.60 DEGREES

\*\*\*\*\*

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1 THROUGH 100

	INCHES	CU. FEET	PERCENT
PRECIPITATION	49.24 ( 7.134)	178732.6	100.00
RUNOFF	10.814 ( 3.5670)	39255.20	21.963
EVAPOTRANSPIRATION	28.623 ( 3.0944)	103900.89	58.132
LATERAL DRAINAGE COLLECTED FROM LAYER 3	9.80244 ( 2.81917)	35582.083	19.90800
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.00039 ( 0.00010)	1.423	0.00080
AVERAGE HEAD ON TOP OF LAYER 4	0.012 ( 0.003)		
PERCOLATION/LEAKAGE THROUGH LAYER 12	0.00000 ( 0.00000)	0.000	0.00000
CHANGE IN WATER STORAGE	-0.002 ( 1.0772)	-5.58	-0.003

\*\*\*\*\*

\*\*\*\*\*

	(INCHES)	(CU. FT.)	
PRECIPITATION	5.58	20254.95852	2590053
RUNOFF	4.673	16963.36455	2590053
DRAINAGE COLLECTED FROM LAYER 3	0.25170	913.66500	3300044
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.000009	0.03142	3300044
AVERAGE HEAD ON TOP OF LAYER 4	0.108		
MAXIMUM HEAD ON TOP OF LAYER 4	0.216		
LOCATION OF MAXIMUM HEAD IN LAYER 3 (DISTANCE FROM DRAIN)	0.0 FEET		
PERCOLATION/LEAKAGE THROUGH LAYER 12	0.000000	0.00000	0
SNOW WATER	3.87	14051.2239	320045
MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.4400		
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.1220		

\*\*\* Maximum heads are computed using McEnroe's equations. \*\*\*

Reference: Maximum Saturated Depth over Landfill Liner  
by Bruce M. McEnroe, University of Kansas  
ASCE Journal of Environmental Engineering  
Vol. 119, No. 2, March 1993, pp. 262-270.

\*\*\*\*\*

\*\*\*\*\*  
FINAL WATER STORAGE AT END OF YEAR 100

LAYER	(INCHES)	(VOL/VOL)
1	2.4568	0.2730
2	5.6662	0.3777
3	0.0270	0.1373
4	0.0000	0.0000
5	4.3550	0.2419
6	22.2384	0.1799
7	29.7952	0.1799
8	29.7952	0.1799
9	29.7952	0.1799
10	29.7952	0.1799
11	32.3435	0.1799
12	12.0937	0.2520
SNOW WATER		0.000

\*\*\*\*\*  
\*\*\*\*\*

Attachment 4

**Attachment 4**

**MYGRT Manual**

# **User's Guide for MYGRT Version 3.0: Software for Simulating Migration of Organic and Inorganic Chemicals In Groundwater**

**TR-111748**

Final Report, December 1998

EPRI Project Manager  
A. Quinn

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## REPORT SUMMARY

---

By using MYGRT™ software, utility managers can quickly estimate the possible effects of waste disposal sites or spills on local groundwater. With this new version of the code, managers can predict the down gradient distribution of organic and inorganic solutes in unsaturated, saturated, or partially saturated zones.

### Background

Originally, the MYGRT code version 1.0 was developed to simulate the migration of inorganics in groundwater. The code has been widely used by utility companies, state regulatory agencies, consultants, and educational institutions. Suggestions by users and the need to add modeling capabilities for organic solutes led to the development of the MYGRT code version 2.0. After using MYGRT v2.0 for many years, it became desirable to enhance the capabilities of MYGRT and convert the code to a Windows 95 and Windows NT compatible versions.

### Objective

- To create PC software for estimating groundwater concentrations of inorganic and organic solutes discharged from waste disposal sites, spills, and other sources

### Approach

The MYGRT code version 3.0 transforms the menu-driven preprocessor in MYGRT version 2.0 into a Windows-based preprocessor while enhancing the mathematical routines from version 2.0. In addition, version 3.0 features partially saturated zones, 3D mixing in the saturated zone, infiltration control by specific user provided conditions, variable leachate input which can generate, discrete, or constant curves, improved plotting, user-specified well screen lengths, and calculation of depth averages rather than single points. The Illinois State TACO analysis has also been embedded.

### Results

The MYGRT version 3.0 software predicts the migration of both inorganic and organic solutes in the unsaturated and saturated zones down gradient of sources. The processes included are advection, dispersion, retardation, and decay. The code can simulate problems in one, two, or three dimensions using either horizontal or vertical views. The model is flexible, allowing users to provide parameters such as seepage velocity, dispersion and retardation factors, or the underlying aquifer characteristics can be provided and these parameters will be calculated.

---

A series of plots can be generated including concentration vs. time, concentration vs. distance, area or cross-sectional contour plots, and concentration vs. depth profiles. Each plot includes a tabular listing of the predicted concentrations. A summary of input data, the plots described above, and the listing of predicted concentrations can be displayed on a color monitor, printed, or saved in a file for later retrieval.

The MYGRT code version 3.0 is PC compatible software that can run in the Microsoft Windows 95 or Microsoft Windows NT 4.0 environments. MYGRT version 3.0 is year 2000 compliant.

The manual includes instructions for installing and using the software, example applications, methods for estimating the input data, and the theoretical basis for the code.

### **EPRI Perspective**

The MYGRT code version 3.0 offers utilities a convenient and inexpensive way to perform a preliminary assessment of the potential groundwater impacts of a waste disposal facility or spill and to develop sensitivity analyses. Screening of this nature can help in determining the need for more-sophisticated models and selecting locations for well monitoring.

### **TR-111748**

#### **Interest Categories**

Waste & water management  
Soil & groundwater remediation  
Environmental compliance planning  
Land & water quality  
Environmental economics & risk management

#### **Keywords**

Solid wastes  
Groundwater  
Mathematical models  
Biogeochemical attenuation  
Transport  
MYGRT code version 3.0

## ABSTRACT

---

The MYGRT Code Version 3 is an interactive, menu-driven code for microcomputers. The code predicts the migration of both inorganic and organic solutes in the unsaturated and saturated zones down gradient of sources (i.e. waste disposal sites or spills). The processes included are advection, dispersion, retardation, and decay. The code can simulate problems in one, two, or three dimensions using either horizontal or vertical views. The results can be displayed on a color monitor, sent to a printer, or saved in a project file for later retrieval.

The system requirements for MYGRT 3 are an IBM compatible PC running Microsoft Windows 95 or Microsoft Windows NT 4.0, 16 MB of available physical RAM, 10 MB of disk space, 256 color video, and a Mouse. Recommended options are 16.7 M color video and a color printer.

This manual includes instructions for installing and using the code, example applications, methods for estimating the input data, and the theoretical basis for the code.

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---

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# 1

## GENERAL OVERVIEW

---

MYGRT Version 3 is intended to be used in simulating single species solute migration through several pathways, starting from surface sources and migrating downward through the unsaturated soil layer, mixing with the underlying groundwater, and then migrating horizontally downgradient through the aquifer. Each of these pathway models may be simulated individually or as an interconnected system of models. Upon defining source concentration as a function of time (piecewise constant), and soil and chemical parameters of the unsaturated/saturated layers, the model will predict the solute concentration as a function of time at any specified location along its pathway.

The MYGRT program is a collection of 22 analytical models. All of these models are based on analytical solutions to the 1D, 2D, and 3D mass transport equations using the integral transform technique. The special cases of spatial averaging (i.e., well screen averages) and zero dispersion are also solved. The integral transform method starts with the partial differential equation, boundary conditions, and initial conditions of a transport problem and proceeds to an exact solution of it. Processes simulated in the various models include advection, dispersion, retardation, and decay, depending on the input data. The aquifer can have a finite or semi-infinite thickness. Up to one, two, or three dimensions can be simulated in the saturated zone.

Model information can be subdivided into four broad categories: source chemical history, unsaturated layer characteristics, leachate/aquifer mixing properties, and aquifer layer characteristics. MYGRT input menus are arranged to represent the direction of solute migration: surface source downward unsaturated flow, water table mixing, and aquifer spread. A summary of the input data can be viewed or printed. The model is flexible allowing users to provide parameters such as seepage velocity, dispersion, and retardation factors or the underlying aquifer characteristics can be provided and these parameters will be calculated.

A series of plots can be generated including concentration vs time, concentration vs distance, areal or cross-sectional contour plots, and concentration vs depth profiles. Each plot includes a tabular listing of the predicted concentrations.

# 2

## USES OF MYGRT

---

The MYGRT code allows users to predict the effect of solutes leaching from waste disposal sites on downgradient groundwater. Both inorganic and organic constituents can be simulated. Solute concentrations can be predicted in the unsaturated zone, at the water table, and at various downgradient locations. The model can accommodate sources in the unsaturated zone, at the top of the water table, or submerged at specified depths in the saturated zone. This provides flexibility so that the simulations for both impoundments and landfills can be more realistic. Leachate concentrations can be more accurately defined, because the model allows concentrations to vary as a function of time. Background concentrations can be included, if desired. The code also allows the user to simulate the effect of closing a disposal site by adding a cap to decrease infiltration. Results are provided automatically for the time period before closure and for a specified period after closure. Results for the saturated zone can be provided at a specific location and depth (e.g., 50 ft downgradient of the disposal site at the water table) or predicted concentrations can be averaged over a specified depth interval corresponding to a well screen.

The MYGRT model estimates groundwater solute concentrations discharged from waste disposal sites, spills and other sources. MYGRT offers utilities a convenient and inexpensive way to perform a preliminary assessment of potential groundwater impacts of a waste disposal facility and to develop sensitivity analyses. Screening of this nature can be used to select locations for well monitoring or determine the need for more-sophisticated models. MYGRT is used to assess impacts for a variety of sites such as ash landfills, MGP sites, underground pipe leaks, gasoline tanks, FGD sludge and ash ponds. MYGRT version 3.0 offers vertical transport through the unsaturated zone, which may be coupled with several transport models in the aquifer describing both a vertical and horizontal orientation.

# 3

## YEAR 2000 COMPLIANCE

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MYGRT is year 2000 ready. No calculations or processing are significantly related to the century indicator.

The developers have tested this code for Y2K related errors and found no problems. The test consisted of changing the clock on the PC to the date January 2, 2000, running MYGRT example 1, and comparing the results without any errors.

# 4

## INSTALLATION

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### System Requirements

The system requirements for MYGRT v 3.0 are:

IBM compatible PC running Microsoft Windows 95 or Microsoft Windows NT 4.0

16 MB of Available Physical RAM

10 MB of Disk Space

256 color video

Mouse

Recommended:

16.7 M color video

Color Printer

Printing can be performed on any printer setup with the Microsoft Windows operating system.

### Installation

To install MYGRT, use the following installation instructions. The instructions assume the distribution media is on floppy disks. If the distribution media is on a compact disk, see the notes below regarding CD. If distribution was by email or Internet FTP, place the distribution files into a temporary folder, run Setup from the temporary folder, and proceed to Step 7.

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*Installation*

	<b>Installation Instructions</b>
Step 1.	Using Windows, close all programs that are currently running.
Step 2.	Insert distribution disk 1 into the floppy drive. (CD: Insert distribution CD into the CD drive)
Step 3.	Press the Start button.
Step 4.	Select Run from the displayed menu.
Step 5.	The <i>Run</i> screen will be displayed; type: A:\Setup (CD: Use CD drive designator, example: E:\Setup)
Step 6.	With the <i>Run</i> screen displayed, press OK.

Follow the installation prompts that appear on the screen as discussed below.

	Installation Screen	Recommended Response	Alternate Response
Step 7	The <i>Welcome</i> screen is displayed.	Press OK to continue with installation.	Press Cancel to stop installation.
Step 8	The <i>Read Me</i> screen is displayed.	Press OK to continue with installation.	Press Cancel to stop installation.
Step 9	The <i>Select Destination Directory</i> screen is displayed. Use the browse list to select an installation directory (Example: C:\Mygrt3).	Press OK to continue with installation.	Press Cancel to stop installation.
Step 10	The <i>Make Backups</i> screen is displayed.	Press Yes to create backup copies of all files replaced during the installation. Next, the <i>Select Backup Directory</i> screen will be displayed. Use the browse list to select a backup directory (Example: C:\Mygrt3\Backup). Press OK to close the <i>Select Backup Directory</i> screen.	Press No if you do not want backup copies created or press Cancel to stop installation.
Step 11	The <i>Group Name</i> screen is displayed.	Enter a group name to appear in the Start Menu when you press the Start button. Press OK to close the <i>Group Name</i> screen.  The installation progress gauge is displayed. Insert additional disks as prompted. When the installation is complete, this screen closes.	Press Cancel to stop installation.
Step 12	The <i>Installation is Complete</i> screen is displayed.	Press OK to close the screen.	

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## Installation

When the installation is complete, you may run the software following the instructions from the section **Running the Software**.

If you encounter an installation message that indicates that a DLL is in use and cannot be updated, it is best to select the IGNORE button and continue with the installation. The rest of the installation will go smoothly and the software should be operational.

The software is designed to use a Windows font size setting of "small fonts". See the Windows documentation for more information.

## Uninstalling

To uninstall MYGRT, use the following uninstallation instructions:

	Uninstallation Instructions
Step 1.	Close all programs that are currently running.
Step 2.	Press the Start button.
Step 3.	Select Settings from the displayed menu.
Step 4.	Select Control Panel from the displayed menu.
Step 5.	Open <i>Add/Remove Programs</i> from the Control Panel window.
Step 6.	Select MYGRT and press Add/Remove from the <i>Add/Remove Programs Properties</i> screen.
Step 7.	Respond to the displayed uninstall prompts.
Step 8.	Press OK from the <i>Add/Remove Programs Properties</i> screen to close it.

Optionally, when the uninstaller is complete, you can use Windows Explorer (or My Computer) to view the installation directory (e.g. C:\Mygrt3) and remove any remaining folders and files. The uninstaller will not remove files or folders that you created. See Windows documentation for information on deleting files and folders.

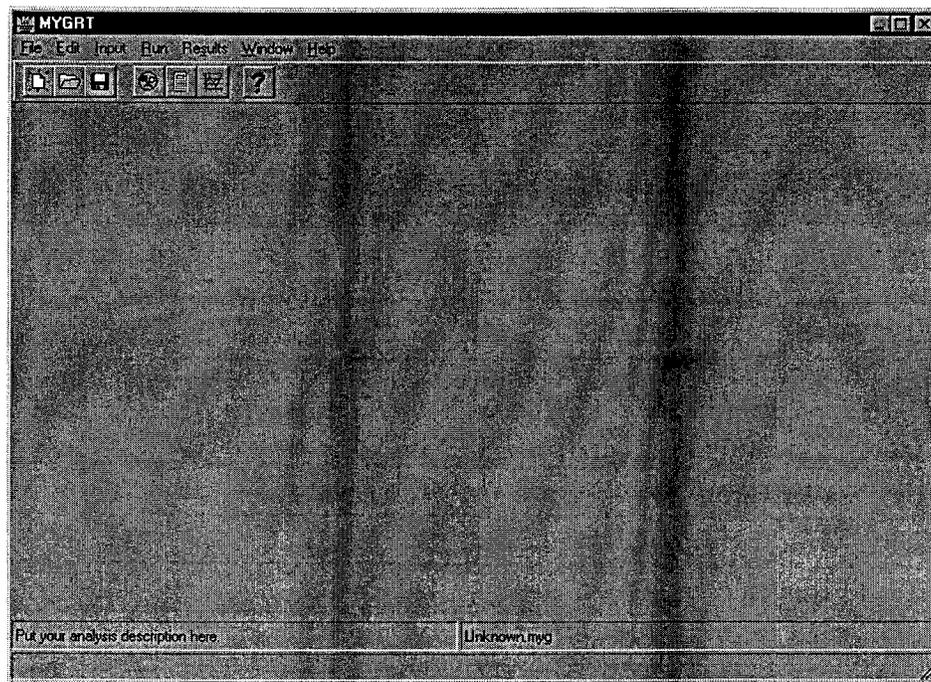
# 5

## RUNNING THE SOFTWARE

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To run MYGRT, perform the following instructions:

	Run Instructions
Step 1.	Using Windows, Press the Start button.
Step 2.	Select Programs.
Step 3.	Select the MYGRT group.
Step 4.	Select the MYGRT 3.0 program icon.
Step 5.	When the <i>About</i> screen is displayed, press OK..
Step 6.	Use the main menu to open an existing project (File   Open) or enter input values and save the projects with a new name (File   Save As).



**Figure 5-1**  
**Main Screen**

The default project file is automatically loaded when the software is started or when you select **File | New** from the menu. MYGRT is ready for you to modify or input new values.

# 6

## WORKING WITH MYGRT

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### Working with Screens

The MYGRT model was designed to provide a consistent user interface. All of the screens in the model look similar and respond to user input in a consistent manner. Screens typically display OK, Cancel, and Help buttons. Use the OK button to save any edit changes you have made and to close the screen. Use the Cancel button to disregard edit changes and to close the screen. The Help button displays a help file topic relevant to the displayed screen. Pressing the keyboard Escape key has the same effect as clicking the Cancel button.

Several screens display buttons with little left or right arrows. The right arrow button saves your data and displays the next screen. The left arrow button saves your data and displays the previous screen. The order of the screens displayed by these buttons is based on the menus.

When the OK button is pressed, data validation is performed to check for invalid data values. Blank fields and non-numeric data cause a validation message if a number is expected. If the validation test passes, the screen closes; otherwise, a message is displayed, and the screen will remain visible.

### Working with Tables

The Source Concentration screen contains a table to display data in rows and columns. Use the scroll bars on the tables to show any additional cells. The screens that contain tables can also be resized (by pressing the minimize and maximize buttons or dragging the lower right corner); the width and height of individual rows and columns can also be changed (by placing the cursor between header cells, clicking, and dragging to the new size). Clicking on the table sets the input focus to the table.

All screens with tables make use of the right mouse button to display a pop-up menu that can be selected. To hide the menu without selecting a menu item, click on an area outside of the menu. Typically, a table popup menu will contain a menu item for printing. Selecting this menu item will print the table using the current column widths.

The tables can be copied to the clipboard and then pasted into your favorite word processor. To copy selected data to the clipboard, select the text you want copied or click the upper left corner of the table. Then press the keyboard keys ([Ctrl]+[C]) at the same time. Open your word processor and select **Edit | Paste** to insert the contents of the clipboard.

## **Working with XY Plots**

A plot window has two parts, the plot pane and the table pane. The dark line between the panes can be used to resize them. To resize the panes, place the cursor over the dark line, click, hold down and drag to the new size.

To customize plots, click the right mouse button on the plot to display a tabbed page screen.

*Style Page*: The Style Page allows changing the markers and axis scale.

*Axis Page*: The Axis Page allows changing the axis position, range, labels, grids, and tick marks.

*Titles Page*: The Titles Page allows editing capabilities of any displayed title.

*Fonts Page*: The Fonts Page lets you change the font type and size displayed in the plot titles.

*Markers Page*: The Markers Page allows the changing of several graph properties, such as bar color and a hatch pattern.

*System Page*: The System Page provides the ability to print and copy your plot to the clipboard. The entire plot can be copied to the clipboard and then pasted into another application, such as a formal report in a word processor.

Pressing the Help button from any of the above pages displays detailed information for the displayed page.

The tables that are displayed beneath the graph in the table pane can be printed or copied to the clipboard. To print the data, click the right mouse button on the table to display a popup menu, and select print. To copy selected data to the clipboard, select the text you want copied or click the upper left corner of the table. Then press the keyboard keys ([Ctrl]+[C]) at the same time. Open another application, such as a word processor or spreadsheet, and select **Edit | Paste** to insert the contents of the clipboard.

## **Working with Contour Plots**

A contour plot has two parts, the plot pane and the table pane. The dark line between the panes can be used to resize them. To resize the panes, place the cursor over the dark line, click, hold down, and drag to the new size.

To customize plots, click the right mouse button on the plot to display a tabbed page screen. Pressing the Help button from any page displays detailed information for the displayed page.

# 7

## USING MYGRT

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### Instructions for Starting a New MYGRT Application

Either a new project or a previously saved project file can be used by MYGRT. After starting MYGRT, click on the File menu at the top - left of the main MYGRT screen. A drop-down menu will appear. Select either the **File | Open** menu item for bringing up a previous case or the **File | New** menu item to start a new simulation case. The Open command will prompt the user for the name and location of the project file previously saved. All MYGRT data files have a "MYG" file extension. Selecting the New command will automatically load a complete set of default values into the data screens. The user will then be required to go through the entry menus and screens to make the appropriate modifications.

### Setup Screen

The Setup screen provides space for a site description and the chemical name. Selecting metric units will result in length units of meters and selecting English units will give units of length in feet. The unit of time is always assumed to be in years. The user can change their choice of length units at any time, and all parameters will automatically be inter-converted. The same is true when selecting the units of concentration for input parameters and output plots.

A summary of the current modeling scenario is listed in the Setup screen. Click on the *Change* button to either view or modify the modeling scenario.

Parameter	Description
Site	An optional parameter, none is required: A brief description of the site that is to be simulated by MYGRT. A small amount of text, less than 30 characters, is recommended for this field because it appears in plots and reports. This text is saved and stored within the MYGRT project file.
Description	An optional parameter, none is required: A brief description of the particular case being run at the site. A small amount of text,

	less than 30 characters, is recommended for this field because it appears in plots and reports. This text is saved and stored within the MYGRT project file.
Solute Name	An optional parameter, none is required: An alphanumeric name or moniker to identify the chemical being simulated. A small amount of text, less than 30 characters, is recommended for this field because it appears in plots and reports.
Solute Type	Selecting "Organic" will allow the chemical to have a 1 <sup>st</sup> order decay rate "k" in the aquifer. Selecting "Inorganic" forces the aquifer decay rate to zero.
Units	Select English or Metric units. When the units are changed, the values of all parameters are converted if needed.
Units for Concentration	Select the units that will be used with the input and output concentrations. Existing concentration data will be converted to the appropriate units.
Colors in Screen Graphics	Select the number of colors you want the screen graphics to be displayed as. The selection of 16.7 million colors will show the best graphics if your computer's display is configured for True Color (24 bit color). See Windows documentation for information.

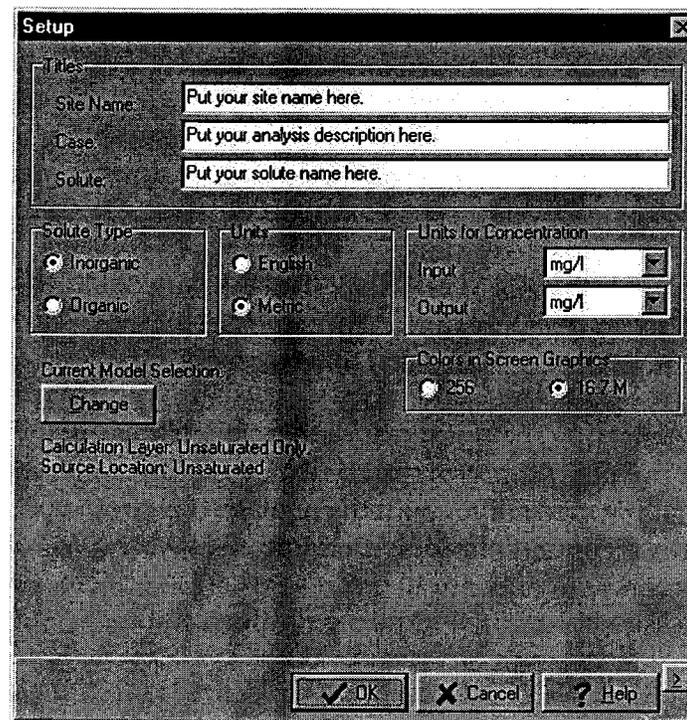


Figure 7-1  
Setup Screen

## Setup Model Screen

Modeling scenarios are grouped into three broad classifications: overall modeling domain (called Calculation Zone Restriction); source location; and saturated zone description. The saturated zone description is further broken down into dimensionality (1D, 2D, 3D); 2D orientation (i.e., areal versus cross-sectional); calculation at a specific depth in the aquifer (i.e., point value) or an average concentration over a specified depth interval (i.e., well screen average); and the relative size or scale of the vertical domain (i.e., finite aquifer thickness versus semi-infinite thickness). The number of choices depends on specific model selections.

As modeling scenario options are chosen, four small color pictures are displayed on the right hand side of the screen showing a schematic diagram of the selected feature.

Parameter	Description
Calculation Zone Restriction	Three physical domains of solute transport are available: solute transport in just the unsaturated layer, just in the saturated layer,

or coupled transport between the unsaturated and saturated layers. If modeling is restricted to only the unsaturated soil layer, then solute transport through the soil is modeled as a 1-D, vertical column. If only the saturated layer simulation is chosen, then transport is restricted to movement within the saturated layer. Both 1-D, 2-D, and 3-D models of transport are available.

The previous MYGRT v 2.0 models are obtained by selecting the Saturated Only option from the Calculation Zone Restriction and then the 2d Saturated Dimension option (discussed below).

Selecting the unsat/sat option will first simulate 1-D vertical transport through the unsaturated layer, mix the resultant infiltrated solute with the aquifer, then transport the solute horizontally through the saturated layer. Several 1-D, 2-D, and 3-D models of saturated transport are available. See Figure 7-3, Figure 7-4, and Figure 7-5 for illustrations.

Source Location	Three starting locations of the solute source are available, depending upon which physical domain of transport is chosen. For unsaturated-only transport, the bottom of the solute source is located at the top of the 1-D soil column. For saturated-only transport, the top and bottom of the solute source are located within the saturated layer, anywhere between the water table and the bottom of the aquifer. For unsat/sat modeling, the bottom of the source must be located either at the top of the 1-D soil column or just above, but in contact, with the water table.
Saturated Dimensions	If solute transport is allowed within the saturated zone, then either a 1-D, a 2-D, or a 3-D model of solute transport can be chosen. Choosing either a 2-D or 3-D model will allow the user to select from several additional options. See Figure 7-3, Figure 7-4, and Figure 7-5 for illustrations.
Resultant Concentration	Normally solute predictions are performed at specified (x,y,z) spatial points within the unsaturated soil or saturated layers. However, a depth-averaged concentration is available for 2-D and 3-D saturated models when the Well Screen Average option is chosen. The depth average option represents the effect of sampling a variable solute concentration over the entire well-screened length.
2d View	When selecting a 2-D saturated model, simulation can be done in either the areal plane (X and Y axis) or in the cross-sectional plane

(X and Z axis). Typically, the areal plane option is chosen when the source length and width dimensions are much greater than the aquifer thickness dimension and when the point of interest (i.e., the observation well) is far down gradient of the source. The cross-sectional plane is appropriate with sources that are very wide but the point of interest is close to the source.

#### Aquifer Thickness Calculation

Either a finite thick or a semi-infinite thick aquifer representation can be chosen. No aquifer is actually infinitely thick but the assumption is made that solute never reaches the lower boundary of the saturated zone during the time period and location of interest. In finite thick aquifers, solute can reach the lower boundary of the aquifer and hence build up along it over time. The semi-infinite thickness models run substantially faster in comparison to the finite thickness models but the resultant concentrations may be under-conservative.

#### Down Gradient Zones

MYGRT is currently restricted to a single down gradient zone of aquifer properties..

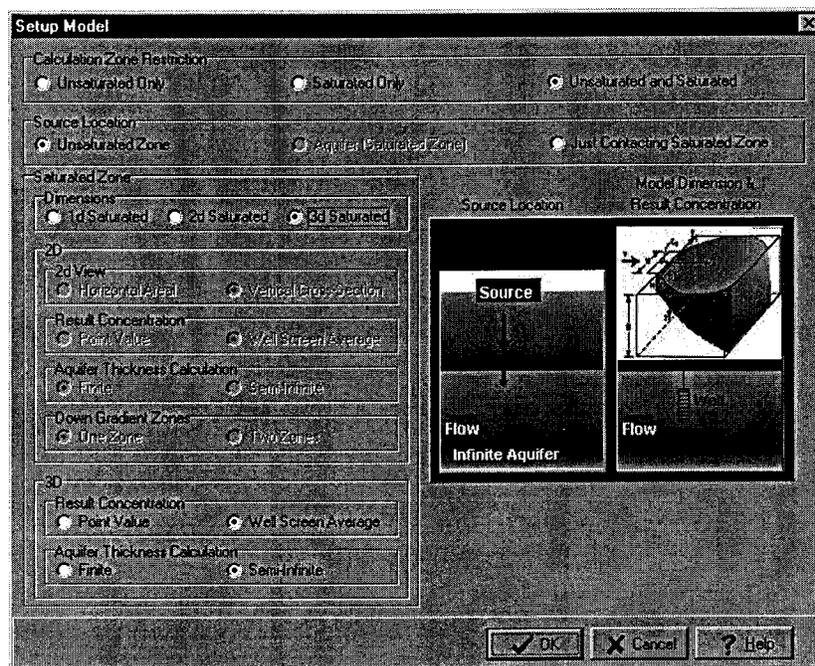


Figure 7-2  
Setup Model Screen

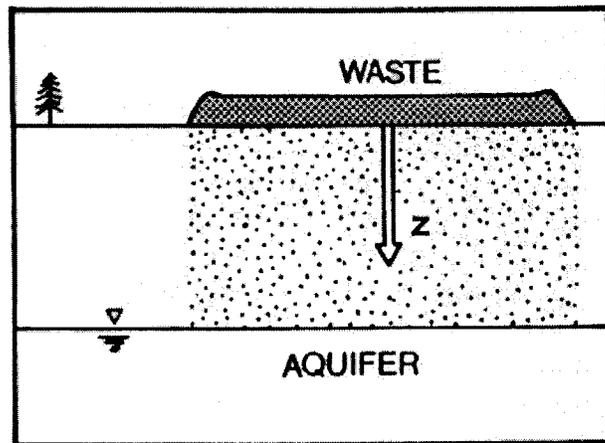


Figure 7-3  
Selection of a 1-D, unsaturated calculation zone restriction.

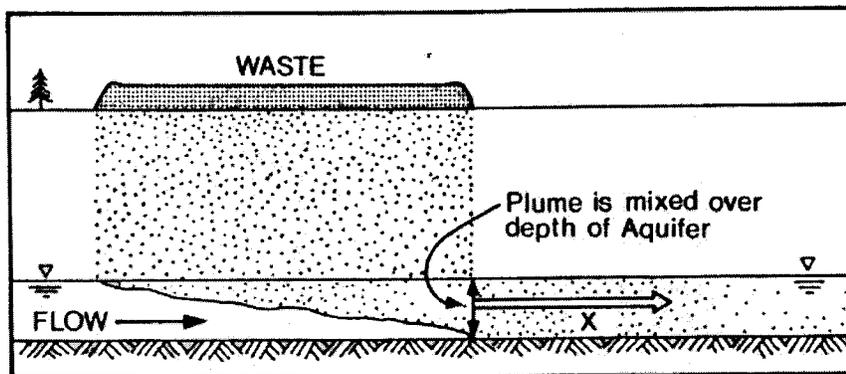
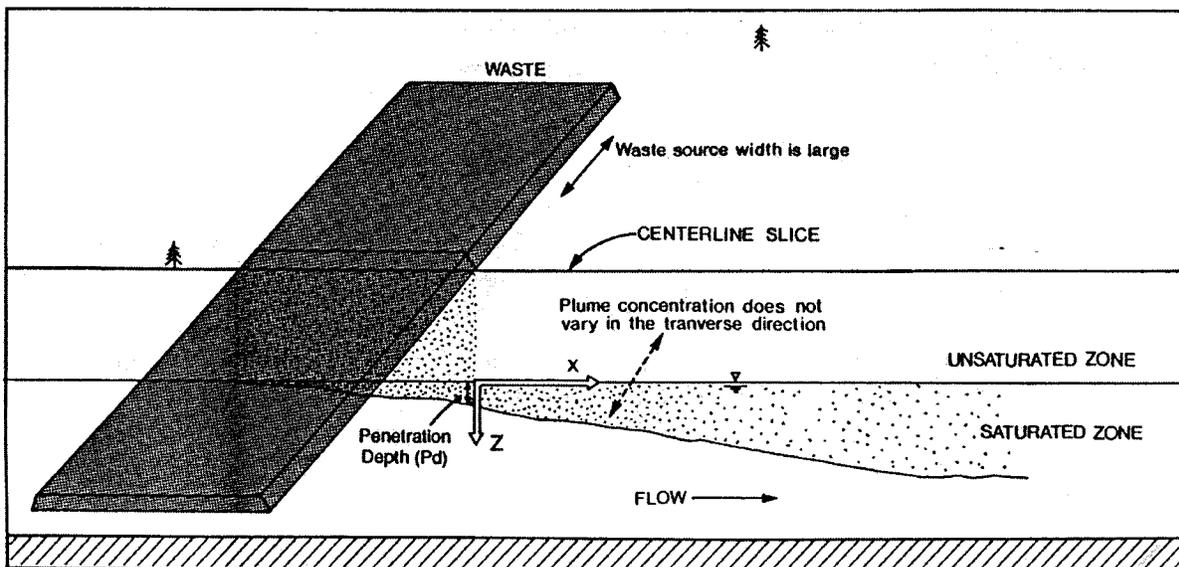


Figure 7-4  
Selection of a 1-D saturated calculation zone restriction.



**Figure 7-5**  
Selection of a 2-D, cross-sectional view for saturated or unsaturated/saturated calculation zone restriction.

## Modeling Scenarios

There are three fundamental modeling scenarios in MYGRT: unsaturated layer calculations only; saturated layer calculations only, or joint calculations in both the unsaturated and saturated layers. Each of these scenarios is discussed below in an outline form:

### I) Unsaturated Layer Modeling Only

The bottom of the source is located on top of the unsaturated soil layer. All calculations are restricted to the unsaturated layer. See Figure 7-3.

### II) Saturated Layer Modeling Only

The top and bottom limits of the source are located at specified depths below the water table. All calculations are restricted to the saturated layer. The following options are available for modeling the saturated domain:

- i) 1D aquifer (along the X axis)
- ii) 2D aquifer
  - 1) areal (along the X & Y axis plane)
  - 2) vertical, cross-sectional (along the X & Z axis plane)

- a) finite or semi-infinite thickness
- b) point or vertically averaged concentrations
- iii) 3D aquifer
  - 1) finite or semi-infinite thickness
  - 2) point or vertically averaged concentrations

### III) Both Unsaturated And Saturated Layer Modeling

A) The bottom of the source is located on top of the water table. The following options are available for modeling the saturated domain:

- i) 1D aquifer (along the X axis)
- ii) 2D aquifer
  - 1) areal (along the X & Y axis plane)
  - 2) vertical, cross-sectional (along the X & Z axis plane)
    - a) finite or semi-infinite thickness
    - b) point or vertically averaged concentrations
- iii) 3D aquifer
  - 1) finite or semi-infinite thickness
  - 2) point or vertically averaged concentrations.

B) The bottom of the source is located on top of the unsaturated layer. Transport through the unsaturated layer is 1D vertically downward. Solute penetrates and then mixes with the groundwater using a "box" model of mass balance. The following options are available for modeling the saturated domain:

- i) 1D aquifer (along the X axis) See Figure 7-4
- ii) 2D aquifer
  - 1) areal (along the X & Y axis plane)
  - 2) vertical, cross-sectional (along the X & Z axis plane)
    - a) finite or semi-infinite thickness
    - b) point or vertically averaged concentrations
- iii) 3D aquifer
  - a) finite or semi-infinite thickness
  - b) point or vertically averaged

Choosing between a 2-D and a 3-D representation of the saturated layer can depend on a number of factors. In general, the 3-D model provides the most accurate representation of solute transport and it is the preferred model of use. When the source is very large and the point of calculation is close to the source (e.g., within a distance of one source width), then a 2-D cross-sectional model will be adequate to represent the longitudinal and vertical transport of solute. See Figure 7-5. In addition, when the saturated layer is relatively thin in comparison to the size of the source and the point of calculation is not directly under the source, a 2-D areal model should be adequate. The only real advantage to using either the 1-D or 2-D models of solute transport in the saturated layer is computational speed, such as when making contour plots of the concentration. It may take 5 minute or so on a 300 MHz PC to calculate a detailed contour plot of solute concentration when using a 3-D, finite thick model. Using a 2-D model will reduce the run time to less than a minute. But in either case, the computation time may be insignificant compared to the gain in confidence when using a 3-D model.

### **Modeling an Initial Solute Concentration at the Down Gradient Edge of the Source**

The previous MYGRT v 2.0 models specified the initial solute concentration at the down gradient edge of the source. This can be obtained in MYGRT v 3.0 by selecting the Saturated Only option from the Calculation Zone Restriction and then either the 1d, 2d, or 3d Saturated Dimension option from the Setup Model screen. To display the Setup Model screen, select the menu **Input | Setup** and then press the *Change* button on the Setup screen.

### **Data Input Screens**

The Unsaturated Zone Properties screen, Saturated Zone Properties screen, and Solute Plume Description screen display the required parameters based on the selections made in the Setup Model screen. Those parameters that are not required will be disabled and will not be used in the concentration calculations. Each screen is organized under tabbed folders. Each tab corresponds to a set of properties that the users can select or input. Certain parameters such as dispersion coefficients, mixing depth, retardation factors can be model estimated based on inputs from the screen or from across several screens. The user can override the model calculation and input the appropriate value for the parameter.

The unsaturated zone screen is tabbed for properties pertaining to Source, Infiltration and Soil. Press the Source Data button to display the Source Concentration screen.

### Unsaturated Zone Parameters (Source)

Parameter	Units	Description
Source Data		Press the Source Data button to display the Source Data screen. See Figure 7-7 for an illustration.
Width of Source	m	The width of the source is specified. The source width is measured in a direction that is perpendicular to the average flow direction of the saturated layer. The width of the solute plume entering the water table is assumed to be the same as the source width itself.
Length of source parallel with aquifer flow direction	m	The length of the source is specified. The source length is measured in a direction that is parallel to the average flow direction of the saturated layer. The length of the solute plume entering the water table is assumed to be the same as the source length itself. Modeling of the plume in the saturated layer starts at the down gradient edge of the source length.

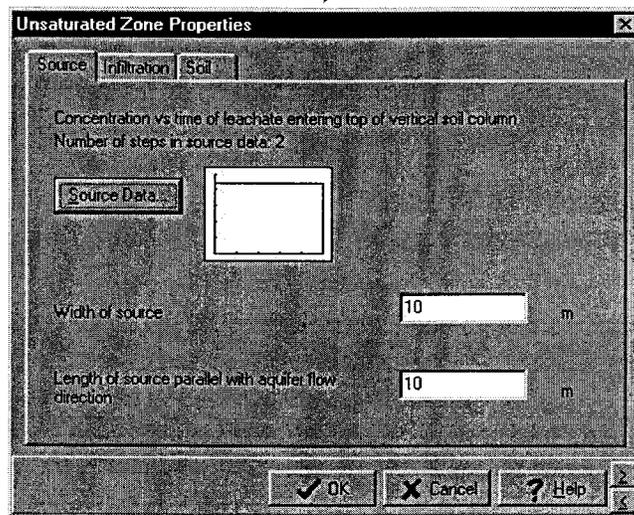


Figure 7-6  
Unsaturated Zone Properties Screen

### Unsaturated Zone Parameters (Infiltration)

Parameter	Units	Description
Vertical Infiltration Rate	m/yr	The average vertical infiltration rate, on a volume per unit area per unit time basis (a Darcy velocity), is specified for the unsaturated soil layer. This value represents the net recharge to the saturated zone.
Use the same rate for aquifer penetration calculation		Checking this option means that the same vertical infiltration rate is assumed to pass through the unsaturated soil layer and through the source (i.e., the leachate flux rate). All unsaturated transport properties and plume penetration calculations are based on the same infiltration rate. If this option is not checked, then the user can specify a separate leaching flux rate in the Saturated Properties screen for calculating the plume penetration depth.
Use Infiltration Rate Substitution		An option is given to allow the infiltration rate to change to a different value at some specified date. Typically, this could represent the effect of capping (or flooding) the unsaturated soil source. The vertical solute transport model uses the first infiltration rate until the specified time, then it switches over to the second infiltration rate for the duration of the simulation. At the moment of the switchover, the vertical solute concentration profile is calculated and then used as the "new" initial condition of the soil column for the remainder of the simulation.
New Vertical Infiltration Rate	m/yr	If the second infiltration rate option is chosen, then the value of the second infiltration rate (Darcy velocity) must be specified. This value can be smaller, the same, or larger than the first infiltration rate.
At Time	yr	If the second infiltration rate option is chosen, then the time of the switchover must be specified. If the switchover date is before the start of the dates used in the boundary conditions, then only the second infiltration rate is used. If the switchover time is greater than any time period used in the run calculations, then only the first infiltration rate is used.

### Unsaturated Zone Parameters (Soil)

Parameter	Units	Description
Vertical Dispersion Coefficient		Either the user or the program can calculate the vertical dispersion coefficient of the unsaturated soil layer. In either case, both the volumetric moisture content and depth to water table parameters have to be specified.
Volumetric Moisture Content	cm <sup>3</sup> /cm <sup>3</sup>	The average moisture content of the unsaturated soil is specified on a volume per volume basis. The moisture content is assumed to have already reached a steady state, constant value before solute transport begins.
Depth to water table below source	m	Depth-to-water table is defined as the distance between the bottom of the source and the top of the water table. Hence, this depth may be less than the total thickness of the unsaturated soil layer if the source is partially buried within the unsaturated soil.
Vertical Dispersion Coefficient	m <sup>2</sup> /yr	The vertical dispersion coefficient of the unsaturated soil layer is either directly specified by the user or is calculated by the program. If the "model calculated" option is chosen, then the vertical dispersivity coefficient is multiplied by the vertical infiltration rate (Darcy velocity), and then divided by the moisture content. The vertical dispersivity coefficient is set equal to 1/10 <sup>th</sup> the depth-to-water table value.
Calc		Press the Calc button to display the computed vertical dispersion coefficient.
Retardation Factor, Rd		The retardation coefficient (unitless) of the solute is specified for the unsaturated soil layer. The retardation coefficient should be set equal to one for conservative solutes, such as sulfate and chloride.
Decay Rate	1/yr	The first order decay rate of organic solutes within the unsaturated soil is specified. This parameter is only entered if the "organic" option of the Solute Type parameter has been chosen in the Setup screen.

## Source Concentration Screen

The Source Concentration screen displays when the Source Data button is pressed on the Unsaturated Zone Parameters (Source) screen or Solute Plume Description (Source) screen. This screen shows a graph of concentration vs. time for input concentration data. Input concentrations are entered from the table below the graph. Press the Add button to add a row to the bottom of the table. Press the Delete button to delete the current row from the table. To print the table, click the right mouse button on the table and select *Print* popup menu item. To print the graph, click the right mouse button on the graph, select the System page and press the *Print* button.

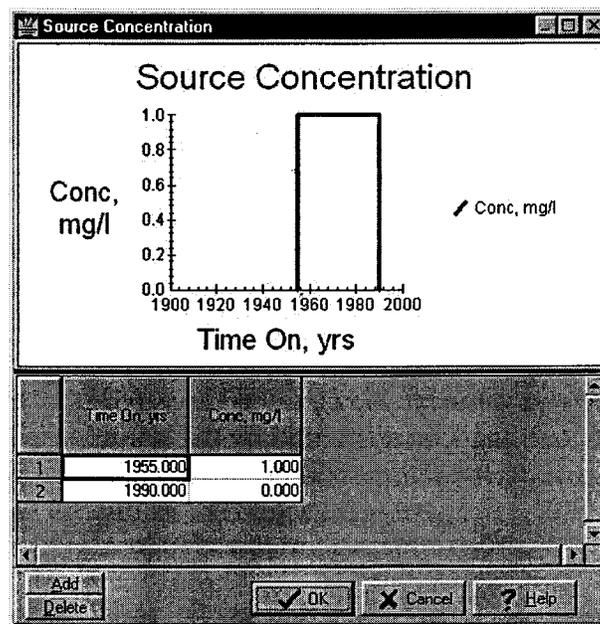
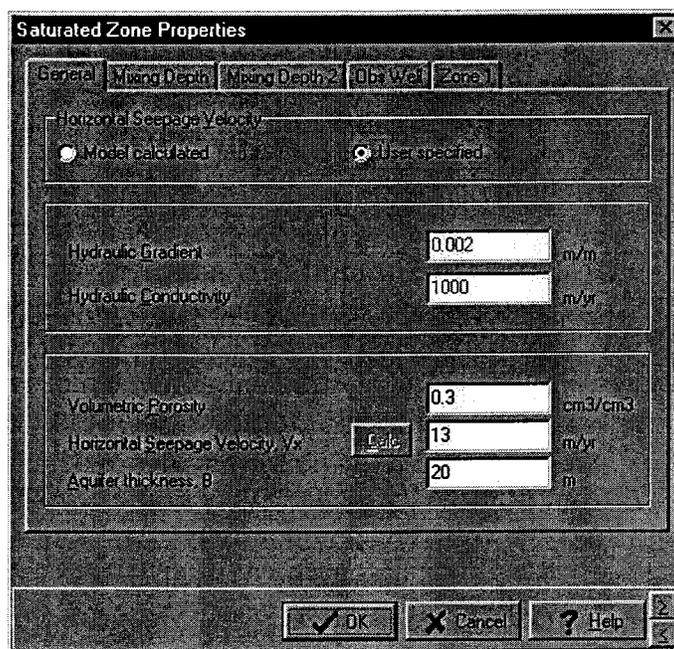


Figure 7-7  
Source Concentration Screen

## Saturated Zone Properties (General)

Parameter	Units	Description
Horizontal Seepage Velocity		The horizontal seepage velocity is either directly specified by the user or model calculated. If model calculated, then the horizontal hydraulic gradient, volumetric porosity, and hydraulic conductivity will also

		have to be specified.
Hydraulic Gradient	m/m	The horizontal hydraulic gradient of the saturated layer is only specified if the dispersion coefficients are model calculated. It is defined as the change in water table elevation per unit of horizontal distance. Its value should be based on the average hydraulic gradient measured or estimated along the flow path from the source.
Hydraulic Conductivity	m/yr	The horizontal hydraulic conductivity of the saturated layer is only specified if the dispersion coefficients are model calculated. Its value should be based on the average hydraulic conductivity measured or estimated along the flow path from the source.
Volumetric Porosity	cm <sup>3</sup> /cm <sup>3</sup>	The volumetric porosity of the saturated layer must always be specified. Its value should be based on the average porosity measured or estimated along the flow path from the source.
Horizontal Seepage Velocity, V <sub>x</sub>	m/yr	The horizontal seepage velocity of the aquifer can either be directly specified by the user or calculated by the program. If program calculated, then the seepage velocity is set equal to the horizontal hydraulic gradient, times the horizontal saturated hydraulic conductivity, and then divided by the volumetric porosity. This calculation should be based on the average aquifer properties measured or estimated along the flow path from the source.
Aquifer Thickness, B	m	The total thickness of the saturated layer is specified. It is the depth over which the solute plume can vertically migrate. This parameter is used in numerous portions of the code, particularly if the finite thickness solute models are chosen. Point observation depths, and well screen depths are all restricted to lie within the specified aquifer thickness. However, even when the semi-infinite depth models are used, the plume penetration depth of mixing is restricted to lie within the specified aquifer thickness.



**Figure 7-8**  
Saturated Zone Properties Screen

The saturated zone screen is tabbed for the following properties: General, Mixing Depth, Mixing Depth-2, Zone 1, and Observation Well.

#### Saturated Zone Properties (Mixing Depth)

Parameter	Units	Description
Mixing Depth		Select whether the mixing depth is specified by the user or model calculated.
Source Infiltration Rate	m	In the Unsaturated Zone Properties screen, if the "Use the same rate for aquifer penetration" option was not chosen, then the infiltration rate of solute leachate from the source must be specified. It can be the same or different than that of the infiltration rate through the unsaturated soil zone. This value will be used in calculating the groundwater mixing or dilution of the leachate with the background aquifer water.
Calculate		Press the Calculate button to compute the mixing depth. This button is enabled when Mixing Depth - Model calculated is selected.

Mixing Depth	m	<p>The vertical mixing depth of the plume under the source is either specified by the user or model calculated. In either case, this depth represents the maximum depth over which the solute leachate from the source will mix with the saturated layer before moving down gradient. The vertical mixing depth increases as the source length, vertical infiltration rate, and the vertical dispersivity coefficient increase. The vertical mixing depth is used in calculating the groundwater mixing of solute leachate with the background aquifer water and for specifying the source dimensions for the aquifer transport models. In all cases, the mixing depth can not exceed the aquifer thickness. Once the solute plume has completely penetrated the aquifer thickness under the source, then the plume becomes two-dimensional in the X and Y-axis planes.</p>
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#### Saturated Zone Properties (Mixing Depth-2)

Parameter	Units	Description
Mixing Depth After Substitution of Second Infiltration Rate		Select whether the mixing depth is specified by the user or model calculated for the case when a second infiltration rate is specified.
Source Infiltration Rate	m	If the second infiltration rate option is chosen in the Unsaturated Zone Properties screen, a second infiltration rate of solute leachate from the source is specified.
Calculate		Press the Calculate button to compute the mixing depth. This button is enabled when Mixing Depth - Model calculated is selected.
Mixing Depth	m	The vertical mixing depth of the plume under the source is either specified by the user or model calculated. In either case, this depth represents the maximum depth over which the solute leachate from the source will mix with the saturated layer before moving down gradient. The vertical mixing depth increases as the source length, vertical infiltration rate, and the vertical dispersivity

coefficient increase. The vertical mixing depth is used in calculating the groundwater mixing of solute leachate with the background aquifer water and for specifying the source dimensions for the aquifer transport models. In all cases, the mixing depth can not exceed the aquifer thickness. Once the solute plume has completely penetrated the aquifer thickness under the source, then the plume becomes two-dimensional in the X and Y-axis planes.

#### Saturated Zone Properties (Obs Well)

Parameter	Units	Description
Depth to top of screen from water table	m	The depth to the top of the observation screen is specified if the "Well screen average" option is selected in the Setup Model screen. Depth is measured with respect to the top of the water table. Set this number to zero if the well screen extends up into the unsaturated zone. In addition, the depth to the top of the screen can not be greater than the specified aquifer thickness.
Depth to bottom of screen from water table	m	The depth to the bottom of the observation screen is specified if the "Well screen average" option is selected in the Setup Model screen. Depth is measured with respect to the top of the water table. In addition, the depth to the bottom of the screen can not be greater than the specified aquifer thickness.

#### Saturated Zone Properties (Zone 1)

Parameter	Units	Description
Dispersion		The dispersion coefficients of the saturated layer are either calculated by the program or specified by the user.
Scale Distance for Dispersion Calculation	m	If dispersion is model calculated, then a scale distance for dispersion is specified. Typically, the furthest, down gradient, observation distance of interest from the source is chosen as the scale distance. The horizontal

dispersivity is estimated as  $1/10^{\text{th}}$  the specified scale distance.

**Calc** Press the Calc button to calculate the dispersion coefficients. This is enabled when Dispersion - Model calculated is selected.

**Horizontal Dispersion Coefficient, Dx**      **m<sup>2</sup>/yr**      Horizontal dispersion coefficient in the saturated layer. It can either be directly specified by the user or calculated by the program. If program calculated, the horizontal dispersivity is multiplied by the horizontal seepage velocity. The horizontal dispersivity is estimated as  $1/10^{\text{th}}$  the specified scale distance.

**Transverse Dispersion Coefficient, Dy**      **m<sup>2</sup>/yr**      Transverse dispersion coefficient in the saturated layer. It can either be directly specified by the user or calculated by the program. If program calculated, a value of  $1/10^{\text{th}}$  the horizontal dispersion coefficient is used.

**Vertical Dispersion Coefficient, Dz**      **m<sup>2</sup>/yr**      Vertical dispersion coefficient in the saturated layer. It can either be directly specified by the user or calculated by the program. If program calculated, a value of  $1/100^{\text{th}}$  the horizontal dispersion coefficient is used.

### Solute Plume Description (Source)

Parameter	Units	Description
Source Data		Press the Source Data button to display the Source Data screen. See Figure 7-7 for an illustration.
Width of source entering aquifer		The width of the source is specified. The source width is measured in a direction that is perpendicular to the average flow direction of the saturated layer. The width of the solute plume entering the water table is assumed to be the same as the source width itself.
Top of Source, Z1	m	Specify the depth to the top of the source. For a submerged source, specify the top of the source with respect to the water table.

Bottom of Source, m  
Z2

Specify the depth to the bottom of the source. For a submerged source, specify the bottom of the source with respect to the water table.

Figure 7-9  
Solute Plume Description Screen

### Solute Plume Description (Down gradient Zone 1)

Parameter	Units	Description
Retardation Factor		The retardation factor is either specified by the user or model calculated.
Bulk Density	g/ml	If the retardation factor is model calculated, then the dry-bulk density of the saturated layer soil needs to be specified.
pH Value		The pH value of the aquifer water is only given as a reminder when determining the retardation coefficient.
Background Conc	mg/l	The background or initial solute concentration in the aquifer is specified. This is the average solute value in the aquifer before solute leachate from the source reaches the

		aquifer.
Partition Coeff, Kd	ml/g	For inorganic solute chemicals, the partition coefficient is specified by the user if the Model Calculated option is chosen for the retardation factor.
Retardation factor, Rd (inorganic)		The retardation factor is either specified by the user or model calculated. If model calculated, the retardation factor is set equal to the partition coefficient times the dry-bulk density, divided by the volumetric porosity coefficient, and then the value of one is added to the resultant calculation.
Octonal-Water Partition Coefficient		For organic solute chemicals, the octonal water partition coefficient is specified by the user if the Model Calculated option is chosen for the retardation factor.
Fraction of organic carbon, foc		For organic solute chemicals, the fraction of organic carbon in the saturated soil layer is specified by the user if the Model Calculated option is chosen for the retardation factor.
Partition Coeff, Kp	ml/g	For organic solute chemicals, the partition coefficient is specified by the user if the Model Calculated option is chosen for the retardation factor.
Retardation factor, Rd (organic)		The retardation factor for organic solute chemicals is either specified by the user or model calculated. If model calculated, the retardation factor is set equal to the partition coefficient times the dry-bulk density, divided by the volumetric porosity coefficient, and then the value of one is added to the resultant calculation.
Decay Rate	1/yr	For organic solute chemicals, the first order decay constant of the solute in the aquifer is specified. A value of zero means that no decay occurs within the aquifer.

### Run Option Screen

This screen is an interactive screen that displays options based on the type of model and the user's input settings.

For the 1-d model unsaturated, three run options are available: concentration versus time for specified depths (up to five depths), and concentration versus depth for specified times (up to five times), and point concentration at a depth and time. These are the base options and are available to the 1-d, 2-d (horizontal areal and vertical cross section orientation), and 3-d models for the saturated zone. The distance along which the concentration is estimated is along the primary axis of orientation of the model.

The 2-d and 3-d saturated models have further features to display concentration contours. The contour planes are dependent on the model orientation (e.g. X - Y for 2-d areal cross section, and X-Z and Y-Z planes for the vertical cross section).

If the result concentration is estimated as a well average concentration, the run options are limited in the Z (vertical direction). Contours are available only in the X-Y plane.

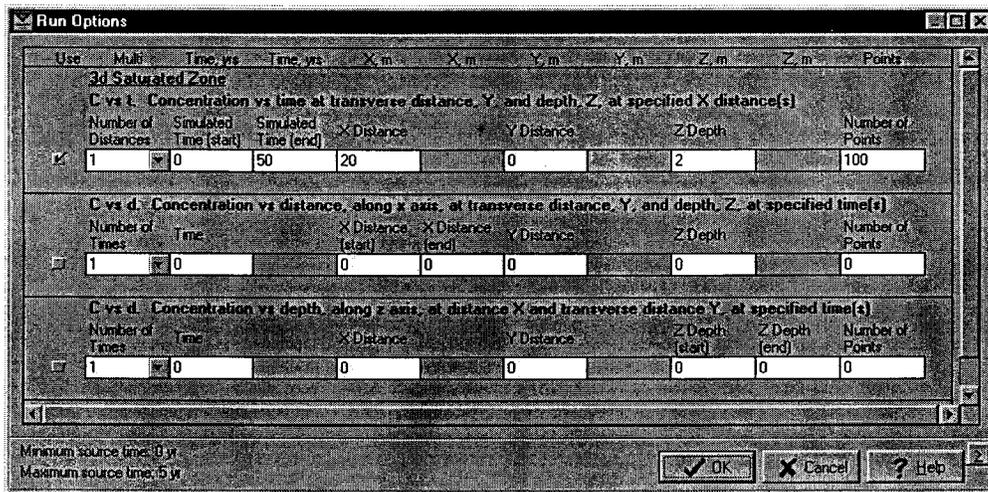


Figure 7-10  
Run Options Screen

## Run Screen

The Run screen provides a location for entry of any notes that are to be associated with this project file. Press the Run button to start the calculation process. All selected run options (from the Run Options screen) will be processed sequentially.

Feature	Description
Notes	An optional parameter, none is required: A note pad is provided at Run time to allow the user to log any thoughts about the data being used in the run. The text in this field appears in reports. This text is saved and stored within the MYGRT project data file.
Run button	Press the Run button to start the calculations for all selected run options.

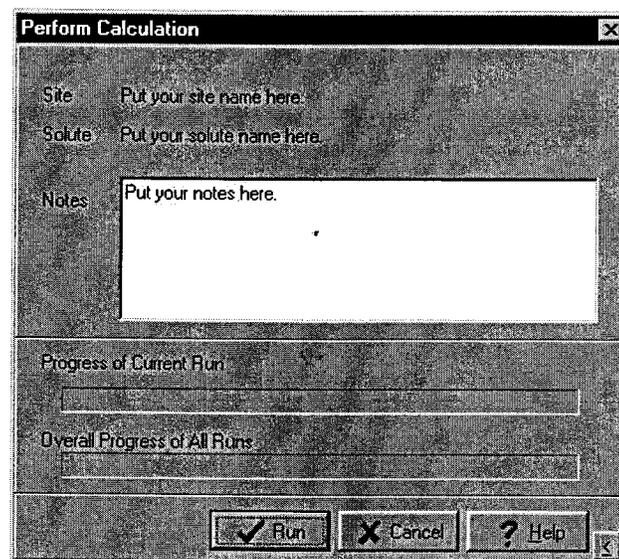


Figure 7-11  
Run Screen

## Generate Plots

The menu item **Results | Generate Plots** will display the calculated results using graphs and tables from all selected run options (from the Run Options screen). The type of output depends on the run option selected.

## Summary of Inputs

The menu item **Results | Summary of Inputs | Parameter Data** displays a screen that provides all of the input parameters entered by the user in one report. Right click on

the screen to print the report. The contents of this screen are not editable. The small down arrow buttons are disabled and will not appear on the printed report.

This screen can remain displayed while working with the model. Press the Update button to display the current values.

Description	Units	Value	Note
<b>General Parameters</b>			
Site		Put your site name here.	
Description		Put your analysis description here.	
Notes		Put your notes here.	
Solute Name		Put your solute name here.	
Organic		No	
Zones Simulated		Unsat/Sat	
Source Location		Unsat	
Saturated Zone Dimension		Sat_3d	
Point or Depth Averaged		Point	
Aquifer Thickness		Finite	
Number of Sat Down Gradient Zones		One	
<b>Unsaturated Zone Parameters</b>			
Unsaturated Infiltration Rate used in Sat		Yes	
Unsaturated Infiltration Rate	m/yr	1	
Infiltration Switching		No	
Unsaturated Moisture Content	cm3/cm3	0.2	
Unsaturated Dispersion Coeff in Z	m2/yr	2	Calc'd

Figure 7-12  
Input Parameters Screen

## Source Data

The menu item **Results | Summary of Inputs | Source Data** displays a screen that shows the source data used in the calculations.

## Write Default Project

The menu command **File | Write Default Project** writes the default Project file. The default Project file contains your initial values that you will use when you use the **File | New** command. Saving a default project should be done with care because this file provides the basis of constructing new applications.

## The Toolbar

The Toolbar, located just under the main menu, provides easy access to some of the most commonly used menu commands.



**Figure 7-13**  
**The Toolbar**

Positioning the cursor over one of the toolbar buttons will display a tooltip, and the status bar at the bottom of the screen will have a help hint as well.

The command associated with each of the buttons is as follows:

Button	Description and Equivalent Menu Command
	Creates a new project <b>File   New</b>
	Opens an existing project <b>File   Open</b>
	Saves current project <b>File   Save</b>
	Displays <i>Setup</i> screen <b>Input   Setup</b>
	Display the Run screen <b>Run   Run Model</b>
	Generates plots for each selected run option <b>Results   Generate Plots</b>
	Displays the help table of contents <b>Help   Contents</b>

# 8

## LIMITATIONS

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Only a single chemical species is simulated at a time. Hence chemical speciation and chemical-chemical interactions are not accounted for. Except for source history concentrations, all physical parameters are assumed to be constant over specified space domains and time periods. The unsaturated vertical seepage velocity can be changed from an initial constant value to a second constant value at a specified switch-over time such as at closure of a disposal site. This allows the user to simulate the effect of changing the source's infiltration rate to the water table. A change in the infiltration rate can occur when surface conditions are modified, such as when capping the source.

Other assumptions relating to solute transport in the model include the following:

- The groundwater seepage velocity is constant, and is not affected by the leachate from a source. In case of a large impoundment, additional flow calculations may need to be performed to check this assumption.
- Dispersion is represented by Fick's Law. Standard procedures for estimating dispersion are incorporated into the model, but the user can select a given value.
- Sorption is treated as linear, equilibrium partitioning process between the aqueous and solid phases. The user has a choice of providing a retardation factor or providing the underlying properties and having the model calculate the factor.
- First-order kinetics adequately simulates solute transformation or decay. A single decay rate is used for both the dissolved and adsorbed phases.

# 9

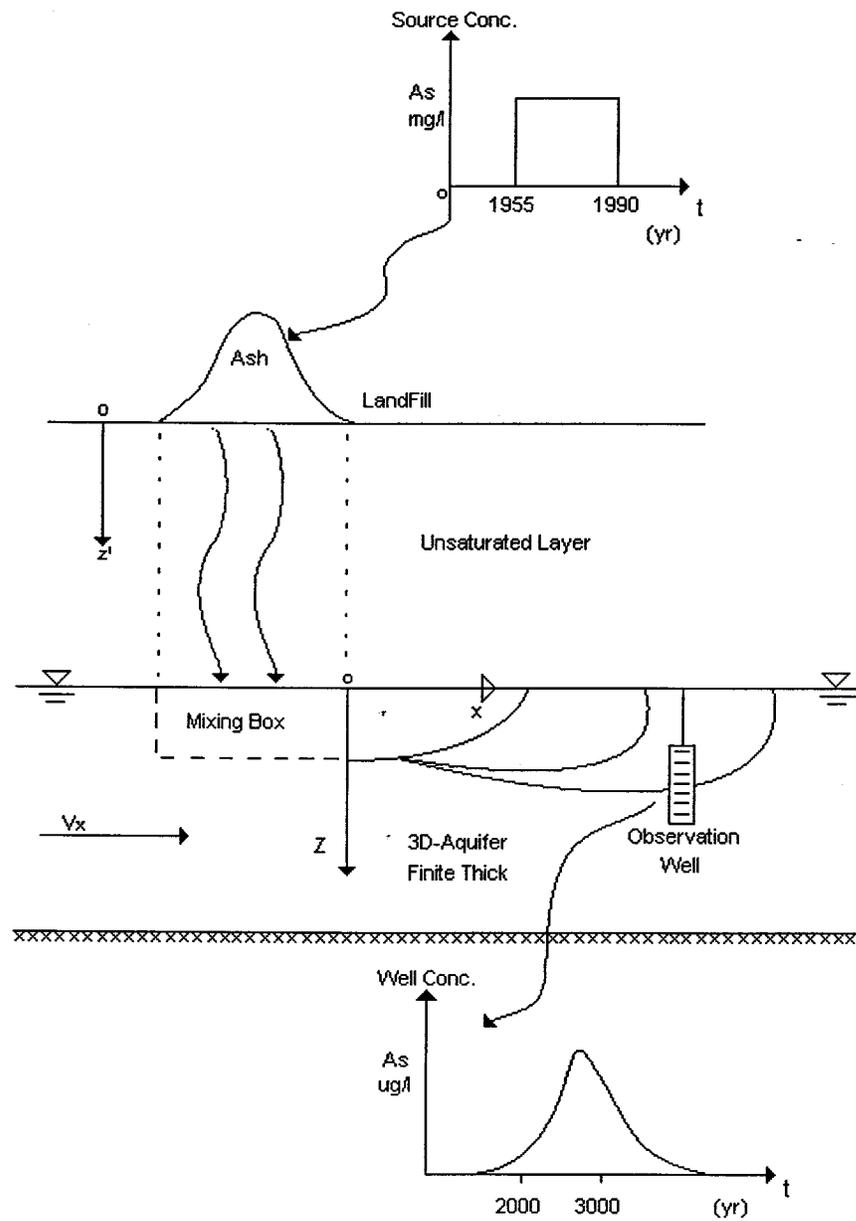
## EXAMPLES

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### Example 1 Ash Landfill

In the first example, we will consider the migration of arsenic from a 200 m by 200 m ash landfill. Arsenic concentration in the landfill leachate is estimated to be an average of 1 mg/l and is migrating with a vertical seepage velocity of 0.3 m/yr with a unsaturated zone moisture content of  $0.2 \text{ cm}^3/\text{cm}^3$ . The leachate started to enter the unsaturated soil layer in 1955 and continued until 1990, when the landfill was closed. Capping reduced the vertical seepage velocity to (1 in/yr)  $0.025 \text{ m/yr}$  from (11.81 in/yr)  $0.3 \text{ m/yr}$ . The landfill rests atop a 4 meter unsaturated soil layer. Underlying the unsaturated layer is a 20 m thick aquifer that is moving with a seepage velocity of 13 m/yr and has a porosity of  $0.3 \text{ cm}^3/\text{cm}^3$ . On-site monitoring wells indicated that landfill leachate was penetrating 3 meters into the aquifer at the down gradient edge of the landfill. At a distance of 150 m down gradient of the landfill is an observation well that is screened in the aquifer between the depths of 1 and 3 meters below the water table. We wish to predict the maximum concentration of arsenic that will reach this observation well.

The most realistic scenario for this problem is to model the leachate moving vertically down through the one-dimensional unsaturated soil beneath the landfill, mixing with the underlying water table and then moving down gradient through a three dimensional, finite thick aquifer. A schematic of this problem is given in Figure 9-1.



1047-11

Figure 9-1  
Example 1, Schematic

### Data Summary of Example 1

All of the modeling data are summarized below:

Field	Value or Selection
Site Name	Ash Landfill-with closure
Case	Example 1
Solute	Arsenic
Solute Type	Inorganic
Units	Metric
Units for Concentration, Input	mg/l
Units for Concentration, Output	ug/l
Colors in screen graphics	16.7M
Calculation Zone Restriction	Unsaturated and Saturated
Source Location	Unsaturated Zone
Saturated Dimensions	3D
Saturated Result Concentration	Well Screen Average
Saturated Aquifer Thickness Calculation	Finite
Width of Source	200 m
Length of source parallel with aquifer flow direction	200 m
Vertical Infiltration Rate	0.3 m/yr
Use the same rate for aquifer penetration calculation	checked
Use Infiltration Rate Substitution	checked
New Vertical Infiltration Rate	0.0254 m/yr
At Time	1990 yr.
Volumetric Moisture Content	0.2 cm <sup>3</sup> /cm <sup>3</sup>
Depth to water table below source	4 m

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*Examples*

Vertical Dispersion Coefficient (model calculated)	0.6 m <sup>2</sup> /yr
Retardation factor, Rd	100
Porosity	0.3 cm <sup>3</sup> /cm <sup>3</sup>
Horizontal seepage velocity, Vx	13 m/yr (User specified)
Aquifer Thickness, B	20m
Mixing Depth	3 m (User specified)
Mixing Depth - 2	3 m (User specified)
Depth to top of screen from water table	1 m
Depth to bottom of screen from water table	3 m
Scale Distance for Dispersion Calculation	150 m
Horizontal Dispersion Coefficient, Dx (model calculated)	195 m <sup>2</sup> /yr
Transverse Dispersion Coefficient, Dy (model calculated)	19.5 m <sup>2</sup> /yr
Vertical Dispersion Coefficient, Dz (model calculated)	1.95 m <sup>2</sup> /yr
pH Value	7
Background Concentration	0 mg/l

Step by step instructions for entering the modeling data are described below. To begin, close MYGRT if it is open and start MYGRT using the Start button and Programs menu. Press the OK button to close the *About* screen. The completed example is "Example1.myg", which you can use to compare your results.

<b>Step</b>	<b>Using Screen</b>	<b>Instruction</b>
1	Main	Double-click the title bar to maximize the <i>Main</i> screen.
2	Main	Select <b>Input   Setup</b> to display the <i>Setup</i> screen.
3	Setup	Edit values and make selections as indicated below. This is illustrated in Figure 9-2.

## Setup Screen:

Field	Value or Selection
Site Name	Ash Landfill-with closure
Case	Example 1
Solute	Arsenic
Solute Type	Inorganic
Units	Metric
Units for Concentration, Input	mg/l
Units for Concentration, Output	ug/l
Colors in Screen Graphics	16.7M

**Setup**

**Titles**

Site Name: Ash Landfill-with closure

Case: Example 1

Solute: Arsenic

**Solute Type**

Inorganic

Organic

**Units**

English

Metric

**Units for Concentration**

Input: mg/l

Output: ug/l

**Colors in Screen Graphics**

256

16.7 M

**Current Model Selection**

Change

Calculation Layer: Unsaturated/Saturated  
 Source Location: Unsaturated  
 Saturated Dimension: 3D  
 Saturated Result Concentration: Well Screen Average  
 Saturated Aquifer Thickness: Finite  
 Saturated Down Gradient Zones: 1

OK Cancel Help

Figure 9-2  
Setup screen as seen when step 6 is completed.

Examples

Step	Using Screen	Instruction
4	Setup	Press the Change button to display the <i>Setup Model</i> screen.
5	Setup Model	Edit values and make selections as indicated below. This is illustrated in Figure 9-3.

Setup Model Screen:

Field	Value or Selection
Calculation Zone Restriction	Unsaturated and Saturated
Source Location	Unsaturated Zone
Saturated Dimensions	3D Saturated
Saturated Result Concentration	Well Screen Average
Saturated Aquifer Thickness Calculation	Finite

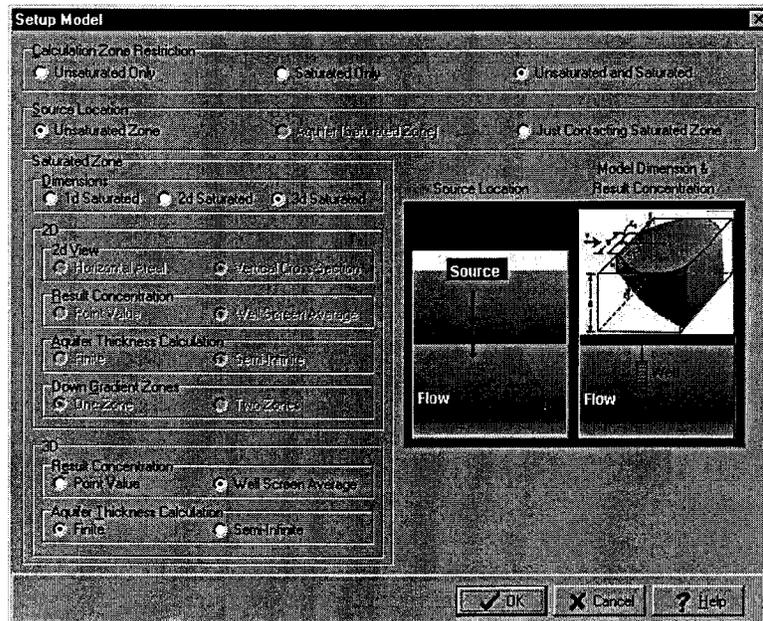


Figure 9-3  
Setup Model screen

Step	Using Screen	Instruction
6	Setup Model	Press the OK button to return close the <i>Setup Model</i> screen and return to the <i>Setup</i> screen.
7	Setup	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the <i>Unsaturated Zone Properties</i> screen.
8	Unsaturated Zone Prop. (Source)	The <i>Source</i> page is displayed.
9	Unsaturated Zone Prop. (Source)	Press the Source Data button to display the <i>Source Concentration</i> screen.
10	Source Concentration	Edit values and make selections as indicated below. This is illustrated in Figure 9-4.

### Source Concentration

Source Data: In 1955 source concentration is set to 1 mg/l, in 1990 site is capped and concentration drops to 0.0

Field (Time On, yrs)	Value or Selection (Conc, mg/l)
1955	1.0
1990	0.0

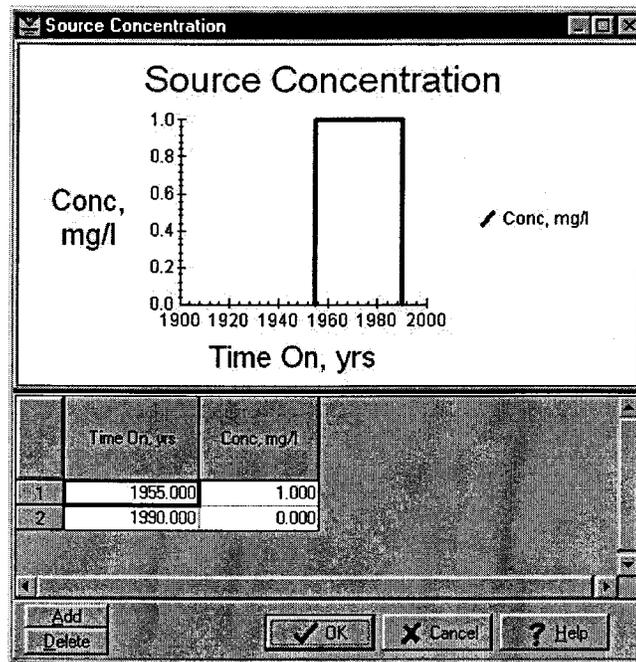
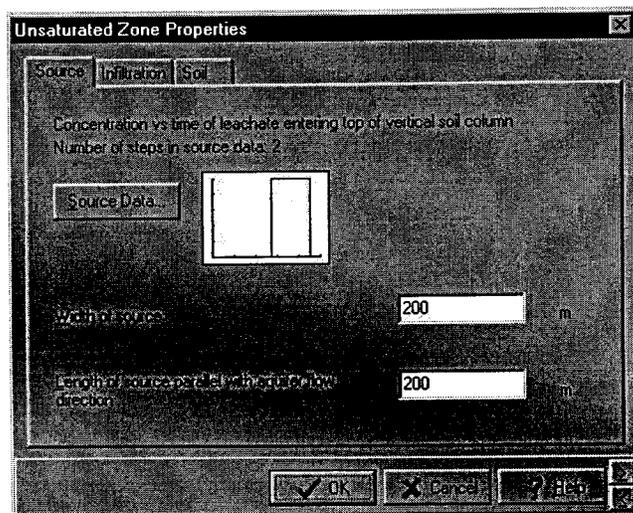


Figure 9-4  
Example 1, Source Concentrations

Step	Using Screen	Instruction
11	Source Concentration	Press the OK button to return to the <i>Unsaturated Zone Properties</i> screen.
12	Unsaturated Zone Prop. (Source)	Edit values and make selections as indicated below. This is illustrated in Figure 9-5.

**Unsaturated Zone Properties (Source Page)**

Field	Value or Selection
Width of source	200 m
Length of source parallel with aquifer flow direction	200 m



**Figure 9-5**  
**Unsaturated Zone Properties (Source Page) screen**

Examples

Step	Using Screen	Instruction
13	Unsaturated Zone Prop. (Source)	Press the Infiltration tab to display the <i>Infiltration</i> page.
14	Unsaturated Zone Prop. (Infiltration)	Edit values and make selections as indicated below. This is illustrated in Figure 9-6.

Unsaturated Zone Properties (Infiltration Page)

Field	Value or Selection
Vertical Infiltration Rate	0.3 m/yr
Use the same rate for aquifer penetration calculation	checked
Use Infiltration Rate Substitution	checked
New Vertical Infiltration Rate	0.0254 m/yr
At Time	1990 yr.

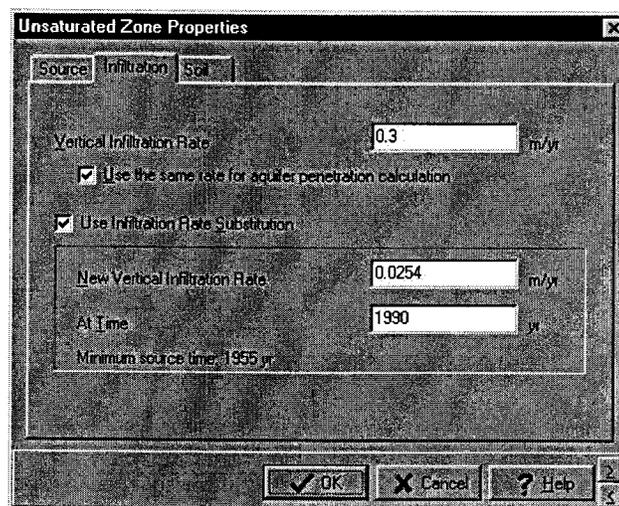


Figure 9-6  
Unsaturated Zone Properties (Infiltration Page)

Step	Using Screen	Instruction
15	Unsaturated Zone Prop. (Infiltration)	Press the Soil tab to display the <i>Soil</i> page.
16	Unsaturated Zone Prop. (Soil)	Edit values and make selections as indicated below. This is illustrated in Figure 9-7.

### Unsaturated Zone Properties (Soil Page)

Field	Value or Selection
Vertical Dispersion Coefficient	Model calculated
Volumetric Moisture Content	0.2 cm <sup>3</sup> /cm <sup>3</sup>
Depth to water table below source	4 m
Vertical Dispersion Coefficient (model calculated)	0.6 m <sup>2</sup> /yr
Retardation factor, Rd	100

The screenshot shows a dialog box titled "Unsaturated Zone Properties" with three tabs: "Source", "Infiltration", and "Soil". The "Soil" tab is active. It contains several input fields and a radio button selection:

- Vertical Dispersion Coefficient:** A radio button selection with "Model calculated" selected and "User specified" unselected.
- Volumetric Moisture Content:** A text box containing "0.2" with units "cm<sup>3</sup>/cm<sup>3</sup>".
- Depth to water table below source:** A text box containing "4" with units "m".
- Vertical Dispersion Coefficient:** A text box containing "0.6" with units "m<sup>2</sup>/yr". A "Calc" button is located to the left of this field.
- Retardation factor, Rd:** A text box containing "100".
- Decay Rate:** A text box containing "0" with units "1/yr".

At the bottom of the dialog box are three buttons: "OK", "Cancel", and "Help".

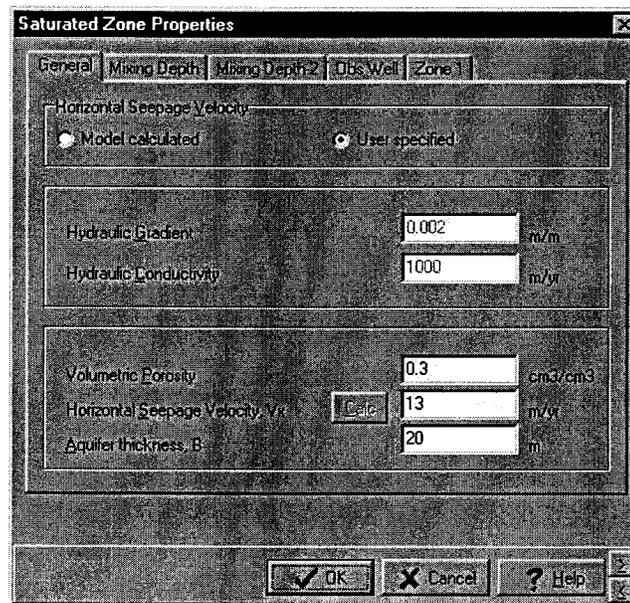
Figure 9-7  
Unsaturated Zone Properties (Soil Page)

Examples

Step	Using Screen	Instruction
17	Unsaturated Zone Prop. (Soil)	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the <i>Saturated Zone Properties</i> Screen.
18	Saturated Zone Prop. (General)	The <i>General</i> page is displayed.
19	Saturated Zone Prop. (General)	Edit values and make selections as indicated below. This is illustrated in Figure 9-8.

**Saturated Zone Properties (General Page)**

Field	Value or Selection
Horizontal Seepage Velocity	User specified
Volumetric Porosity	0.3 cm <sup>3</sup> /cm <sup>3</sup>
Horizontal Seepage Velocity, V <sub>x</sub>	13 m/yr
Aquifer thickness, B	20m



**Figure 9-8**  
**Saturated Zone Properties (General Page)**

Step	Using Screen	Instruction
20	Saturated Zone Prop. (General)	Press the Mixing Depth tab to display the <i>Mixing Depth</i> page.
21	Saturated Zone Prop. (Mixing Depth)	Edit values and make selections as indicated below. This is illustrated in Figure 9-9.

### Saturated Zone Properties (Mixing Depth Page)

Field	Value or Selection
Mixing Depth	User specified
Mixing Depth	3 m

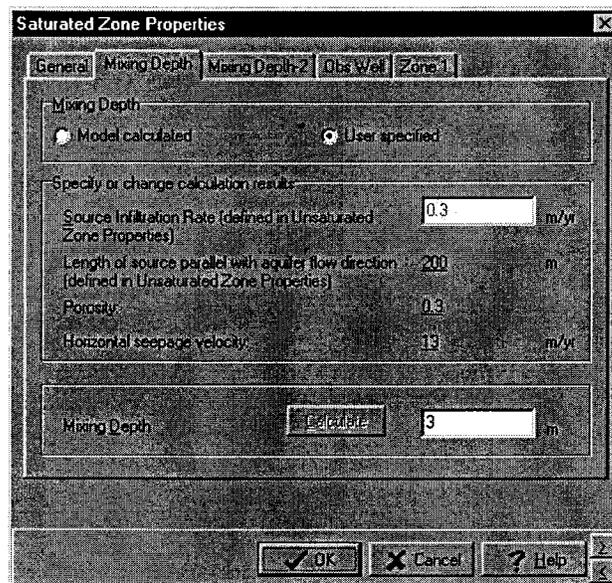


Figure 9-9  
Saturated Zone Properties (Mixing Depth Page)

Examples

Step	Using Screen	Instruction
22	Saturated Zone Prop. (Mixing Depth)	Press the Mixing Depth-2 tab to display the <i>Mixing Depth-2</i> page.
23	Saturated Zone Prop. (Mixing Depth-2)	Edit values and make selections as indicated below. This is illustrated in Figure 9-10.

Saturated Zone Properties (Mixing Depth-2 Page)

Field	Value or Selection
Mixing Depth After Substitution of Second Infiltration Rate	User specified
Mixing Depth	3 m

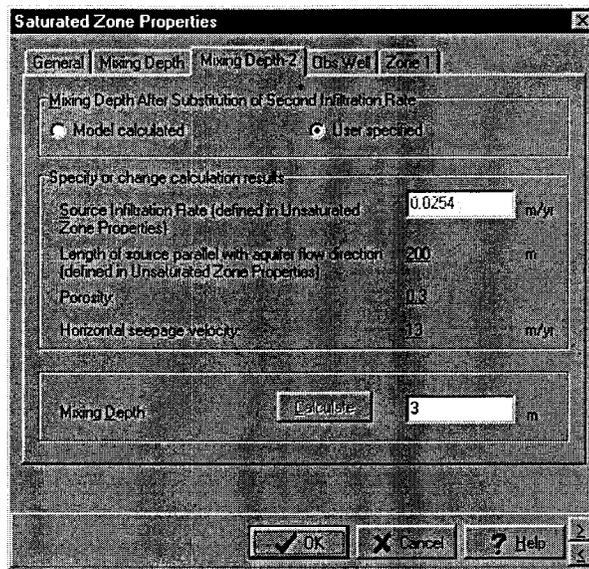


Figure 9-10  
Saturated Zone Properties (Mixing Depth-2 Page)

Step	Using Screen	Instruction
24	Saturated Zone Prop. (Mixing Depth-2)	Press the Obs Well tab to display the <i>Obs Well</i> page.
25	Saturated Zone Prop. (Obs Well)	Edit values and make selections as indicated below. This is illustrated in Figure 9-11.

### Saturated Zone Properties (Obs Well Page)

Field	Value or Selection
Depth to top of screen from water table	1 m
Depth to bottom of screen from water table	3 m

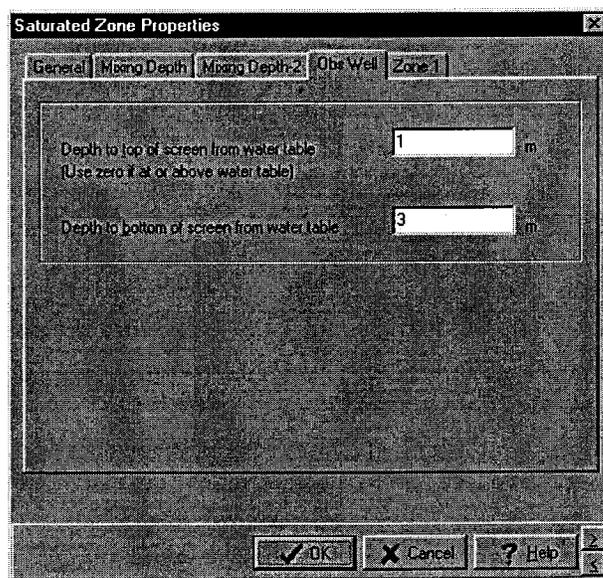


Figure 9-11  
Saturated Zone Properties (Obs Well Page)

Examples

Step	Using Screen	Instruction
26	Saturated Zone Prop. (Obs Well)	Press the Zone 1 tab to display the Zone 1 page.
27	Saturated Zone Prop. (Zone 1)	Edit values and make selections as indicated below. This is illustrated in Figure 9-12.

Saturated Zone Properties (Zone 1 Page)

Field	Value or Selection
Dispersion	Model calculated
Scale Distance for Dispersion Calculation	150 m

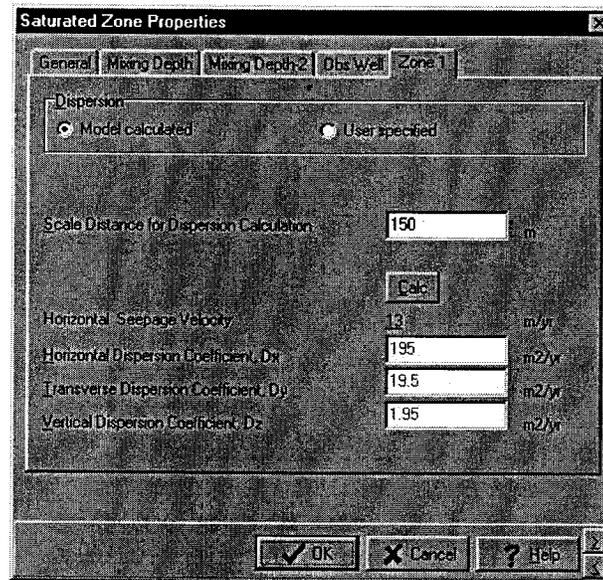


Figure 9-12  
Saturated Zone Properties (Zone 1 Page) screen

Step	Using Screen	Instruction
28	Saturated Zone Prop. (Zone 1)	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the <i>Plume Description</i> Screen.
29	Plume Description (Down Gradient Zone 1)	The <i>Down Gradient Zone 1</i> page is displayed.
30	Plume Description (Down Gradient Zone 1)	Edit values and make selections as indicated below. This is illustrated in Figure 9-13.

### Solute Plume Properties (Down Gradient Zone 1)

Field	Value or Selection
Retardation Factor	User specified
pH Value	7
Background Conc	0 mg/l
Retardation factor, Rd	100

**Arsenic Plume Description**

Downgradient Zone

Retardation Factor  
 Model calculated  User specified

Bulk Density, g/ml: 1.6      pH Value: 7      Background Conc: 0 mg/l

Inorganic Chemicals  
 Partition coef. Kd: 2 m/g      Retardation factor, Rd: 100

Organic Chemicals  
 Octanol-Water Partition Coefficient: 5  
 Fraction of arsenic carbon content: 0.001  
 Partition coef. Kp: 5 m/g      Retardation factor, Rd: 1  
 Decay Rate: 0 1/yr

OK Cancel Help

**Figure 9-13**  
**Solute Plume Properties (Down Gradient Zone 1)**

Step	Using Screen	Instruction
31	Plume Description (Down Gradient Zone 1)	Press the OK button to close the screen.

## Plotting Results for Example 1

We will now make a plot of concentration versus time for an observation well located at the distance X=150 m, Y=0 m in the aquifer. See Run Options screen for details on entering distances, depths, and times. Our goal is to determine the maximum concentration of the plume at this location. Specifying 200 plotting points for the output graph will produce a detailed graph of the predicted concentration curve. The beginning and ending simulation times of the output plot need to be chosen. Unfortunately, it is not always obvious what these values should be. Picking a simulation time window too early will miss the leading edge of the plume and picking a time window too late will either miss the trailing edge or the maximum value of the plume. In addition, a very narrow plume may not even show up on a graph if too few plotting points are used. Specifying too many plotting points will un-necessarily slow down the plotting process. The user can always use trial-and-error guessing for the plotting time window but a better estimate can be made if the travel time of the plume is used.

When trying to determine the maximum concentration of the plume, the simulation time window should be bracketed around the following estimate of the travel time, which is only based on advection:

$$\text{Advected Travel Time} = \frac{(\text{Travel Distance}) * (\text{Retardation Coefficient})}{(\text{Seepage Velocity})}$$

### Before Closure

Unsaturated layer travel	= (4 m)*(100)/(0.3 m/yr)	= 1330
Aquifer layer travel	= (150 m)*(100)/(13 m/yr)	= 1153
Total travel date	= 1955 + 1330 + 1153	= Year 4438

### After Closure

Unsaturated layer travel	= (4 m)*(100)/(0.025 m/yr)	= 16000
Aquifer layer travel	= (150 m)*(100)/(13 m/yr)	= 1153
Total travel date	= 1955 + 16000 + 1153	= Year 19000

Select simulation time between the years 1955 and 19000.

Step	Using Screen	Instruction
32	Main	Select <b>Run   Options</b> to display the <i>Run Options</i> screen.

33 Run Options

Edit values and make selections as indicated below. This is illustrated in Figure 9-14.

Run Options

Field	Value or Selection
The "Use" checkbox for C vs. t (Concentration vs. Time)	Checked
Number of Distances	1
Simulated Time (start)	1955
Simulated Time (end)	19000
X Distance	150
Y Distance	0
Number of Points	200

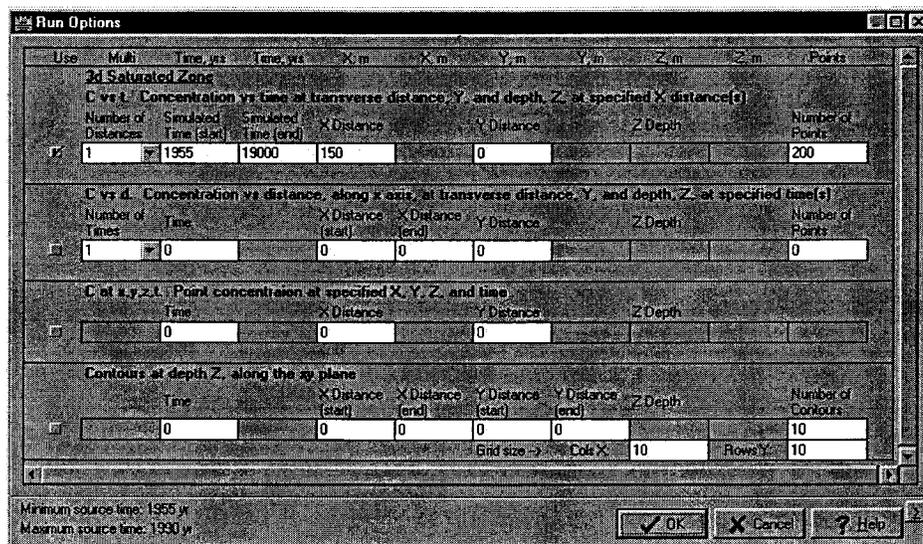


Figure 9-14 Run Options screen

Examples

Step	Using Screen	Instruction
34	Run Options	Press OK to close the screen.
35	Main	Select <b>Run   Run Model</b> to display the <i>Perform Calculation</i> screen.
36	Perform Calculation	Press the Run1 button to start the calculations. After the calculations are complete, a message indicates the number of points calculated. Press the OK button to return to the <i>Main Screen</i> .
37	Main	Select <b>Results   Generate Plots</b> to display the plots for the run options selected earlier. See generated plot in Figure 9-15.

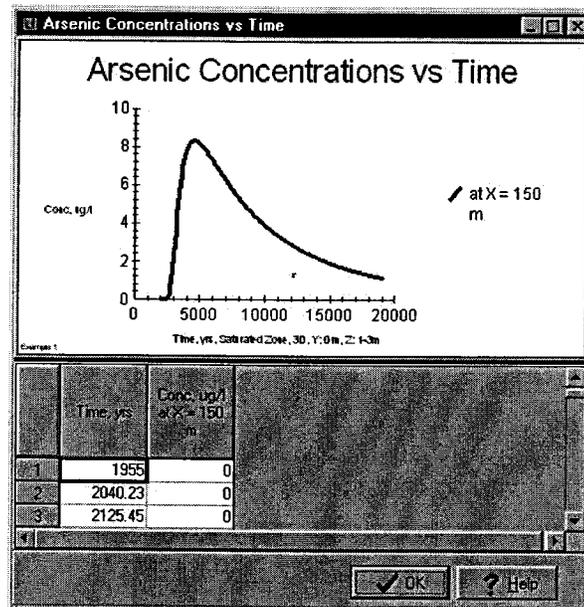


Figure 9-15  
Example 1, Plot of Calculated Results

Step	Using Screen	Instruction
38	Arsenic Concentrations vs Time	Press the OK button to close the plot screen.
39	Main Screen	Select <b>File   Save As</b> to display the <i>Save As</i> screen
40	Save As	Enter "MyExample1" for the File name, and press the Save button to save the project file and close the screen.

## Example 2 Ash Landfill Concentration Contours

Building on the first example, we will go through the steps to display the concentration contours in the XY plane from Example 1. Select the menu **File | Open** to open the project file "MyExample1.myg". If you have not finished example 1 you can open the completed project file "Example1.myg" to start this example. The completed example is "Example2.myg", which you can use to compare your results.

Step	Using Screen	Instruction
1.	Main	Double-click the title bar to maximize the <i>Main</i> screen.
2	Main	Select <b>Run   Options</b> to display the <i>Run Options</i> screen.
3	Run Options	Edit values and make selections as indicated below. This is illustrated in Figure 9-16.

### Run Options Screen

Field	Value or Selection
The "Use" checkbox for Contours at depth Z along the xy plane.	Checked. Uncheck all other checkboxes.
Time	5000
X Distance (start)	0
X Distance (end)	500
Y Distance (start)	-250
Y Distance (end)	250
Number of Contours	10
Grid Size, Cols X	25
Grid Size, Rows Y	25

Examples

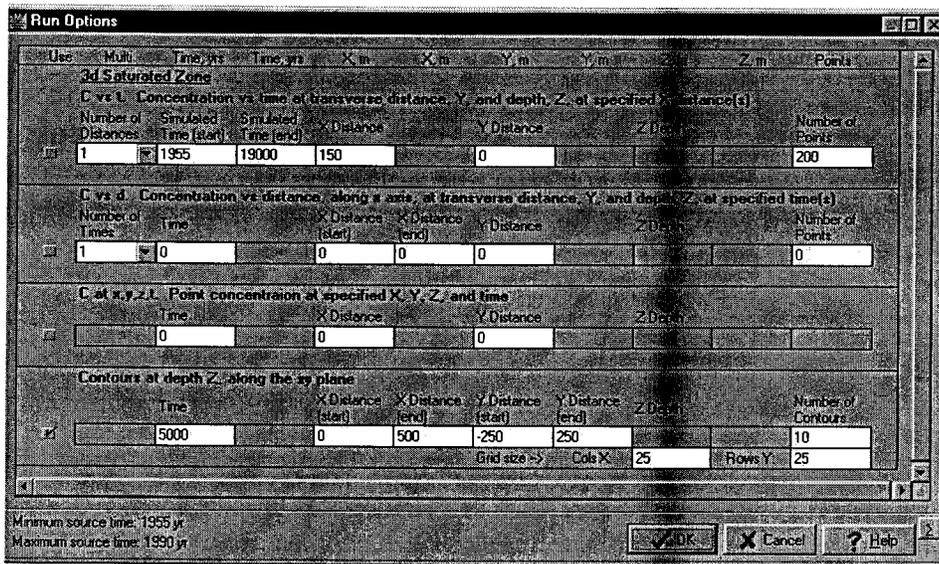


Figure 9-16  
Run Options Screen

Step	Using Screen	Instruction
4	Run Options	Press OK to close the screen.
5	Main	Select <b>Run   Run Model</b> to display the <i>Perform Calculation</i> screen. This calculation takes 4 minutes on a Pentium 450 MHz.
6	Perform Calculation	Press the Run button to start the calculations. After the calculations are complete, a message indicates the number of points calculated. Press the OK button to return to the <i>Main Screen</i> .
7	Main	Select <b>Results   Generate Plots</b> to display the plots for the run options selected earlier. See generated plot in Figure 9-17.

Selecting the run option “Contours at depth Z, along the xy plane” shows the contour plot shown below.

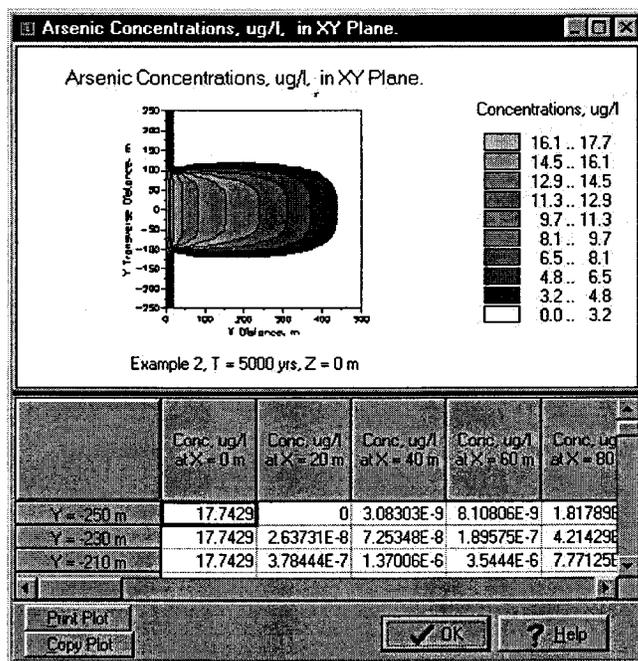
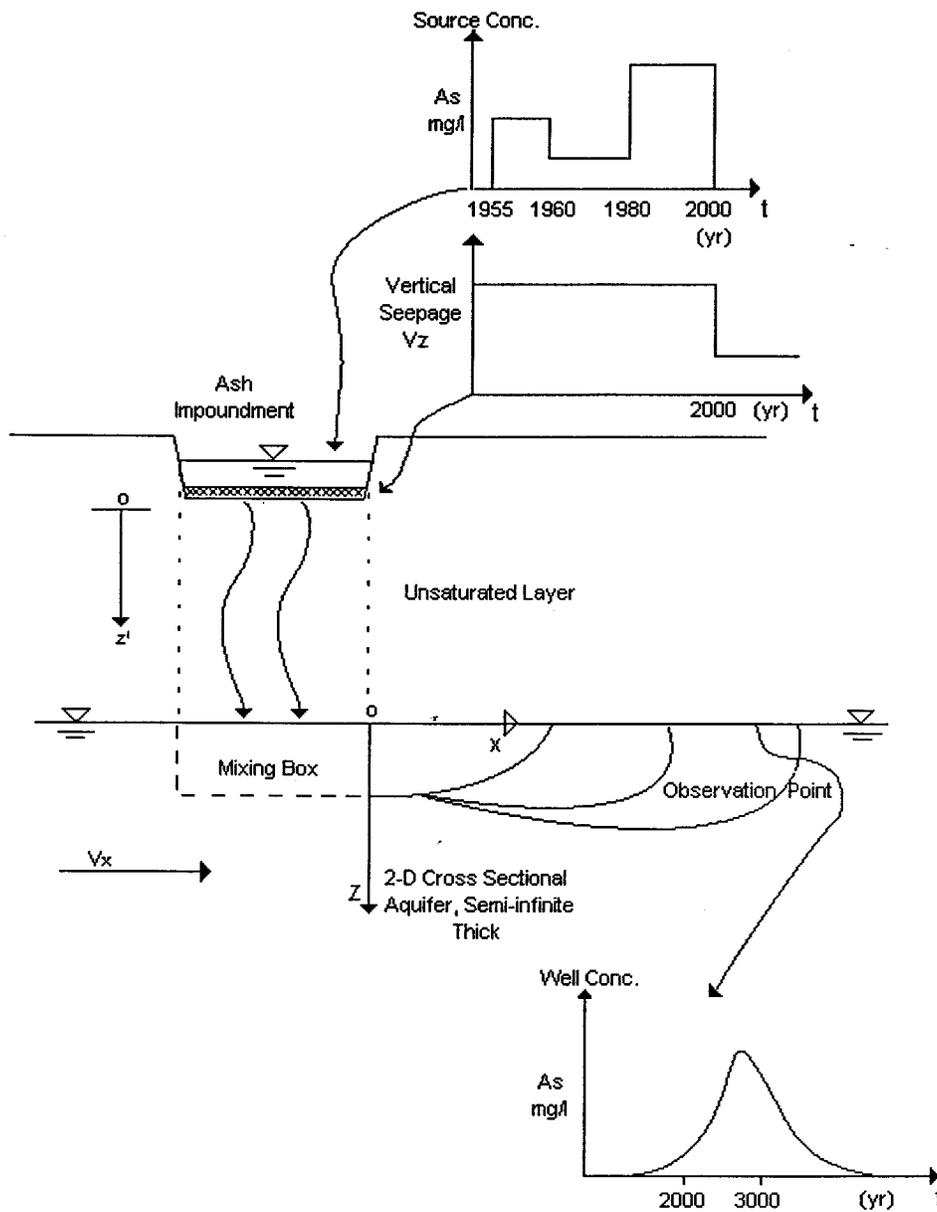


Figure 9-17  
Example 2, Concentration Contours

Step	Using Screen	Instruction
8	Arsenic Concentrations in XY Plane	Press the OK button to close the plot screen.

### **Example 3 Ash Impoundment**

In this example, we wish to simulate leachate migration of boron from a pond containing bottom ash, downward movement through the unsaturated layer, then into a two-dimensional, cross-sectional aquifer of semi-infinite thickness. The pond is so large that there is no need to simulate the transverse (Y axis) transport. In addition, we want to know what effect capping (i.e., reduced infiltration) of the pond source has on the off-site migration. A schematic of the problem is given in Figure 9-18.



10-1201

Figure 9-18  
Example 3, Schematic

The unlined pond is 50 m long (measured parallel to the groundwater flow direction) and 200m wide(measured perpendicular to groundwater flow direction). An observation well is located 80 m down gradient of the pond and is screened in the

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## Examples

aquifer between 0 to 5 meters below the water table. Since the observation point is much closer than the pond width, there is no need to simulate-transverse (if any) migration of boron. Underlying the unsaturated layer is a 300 m thick aquifer that is moving with a seepage velocity of 20 m/yr and has a porosity of  $0.3 \text{ cm}^3/\text{cm}^3$ . On-site monitoring wells indicated that landfill leachate was penetrating 40 meters into the aquifer at the down gradient edge of the landfill. This mixing depth is estimated to be only 30 m deep after capping. We wish to estimate the maximum concentration of boron that will ever reach the observation well.

The boron concentration in the pond varied over time because of significant changes in the bottom ash composition. The unlined pond received its first quantity of bottom ash sluice in 1955. The boron concentration in the pond water was a constant value of 1 mg/l between 1955 and 1960. The vertical seepage rate under the pond is estimated to be 1 m/yr and the moisture content to be  $0.2 \text{ cm}^3/\text{cm}^3$ . Between 1960 and 1980, the boron concentration was about 0.2 mg/l. A switch in coal source resulted in a boron concentration of 4 mg/l in the pond water in 1980 and is expected to remain at that level until the year 2000. The pond will be completely deactivated in the year 2000. The bottom ash is being removed and reused. The pond will be capped to reduce rain infiltration to  $\frac{1}{2}$  the prior seepage rate (i.e., reduced to 0.5 m/yr). No additional boron leachate will be allowed to enter the soil but the underlying unsaturated soil and aquifer still contain boron from migration prior to the year 2000.

The most realistic scenario for this problem is to model the leachate as it moves vertically down through the one-dimensional unsaturated soil, mixes with the underlying water table and then moves down gradient through the two dimensional, semi-infinite thick aquifer.

### Data Summary of Example 3

All of the modeling data are summarized below:

Field	Value or Selection
Site Name	Pond-closure
Case	Example 3
Solute	Boron
Solute Type	Inorganic
Units	Metric
Units for Concentration, Input	mg/l
Units for Concentration, Output	ug/l

Colors in screen graphics	16.7M
Calculation Zone Restriction	Unsaturated and Saturated
Source Location	Unsaturated Zone
Saturated Dimensions	2D Saturated
Saturated 2D View	Vertical Cross-Section
Saturated Result Concentration	Well Screen Average
Saturated Aquifer Thickness Calculation	Semi-Infinite
Width of source	200 m
Length of source parallel with aquifer flow direction	50 m
Vertical Infiltration Rate	1.0 m/yr
Use the same rate for aquifer penetration calculation	Checked
Use Infiltration Rate Substitution	Checked
New Vertical Infiltration Rate	0.5 m/yr
At Time	2000 yr.
Vertical Dispersion Coefficient	(Model calculated)
Volumetric Moisture Content	0.2 cm <sup>3</sup> /cm <sup>3</sup>
Depth to water table below source	4m
Retardation factor, Rd	11
Volumetric Porosity	0.3 cm <sup>3</sup> /cm <sup>3</sup>
Horizontal Seepage Velocity, Vx	20 m/yr (User specified)
Aquifer thickness, B	300 m
Mixing Depth	40 m (User specified)
Mixing Depth - 2	30 m (User specified)
Depth to top of screen from water table	0 m
Depth to bottom of screen from water table	5 m
Horizontal Dispersion Coefficient, Dx (model calculated)	160 m <sup>2</sup> /yr (User specified)

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*Examples*

Transverse Dispersion Coefficient, Dy (model calculated)	16 m <sup>2</sup> /yr (User specified)
Vertical Dispersion Coefficient, Dz (model calculated)	2 m <sup>2</sup> /yr (User specified)
pH Value	7
Background Conc	0 mg/l
Retardation factor, Rd	11 (User specified)
Use Check box for C vs. t (Concentration vs. Time)	Checked
Number of Distances	1
Simulated Time (start)	1955
Simulated Time (end)	2500
X Distance	80
Number of Points	200

Step by step instructions for entering the modeling data are described below. To begin, close MYGRT if it is open and start MYGRT using the Start button and Programs menu. The completed example is "Example3.myg", which you can use to compare your results.

Step	Using Screen	Instruction
1.	Main	Double-click the title bar to maximize the <i>Main</i> screen.
2	Main	Select <b>Input   Setup</b> to display the <i>Setup</i> screen.
3	Setup	Edit values and make selections as indicated below. This is illustrated in Figure 9-19.

## Setup Screen:

Field	Value or Selection
Site Name	Pond-closure
Case	Example 3
Solute	Boron
Solute type	Inorganic
Units	Metric
Units for Concentration, Input	mg/l
Units for Concentration, Output	ug/l
Colors in screen graphics	16.7M

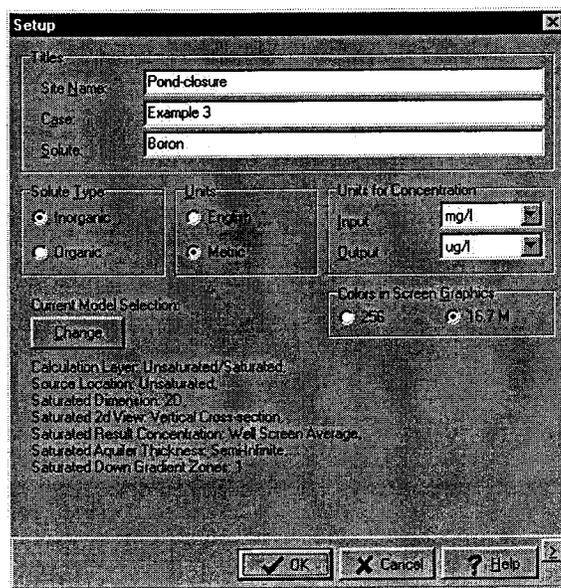


Figure 9-19  
Setup screen as seen when step 6 is completed.

Examples

Step	Using Screen	Instruction
4	Setup	Press the Change button to display the <i>Setup Model</i> screen.
5	Setup Model	Edit values and make selections as indicated below. This is illustrated in Figure 9-20.

Setup Model Screen:

Field	Value or Selection
Calculation Zone Restriction	Unsaturated and Saturated
Source Location	Unsaturated Zone
Saturated Dimensions	2D Saturated
2D View	Vertical Cross-Section
Saturated Result Concentration	Well Screen Average
Saturated Aquifer Thickness Calculation	Semi-Infinite

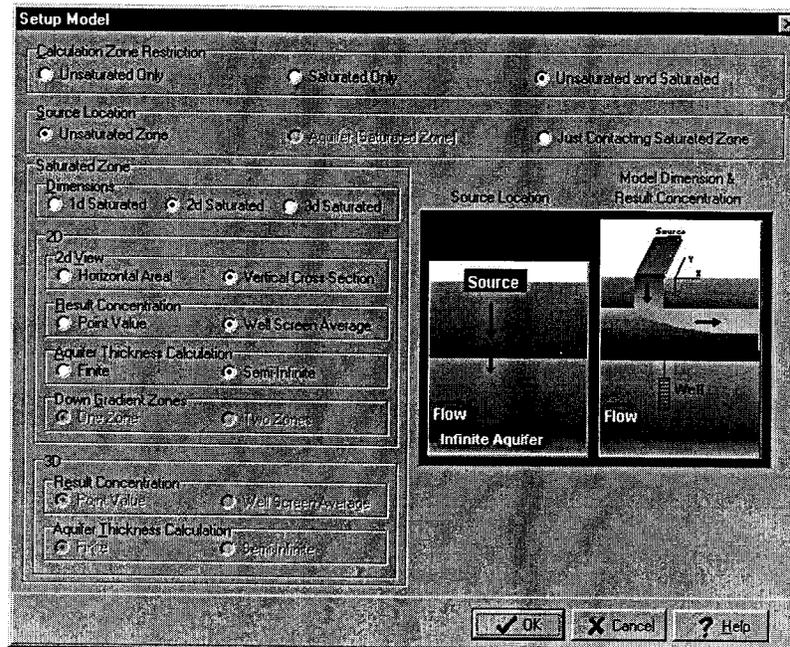


Figure 9-20  
Setup Model Screen

Step	Using Screen	Instruction
6	Setup Model	Press the OK button to return close the <i>Setup Model</i> screen and return to the <i>Setup</i> screen.
7	Setup	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the <i>Unsaturated Zone Properties</i> Screen.
8	Unsaturated Zone Prop. (Source)	The <i>Source</i> page is displayed.
9	Unsaturated Zone Prop. (Source)	Press the Source Data button to display the <i>Source Concentration</i> screen.
10	Source Concentration	Edit values and make selections as indicated below. This is illustrated in Figure 9-21.

### Source Concentration

Source Data – 1 mg/l between the years 1955 and 1960, 0.2 mg/l between 1960 and 1980, 4. mg/l between 1980 and 2000

Field (Time On, yrs)	Value or Selection (Conc, mg/l)
1955	1.0
1960	0.2
1980	4
2000	0

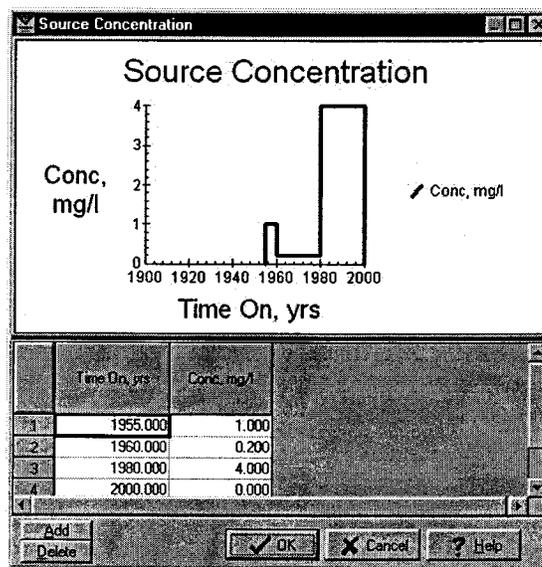


Figure 9-21  
Example 3, Source Concentrations

Examples

Step	Using Screen	Instruction
11	Source Concentration	Press the OK button to return to the <i>Unsaturated Zone Properties</i> screen.
12	Unsaturated Zone Prop. (Source)	Edit values and make selections as indicated below. This is illustrated in Figure 9-22.

Unsaturated Zone Properties (Source Page)

Field	Value or Selection
Width of source	200 m
Length of source parallel with aquifer flow direction	50 m

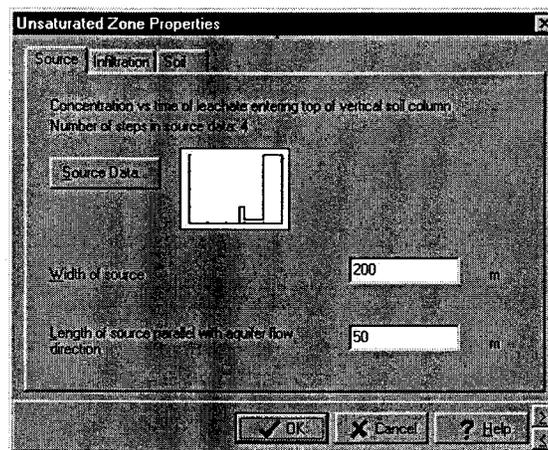


Figure 9-22  
Unsaturated Zone Properties (Source Page)

Step	Using Screen	Instruction
13	Unsaturated Zone Prop. (Source)	Press the Infiltration tab to display the <i>Infiltration</i> page.
14	Unsaturated Zone Prop. (Infiltration)	Edit values and make selections as indicated below. This is illustrated in Figure 9-23.

### Unsaturated Zone Properties (Infiltration Page)

Field	Value or Selection
Vertical Infiltration Rate	1.0 m/yr
Use the same rate for aquifer penetration calculation	Checked
Use Infiltration Rate Substitution	Checked
New Vertical Infiltration Rate	0.5 m/yr
At Time	2000 yr.

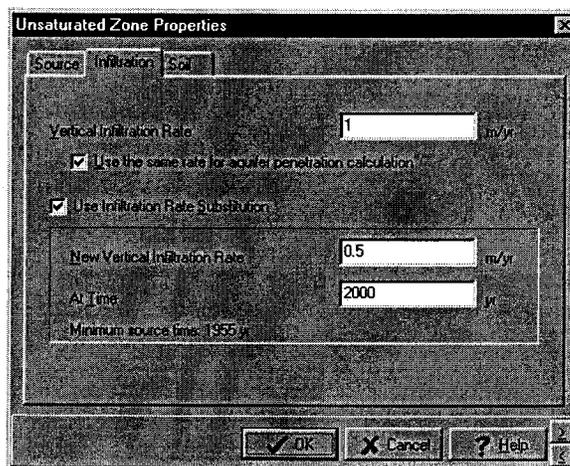


Figure 9-23  
Unsaturated Zone Properties (Infiltration Page)

Examples

Step	Using Screen	Instruction
15	Unsaturated Zone Prop. (Infiltration)	Press the Soil tab to display the <i>Soil</i> page.
16	Unsaturated Zone Prop. (Soil)	Edit values and make selections as indicated below. This is illustrated in Figure 9-24.

Unsaturated Zone Properties (Soil Page)

Field	Value or Selection
Vertical Dispersion Coefficient	Model calculated
Volumetric Moisture Content	0.2 cm <sup>3</sup> /cm <sup>3</sup>
Depth to water table below source	4 m
Vertical Dispersion Coefficient (model calculated)	2 m <sup>2</sup> /yr
Retardation factor, Rd	11

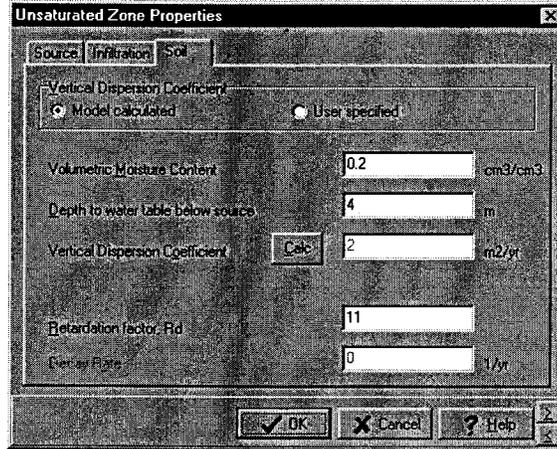


Figure 9-24  
Unsaturated Zone Properties (Soil Page)

Step	Using Screen	Instruction
17	Unsaturated Zone Prop. (Soil)	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the <i>Saturated Zone Properties</i> Screen.
18	Saturated Zone Prop. (General)	The <i>General</i> page is displayed.
19	Saturated Zone Prop. (General)	Edit values and make selections as indicated below. This is illustrated in Figure 9-25.

### Saturated Zone Properties (General Page)

Field	Value or Selection
Horizontal Seepage Velocity	User specified
Volumetric Porosity	0.3 cm <sup>3</sup> /cm <sup>3</sup>
Horizontal Seepage Velocity, V <sub>x</sub>	20 m/yr
Aquifer thickness, B	300 m

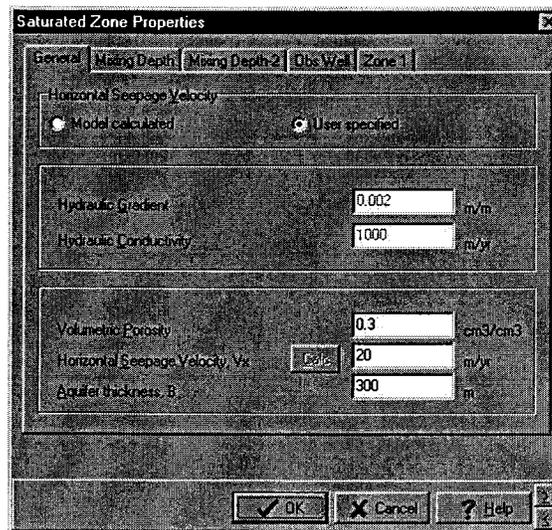


Figure 9-25  
Saturated Zone Properties (General Page)

Examples

Step	Using Screen	Instruction
20	Saturated Zone Prop. (General)	Press the Mixing Depth tab to display the <i>Mixing Depth</i> page.
21	Saturated Zone Prop. (Mixing Depth)	Edit values and make selections as indicated below. This is illustrated in Figure 9-26.

Saturated Zone Properties (Mixing Depth Page)

Field	Value or Selection
Mixing Depth	User specified
Mixing Depth	40 m

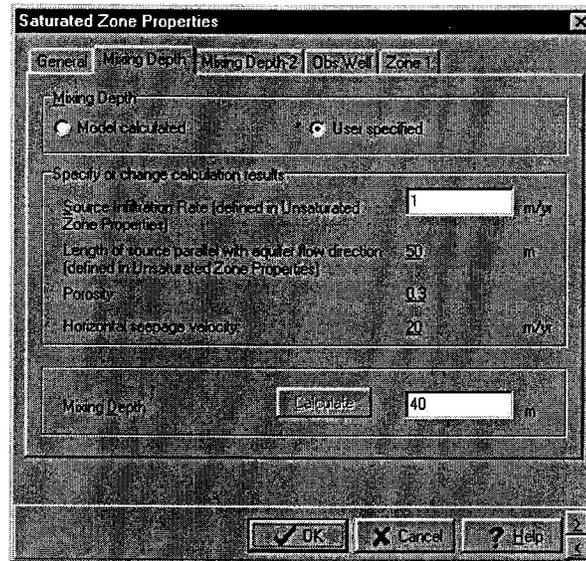


Figure 9-26  
Saturated Zone Properties (Mixing Depth Page)

Step	Using Screen	Instruction
22	Saturated Zone Prop. (Mixing Depth)	Press the Mixing Depth-2 tab to display the <i>Mixing Depth-2</i> page.
23	Saturated Zone Prop. (Mixing Depth-2)	Edit values and make selections as indicated below. This is illustrated in Figure 9-27.

### Saturated Zone Properties (Mixing Depth-2 Page)

Field	Value or Selection
Mixing Depth After Substitution of Second Infiltration Rate	User specified
Mixing Depth	30 m

The screenshot shows the 'Saturated Zone Properties' dialog box with the 'Mixing Depth-2' tab selected. The 'Mixing Depth After Substitution of Second Infiltration Rate' section has 'User specified' selected. The 'Specify or change calculation results' section contains the following values:

Parameter	Value	Unit
Source Infiltration Rate (defined in Unsaturated Zone Properties)	0.5	m/y
Length of source parallel with aquifer flow direction (defined in Unsaturated Zone Properties)	50	m
Porosity	0.3	
Horizontal seepage velocity	20	m/y

The 'Mixing Depth' section shows a value of 30 m. The dialog box includes 'OK', 'Cancel', and 'Help' buttons at the bottom.

Figure 9-27  
Saturated Zone Properties (Mixing Depth-2 Page)

Examples

Step	Using Screen	Instruction
24	Saturated Zone Prop. (Mixing Depth-2)	Press the Obs Well tab to display the <i>Obs Well</i> page.
25	Saturated Zone Prop. (Obs Well)	Edit values and make selections as indicated below. This is illustrated in Figure 9-28.

Saturated Zone Properties (Obs Well Page)

Field	Value or Selection
Depth to top of screen from water table	0 m
Depth to bottom of screen from water table	5 m

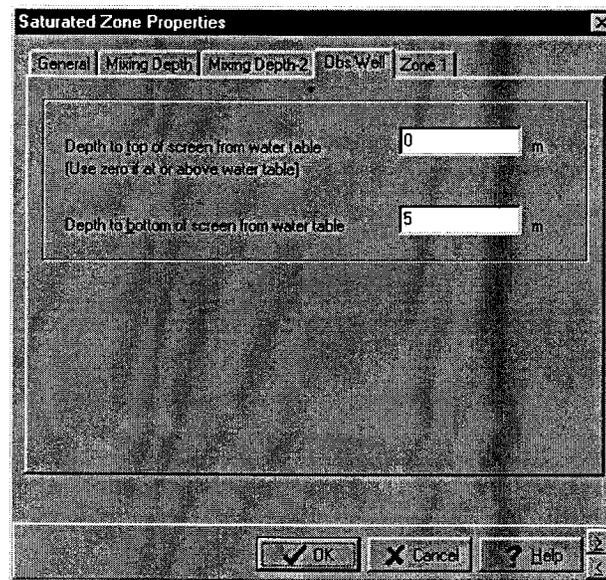
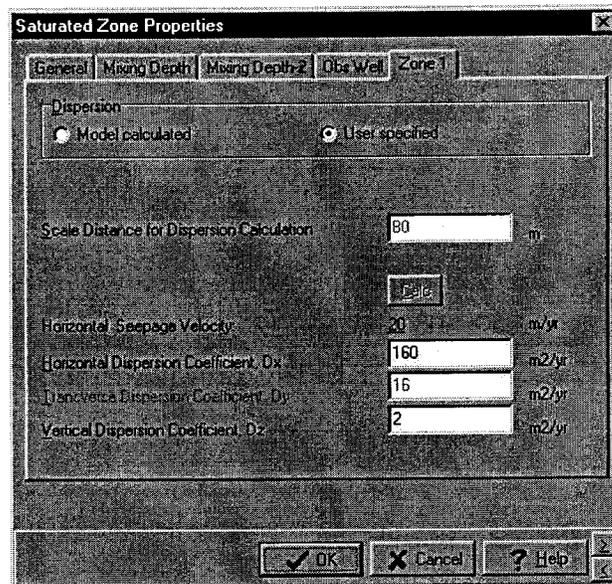


Figure 9-28  
Saturated Zone Properties (Obs Well Page)

Step	Using Screen	Instruction
26	Saturated Zone Prop. (Obs Well)	Press the Zone 1 tab to display the <i>Zone 1</i> page.
27	Saturated Zone Prop. (Zone 1)	Edit values and make selections as indicated below. This is illustrated in Figure 9-29.

**Saturated Zone Properties (Zone 1 Page)**

Field	Value or Selection
Dispersion	User specified
Horizontal Dispersion Coefficient, Dx	160 m <sup>2</sup> /yr
Vertical Dispersion Coefficient, Dz	2 m <sup>2</sup> /yr



**Figure 9-29**  
**Saturated Zone Properties (Zone 1 Page)**

Examples

Step	Using Screen	Instruction
28	Saturated Zone Prop. (Zone 1)	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the <i>Plume Description</i> Screen.
29	Plume Description (Down Gradient Zone 1)	The <i>Down Gradient Zone 1</i> page is displayed.
30	Plume Description (Down Gradient Zone 1)	Edit values and make selections as indicated below. This is illustrated in Figure 9-30.

**Solute Plume Properties (Down Gradient Zone 1)**

Field	Value or Selection
Retardation Factor	User specified
pH Value	7
Background Conc	0 mg/l
Retardation factor, Rd	11

**Figure 9-30**  
**Solute Plume Properties (Down Gradient Zone 1)**

Step	Using Screen	Instruction
31	Plume Description (Down Gradient Zone 1)	Press the OK button to close the screen.
32	Main	Select <b>Run   Options</b> to display the <i>Run Options</i> screen.
33	Run Options	Edit values and make selections as indicated below. This is illustrated in Figure 9-31.

### Run Options

Field	Value or Selection
Use Check box for C vs. t (Concentration vs. Time)	Checked
Number of Distances	1
Simulated Time (start)	1955
Simulated Time (end)	2500
X Distance	80
Number of Points	200

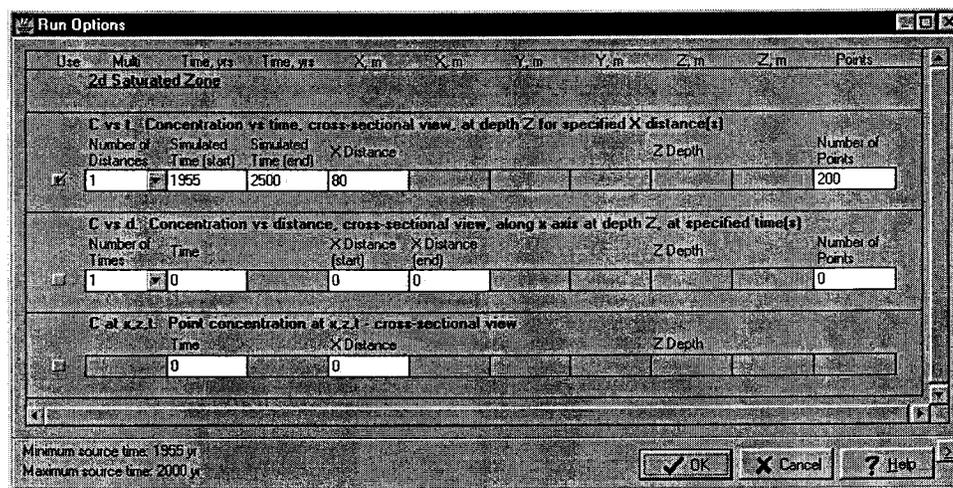


Figure 9-31  
Run Options

Examples

Step	Using Screen	Instruction
34	Run Options	Press OK to close the screen.
35	Main	Select <b>Run   Run Model</b> to display the <i>Perform Calculation</i> screen.
36	Perform Calculation	Press the Run button to start the calculations. After the calculations are complete, a message indicates the number of points calculated. Press the OK button to return to the <i>Main Screen</i> .

### Plotting Results for Example 3

To make a plot of concentration versus time, see Run Options screen for details on entering distances, depths, and times. The plot is shown in Figure 9-32.

Step	Using Screen	Instruction
37	Main	Select <b>Results   Generate Plots</b> to display the plots for the run options selected earlier. See generated plot in Figure 9-32.

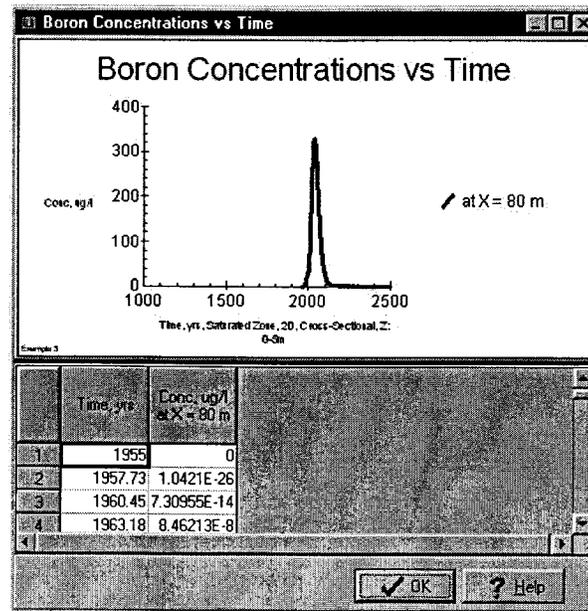


Figure 9-32  
Example 3, Plot of Calculated Results

<b>Step</b>	<b>Using Screen</b>	<b>Instruction</b>
38	Boron Concentrations vs Time	Press the OK button to close the plot screen.

# A

## DESCRIPTION OF INPUT DATA

---

The data needed to run the code can be obtained from limited field measurements or published reports. Procedures for estimating input parameters are presented below.

### *Longitudinal Seepage Velocity*

The longitudinal seepage velocity  $V_x$  (m/yr) can be calculated using a form of Darcy's law. Darcy's law states that the flow velocity is proportional to the hydraulic gradient,  $I_x$ . The proportionality constant,  $K_x$ , is called the saturated hydraulic conductivity. To convert from Darcy velocity to seepage velocity (what MYGRT v 3.0 uses), the Darcy velocity is divided by the aquifer porosity,  $\theta$ :

$$V_x = \frac{K_x I_x}{\theta} \quad (\text{A-1})$$

where

$K_x$  = saturated, horizontal hydraulic conductivity of the aquifer, m/yr

$I_x$  = hydraulic gradient of aquifer, m/m

$\theta$  = porosity, decimal fraction (vol/vol) of aquifer.

The hydraulic gradient,  $I_x$ , is the change in water level elevation over a given distance,  $(H_2 - H_1) / \Delta X$ , preferably between two wells aligned along the predominant direction of flow. Additional information on estimating and measuring these parameters is included in EPRI Reports (EA-4301, EA-4156, and EA-4952; Freeze and Cherry, 1979; U.S. EPA, 1986; and Mills et al. (1985). A one-dimensional example showing the effect of advection is shown in Figure A-1.

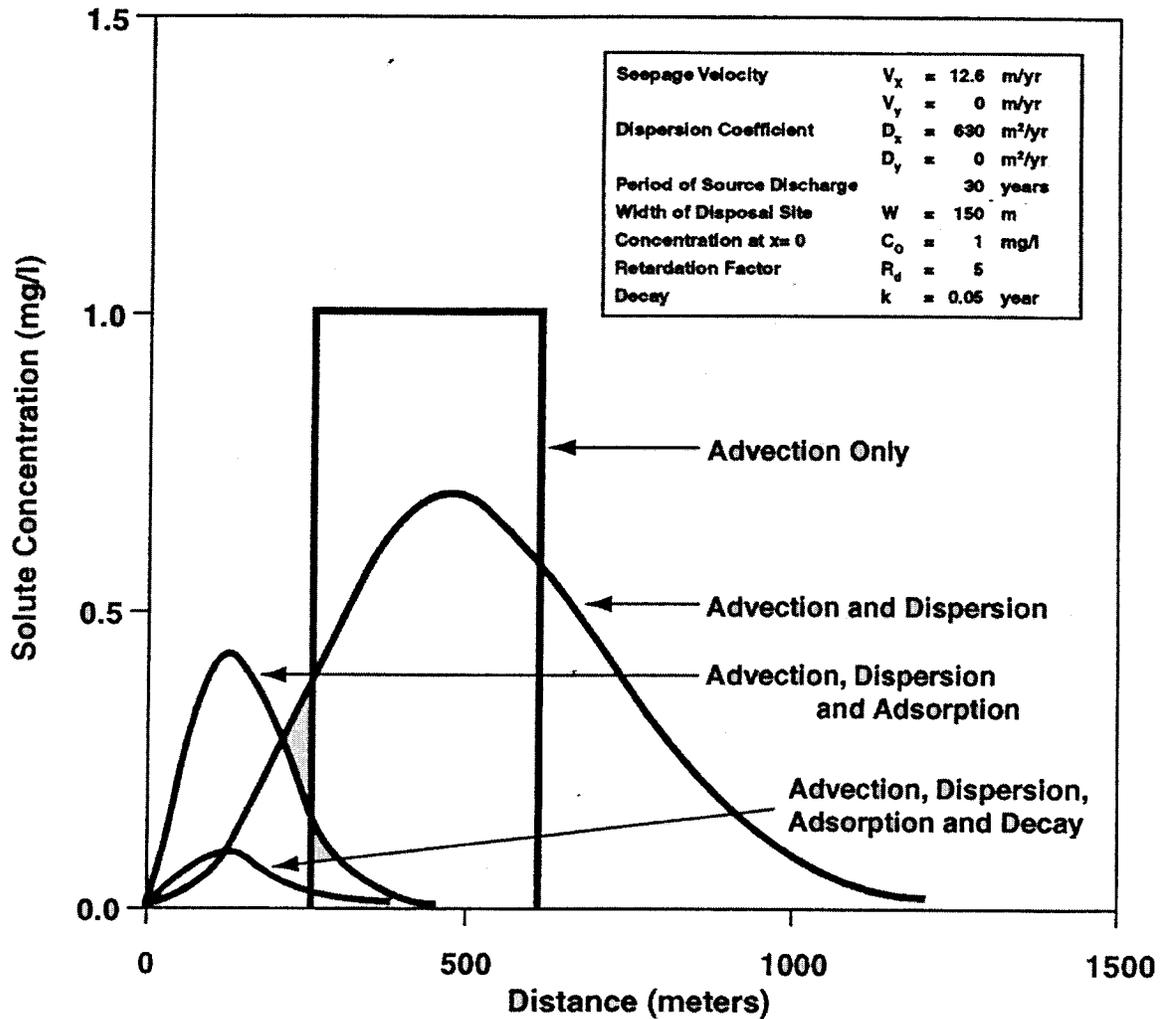


Figure A-1  
A one-dimensional example showing the individual effects of advection, dispersion, adsorption (retardation), and first-order decay.

### Dispersion

Dispersion spreads solutes, causing some to arrive sooner than the average seepage velocity would predict and some to lag behind. It is most likely caused by spatial variations in seepage velocity and flowpaths in a porous medium. Dispersion can be estimated as a function of the longitudinal seepage velocity or from field tracer tests. Site-specific data from tracer tests are not readily available. For screening calculations, approximations can be made as discussed in this section.

For one-dimensional cases, only an estimate of longitudinal dispersion is needed (i.e., along the primary direction of flow). The longitudinal dispersion coefficient  $D_x$  can be estimated as follows (Gelhar et al., 1985).

$$D_x = \alpha_L V_x \quad (\text{A-2})$$

where

$D_x$  = longitudinal dispersion,  $\text{m}^2/\text{yr}$

$\alpha_L$  = longitudinal dispersivity coefficient, m

$V_x$  = average seepage velocity in primary direction of flow,  $\text{m}/\text{yr}$ .

The dispersion coefficient,  $D_x$ , appears to increase with increasing distance from the source. A one-dimensional example showing the effect of dispersion is shown in Figure A-1.

For two-dimensional cases, estimates are needed for both longitudinal dispersion and transverse dispersion (perpendicular to the primary direction of flow). The longitudinal dispersion can be estimated as shown above. The transverse (horizontal or lateral) dispersion ( $\alpha_T$ ) typically is estimated as 0.1 to 0.3 times the longitudinal dispersion.

For three-dimensional cases and cross-sectional 2-D cases, estimates are also needed for the vertical dispersion. Vertical dispersion is typically much smaller than either longitudinal or transverse dispersion and can be estimated as  $1/10^{\text{th}}$  to  $1/100^{\text{th}}$  times the longitudinal dispersion.

### **Retardation**

A linear, equilibrium sorption constant approach is used for the MYGRT v 3.0 code to represent retardation due to processes such as adsorption and ion-exchange. Other processes are also being investigated under EPRI research on chemical attenuation which may alter the migration of reactive solutes (EA-3356, EA-4544, EA-5741). The code represents sorption using a retardation factor. This factor is defined as follows:

$$R_d = 1 + \frac{K_p \rho_b}{\theta} \quad (\text{A-3})$$

where

$R_d$  = retardation factor (unitless)

---

Description of Input Data

- $K_p$  = solution: solid phase linear partition coefficient (ml/g)
- $\rho_b$  = dry bulk density of permeable material (g/ml)
- $\theta$  = volumetric moisture content (vol/vol) for unsaturated media and porosity for saturated media.

A one-dimensional example showing the effect of retardation is shown in Figure A-1.

The partition coefficient,  $K_p$ , is sometimes referred to as  $K_d$  or  $K_p$ , a distribution coefficient, in groundwater literature.  $K_d$  is synonymous with  $K_p$  which is more commonly encountered in chemical and surface water literature. If a solute does not interact with the solid phase,  $K_p$  equals 0 and the retardation factor, as defined by the above equation, equals 1. Examples of such non-retarding solutes are chlorides and nitrates. Sulfate also behaves like chlorides unless highly weathered soils high in aluminum and iron oxides/hydroxides are present or in some cases with acidic solutions, in which case sulfate may adsorb. An example of a constituent that is moderately retarded is selenium and one that is strongly retarded is inorganic mercury.

The average velocity of a solute affected by retardation can be estimated as the seepage velocity divided by the retardation factor. For example, if  $R_d$  was 5 for boron and the seepage velocity was 10 m/yr, the boron would travel on the average about 2 m/yr. In addition to retardation slowing the arrival time of a constituent, retardation together with dispersion lowers the peak solute concentration in the groundwater.

The  $K_p$  term is an empirical coefficient determined in the laboratory for a specific constituent under a particular set of conditions (e.g., for metals: pH, type of permeable media, specific concentrations of other solutes, redox conditions).  $K_p$  can be measured in the laboratory as:

$$K_p = \frac{X}{c} \quad (\text{A-4})$$

where

- $K_p$  = solution: solid phase, linear partition coefficient, ml/g
- $X$  = concentration of solute sorbed on soil, g/g
- $c$  = concentration of solute in solution, g/ml.

### **$K_p$ Values For Organic Solutes**

Because most organic compounds are nonpolar and would prefer to be in an organic phase rather than water, a method for estimating  $K_p$  has been developed based on the octanol-water partition coefficient and the organic matter content of the permeable media. This approximation for  $K_p$  is given below (Karickhoff et al., 1979):

$$K_p = 0.63 X_{oc} K_{ow} \quad (\text{A-5})$$

Where

$X_{oc}$  = decimal fraction of organic carbon present in the solid phase (suspended solids, or soil) kg/kg

$K_{ow}$  = octanol-water partition coefficient, dimensionless.

If data are available, the above equation can be modified to consider the grain-size of the permeable media in addition to organic carbon content. The modified equation is given below (Karickhoff et al., 1979):

$$K_p = 0.63 K_{ow} [0.2(1-f)X_{oc}^s + fX_{oc}^f] \quad (\text{A-6})$$

where

$K_{ow}$  = octanol-water partition coefficient, dimensionless

$f$  = decimal fraction of fine soil ( $\leq 50 \mu\text{m}$  in diameter, i.e., silt and clay)

$X_{oc}^s$  = organic carbon content of coarse soil fraction, decimal fraction

$X_{oc}^f$  = organic carbon content of fine soil fraction, decimal fraction.

The octanol-water partition coefficient can be determined experimentally by, in essence, adding a compound to a 50:50 suspension of octanol and water, equilibrating, and then measuring the concentration of the compound in both phases. The value of the octanol-water partition coefficient is simply the ratio of the concentration in the octanol to that in the water at equilibrium. Values for compounds likely to be of interest to utilities have been compiled (Gherini et al., 1988 and 1989).

### Decay Or Transformation

Decay (and transformation) of organic compounds in the environment will further change their concentrations. These processes include biotransformation, hydrolysis, volatilization and photolysis. (Except for shallow groundwater systems, photolysis and volatilization are not likely to be significant). The processes are rate-limited and can be represented using first-order equations. Methods for estimating the rate constants for the specific processes are presented in Gherini et al., 1989. The total transformation rate can be represented as the sum of the individual rate constants as given below:

$$\begin{aligned}\frac{\partial c}{\partial t} &= k_v c + k_h c + k_p c + k_b c + k_o c, \quad \text{or} \\ &= k_v + k_h + k_p + k_b + k_o \quad \text{or} \quad (\text{A-7}) \\ &= (\sum_i k_i) c\end{aligned}$$

where

- $k_v$  = volatilization rate constant, 1/day
- $k_h$  = hydrolysis rate constant, 1/day
- $k_p$  = photolysis rate constant, 1/day
- $k_b$  = biotransformation rate constant, 1/day
- $k_o$  = rate constant for other transformation processes, 1/day.

The sum of the pertinent rate process coefficients is used as input to the MYGRT v 3.0 code. Such values are also available in the literature and to a limited extent from on-line data bases. A one-dimensional example showing the effect of first-order decay is shown in Figure A-1.

In MYGRT, the first-order decay rate parameter,  $k$ , is assumed to be the same for both the liquid and solid phases of solute. This can be seen in the partial differential equation of solute transport, where a " $-R_d k C$ " term is used to represent all first-order decay processes in the soil and aquifer. If the first-order decay rate of the liquid phase,  $k_{\text{liquid}}$ , and the first-order decay rate of the solid phase,  $k_{\text{solid}}$ , are different, then the following algorithm can be used to find the equivalent first-order decay rate " $k$ ":

$$k = \frac{\left( k_{liquid} + \frac{k_{solid} \rho_b K_d}{\theta} \right)}{R_d} \quad (A-8)$$

Where

- $\rho_b$  = dry bulk density of permeable material (g/ml)
- $\theta$  = volumetric moisture content (vol/vol) for unsaturated media and porosity for saturated media.

### Source Concentration

There are three possible cases to consider when defining the source concentration as a function of time. In the MYGRT v 3.0 *Source Location* screen, these scenarios are labeled as follows in the program: "Aquifer(Saturated Zone)", which we will call Case 1 in the manual; "Unsaturated Zone", which we will call Case 2 in the manual; and "Just Contacting Saturated Zone", which we will call Case 3 in the manual.

In Case 1, the user specifies solute concentration in the groundwater at the down gradient edge of the source (e.g., disposal site). MYGRT then computes the down gradient concentrations as the solutes are dispersed laterally and longitudinally. Case 1 would correspond to the concentration measured in an observation well at that location. A schematic of this is shown in Figure A-2)a.

In Case 2, the solute source is assumed to be at the top of the unsaturated soil column. The solute concentration  $C_{unsat-bc}$  enters into the top of the soil as a function of time. MYGRT then simulates the vertical migration of the solute through the unsaturated zone. The resultant leachate concentration reaching the water table interface is then mixed with the underlying aquifer water. The user specifies the width ( $W_{source}$ ) and length ( $L_{source}$ ) dimensions of the surface source, the porosity ( $\theta$ ), and penetration depth ( $P_d$ ) of the saturated portion of the formation being simulated and the net leachate infiltration rate ( $I_{infl}$ ). The code then calculates the resulting solute concentration in the groundwater assuming mixing (mass balance) between the leachate and up gradient groundwater, as shown below in Eq. (A-9). MYGRT then simulates the horizontal migration of the mixed solute concentration through the saturated zone. A schematic of this option is shown in Figure A-2)b.

In Case 3, the source is assumed to be just above and in contact with the water table. The user specifies the source concentration entering the top of the aquifer. Groundwater mixing is computed using the algorithm of Eq. (A-9).

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Description of Input Data

$$C_{bc} = \frac{(C_{ic} Q_{gw} + C_{lcht} Q_{lcht})}{(Q_{gw} + Q_{lcht})} \quad (A-9)$$

where the volumetric flow rates  $Q_{gw}$  and  $Q_{lcht}$  are defined as:

$$Q_{gw} = V_x \theta W_{source} P_d \quad (A-10)$$

$$Q_{lcht} = I_{inf} A_{source}$$

$C_{bc}$  = initial concentration in the aquifer at the down gradient edge of source (e.g., disposal site) (mg/l)

$C_{ic}$  = initial or background concentration in the aquifer (mg/l)

$C_{lcht}$  = interstitial solution concentration entering from the unsaturated layer (mg/l). It is generated by the GWIS model for Case 2 and is specified by the user for Case 3.

$Q_{gw}$  = groundwater volumetric flow rate at up gradient edge of source ( $m^3/yr$ )

$Q_{lcht}$  = volumetric infiltration flow rate through the unsaturated layer ( $m^3/yr$ )

$V_x$  = longitudinal seepage velocity in the aquifer (m/yr)

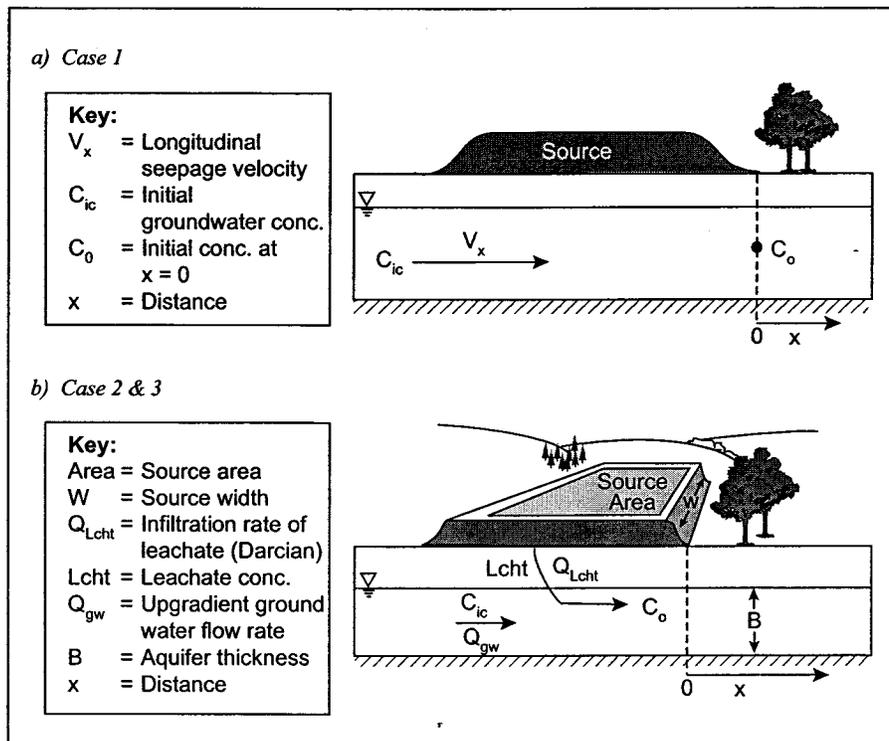
$\theta$  = porosity of aquifer (vol/vol)

$W_{source}$  = width of source (m)

$P_d$  = mixing depth, up to the thickness of the saturated zone (m)

$I_{inf}$  = infiltration flux rate through unsaturated layer (m/yr)

$A_{source}$  = area of source ( $m^2$ ), where  $A_{source} = L_{source} W_{source}$ .



**Figure A-2**  
Schematic showing source location options: a) Case 1 - source located in aquifer (saturated zone); b) Case 2 - source located in unsaturated zone, Case 3 - source just contacting saturated zone.

### Penetration Depth

The penetration depth is the thickness of the solute plume that develops beneath the source (e.g., disposal site) at the down gradient edge. The solutes are carried downward by infiltration of water through the site. An estimate of the plume depth for landfills situated above the water table can be made using the equation below (EPA, 1988):

$$P_d = \sqrt{2\alpha_v L_{source}} + B \left\{ 1 - e^{-\frac{L_{source} I_{infil}}{BV_x \theta}} \right\} \quad (A-11)$$

where

$P_d$  = penetration depth (m)

$\alpha_v$  = vertical dispersivity coefficient in the saturated layer (m)

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### Description of Input Data

$L_{\text{source}}$  = length of source (e.g., landfill) parallel to primary ground water flow direction (m)

$B$  = thickness of saturated layer (m)

$V_x$  = longitudinal seepage velocity in saturated layer (m/yr)

$I_{\text{infl}}$  = vertical infiltration velocity (Darcy) through the unsaturated layer (m/yr)

$\theta$  = effective porosity of saturated layer (vol/vol)

The estimated penetration depth is then compared to the aquifer thickness. If the penetration depth is greater than the thickness, the value is set equal to the thickness of the aquifer.

### Numerical Integration Of Integrals

There are several integrals used in the MYGRT codes that have no known solution in terms of closed form functions. These integrals are solved using the Gauss-Legendre integration scheme (Press et al., 1989; page 121). The general form of solution is as follows:

$$\int_{t'=a}^b G(t') dt' = \sum_{i=1}^{N_{\text{pts}}} W_i G(Z_i) \quad (\text{A-12})$$

where the function  $G(t')$  is integrated between the limits of  $t' = a$  and  $b$ . The term  $W_i$  is the  $i^{\text{th}}$  Gauss weight,  $Z_i$  is the  $i^{\text{th}}$  Gauss evaluation point, and  $N_{\text{pts}}$  is the polynomial degree. Normalized Gauss weights and evaluation points, given to 30 digit accuracy, are given by Stroud and Secrest (1966) for polynomial degrees ranging between  $N_{\text{pts}} = 5$  and 256. Transformation of normalized (-1, 1) limits of integration to arbitrary (a, b) limits of integration is given by Abramowitz and Stegun (1972; page 887, Eq. 25.4.30). The formula given above is only accurate for monotonic functions. If the function  $G(t)$  is not monotonic, then the integral must be broken up into sub-regions over which the function is monotonic. Each sub-region is integrated separately and then added together to get the total integral.

### Mathematical Representation of Boundary Conditions In Both the Unsaturated and Saturated Layers

MYGRT v 3.0 only allows the user to specify solute boundary conditions as step functions over time in the *Source Concentration* screen. However, if the unsat/sat option

is chosen from the Calculation Zone Restriction option list in the *Setup Model* screen, then MYGRT will automatically create a boundary condition for the saturated layer model. The time varying solute concentration from the bottom of the unsaturated layer is mixed with the underlying aquifer water using Eq. (A-9) and then redefined as the time varying boundary condition for the saturated layer model of transport. This concentration is then uniformly applied over the depth of penetration of the plume at the down gradient edge of the source.

A two step algorithm is used to generate the times at which the boundary condition is computed by MYGRT for the saturated layer. First, a "course mesh" of time values are generated between the beginning time  $t_{ON1}$  of the simulation and time "t" of interest. Based on retarded advection only, the time needed for each of the user specified step concentrations to reach the water table is estimated. Model GWIS is run by MYGRT to predict the resultant solute concentration at the bottom of the unsaturated layer at each of the course mesh time values. A linear function is fitted between each of the course mesh times versus the predicted boundary condition concentrations (aquifer mixed). The change in concentration slope and change in concentration between each time interval is computed. Then each time interval is checked to determine if either the concentration slope changes more than 10% from the previous slope or if the concentration changes by more than 5% compared to the peak concentration. If either condition occurs, the time interval is "refined" by subdividing it into an additional 13 time periods. Depending on the number of user specified boundary conditions for the unsaturated layer and the particular transport properties, the above algorithm will identify several hundred refined time values. In the second step, the saturated layer boundary condition is re-computed by the GWIS program at each of the "fine mesh" time values. The resultant concentrations are then curve-fitted with linear functions versus time. At the end of this two step process, the boundary condition versus time for the saturated layer will typically be represented by about one hundred linear functions.

The boundary conditions have now been subdivided into a total of  $N_{bc}$  segments of time, over which the solute concentration at the boundary is assumed to vary linearly with time. For example, consider the  $j^{th}$  subdivision, which represents the linear variation in the boundary condition between the time  $t_{ONj}$  and  $t_{OFFj}$ :

$$C_{bc}(t) = \{C_{bcj} + (t - t_{ONj})Slope_j\} \{H(t - t_{ONj}) - H(t - t_{OFFj})\} \quad (A-13)$$

Where  $H(.)$  is the Heaviside unit step function;  $C_{bcj}$  is the solute concentration of the boundary condition at the start of time  $t_{ONj}$ ; and  $Slope_j$  is the slope of the linear variation in the solute concentration versus time, curve fitted to pass through the concentration  $C_{bcj}$  at time  $t_{ONj}$ .

### **Mathematical Representation of Initial Conditions In the Unsaturated Layer**

MYGRT v 3.0 only allows the user to specify a constant initial condition,  $C_{ic0}$ , for the solute concentration in the unsaturated layer and another constant value for the saturated layer. However, MYGRT has to re-compute the initial condition for the unsaturated layer if the infiltration rate is changed during a given simulation. This occurs if the Infiltration Rate Substitution option of the *Unsaturated Zone Properties* screen is selected. The saturated layer does not have to be re-initialized because none of its transport properties are assumed to have changed, only the leachate concentration at the boundary will change over time. MYGRT handles the effect of the change in infiltration by computing the concentration versus depth profile in the unsaturated layer at the specified time of the infiltration switch. The solute concentration in the unsaturated layer is computed by GWIS at more than 100 subdivided depths, depending upon the number of user specified boundary conditions. These concentrations are then curve fitted to a total of  $N_{ic}$  linear functions versus depth at the switch time. MYGRT then uses these fitted functions as the initial condition of the unsaturated layer for all times greater than the switch time.

For example, consider the  $j^{\text{th}}$  depth subdivision, which represents the variation in the initial condition between the depth  $z_{ONj}$  and  $z_{OFFj}$ . The mathematical representation of the linear variation in concentration over this depth interval is given by:

$$C_{ic}(z) = \{C_{icj} + (z - z_{ONj})Slope_j\} \{H(z - z_{ONj}) - H(z - z_{OFFj})\} \quad (A-14)$$

Where  $H(\cdot)$  is the Heaviside unit step function;  $C_{icj}$  is the solute concentration of the initial condition at the top of depth  $z_{ONj}$ ; and  $Slope_j$  is the slope of the linear variation in the solute concentration versus depth, curve fitted to pass through the concentration  $C_{icj}$  at depth  $z_{ONj}$ .

### **MYGRT v 3.0 Models**

MYGRT v 3.0 consists of a collection of 22 transport codes written in FORTRAN that simulate various 1-D, 2-D, and 3-D domains. A list of the possible solution scenarios is given in Table A-1, along with the corresponding model name. A brief mathematical description of the models is given in Appendices B-G. A list of the mathematical symbols used in the models and their description is given in Table A-2.

**Table A-1**  
**Names of the 22 calculation codes used by MYGRT v 3.0.**

Transport Model	Point Value Calculation	Well Screen Average Calculation
1-D	GW1S & GW1SBIC	NA
2-D Horizontal Areal	GW2SI	NA
2-D Vertical Cross-Section: Finite Depth	GW2SF	GW2SFa
2-D Vertical Cross-Section: Semi-Infinite Depth	GW2SS	GW2SSa
3-D: Finite Depth	GW3SIF	GW3SIFa
3-D: Semi-Infinite Depth	GW3SIS	GW3SISa

NA - Not applicable

A brief derivation for each of the transport equations is given in Appendices B - G. A complete derivation of the integral transform solution to the transport equation used in Model GW3SIF is given in Appendix I. Model GW3SIF was derived in response to the Illinois State TACO project. Model GW3SIS is the exact solution to the "Domenico" scenario. The well screen averaging algorithm is presented in Appendix H. Only 11 models are shown in the table but each code contains a separate algorithm for the case of zero longitudinal dispersion.

**Table A-2**  
**List of symbols used in the mathematical equations of Appendices B - I.**

Symbol	Explanation	Unit
$\infty$	Infinity	
$\Psi_m$	$M^{\text{th}}$ eigenvalue for case of finite thick aquifers	
B	Aquifer thickness	(m)
C	Predicted solute concentration in aquifer	(mg/l)
$C_{bcj}(t)$	The solute concentration of the $j^{\text{th}}$ boundary condition, as a function of time	(mg/l)
$C_{ic}$	Initial solute concentration in aquifer	(mg/l)
$C_{ic}$	The initial or background concentration	(mg/l)
$C_{icj}(z)$	The solute concentration of the $j^{\text{th}}$ initial condition, as a function of depth in the unsaturated layer	(mg/l)
$D_x$	Longitudinal dispersion coefficient	(m <sup>2</sup> /yr)
$D_y$	Transverse-horizontal dispersion coefficient	(m <sup>2</sup> /yr)
$D_z$	Vertical dispersion coefficient	(m <sup>2</sup> /yr)
$e^{(.)}$	Exponential function	
erf(.)	Error function	
erfc(.)	Complimentary error function	
H(.)	Heaviside unit step function	
k	First-order decay rate of solute in the aquifer	(yr <sup>-1</sup> )
Max[A,B]	Given the parameters A and B, use the parameter with the largest value.	
Min[A,B]	Given the parameters A and B, use the parameter with the smallest value.	
$N_{bc}$	Number of boundary conditions	
$N_{ic}$	Number of initial conditions	
$R_d$	Retardation factor of the solute	Unitless
t	Time	(yr)

*Description of Input Data*

$t'$	Time relative to the start of the first boundary condition, where $t' = t - t_{ON1}$	(yr)
$t_{1j}$	Time relative to the end of the $j^{\text{th}}$ boundary condition, $\text{Max}[0, t - t_{OFFj}]$	(yr)
$t_{2j}$	Time relative to the start of the $j^{\text{th}}$ boundary condition, $\text{Max}[0, t - t_{ONj}]$	(yr)
$t_{OFFj}$	The time at which the $j^{\text{th}}$ boundary condition is to end	(yr)
$t_{ONj}$	The time at which the $j^{\text{th}}$ boundary condition is to start	(yr)
$V_x$	Longitudinal seepage velocity in the aquifer	(m/yr)
$x$	Longitudinal distance from source	(m)
$y$	Transverse-horizontal distance along the Y axis	(m)
$y_{1j}$	Transverse-horizontal distance along the Y axis at which the $j^{\text{th}}$ boundary condition starts	(m)
$y_{2j}$	Transverse-horizontal distance along the Y axis at which the $j^{\text{th}}$ boundary condition ends	(m)
$z$	Depth	(m)
$z_{1j}$	Depth at which either the $j^{\text{th}}$ initial condition in the unsaturated layer or the $j^{\text{th}}$ boundary condition in the saturated layer starts	(m)
$z_{2j}$	Depth at which either the $j^{\text{th}}$ initial condition in the unsaturated layer or the $j^{\text{th}}$ boundary condition in the saturated layer ends	(m)

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# B

## MODELS GW1S & GW1SBIC

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One Dimensional, Semi-Infinite Length Domain

Mass Transport Equation

$$R_d \frac{\partial c}{\partial t} + U \frac{\partial c}{\partial x} = D \frac{\partial^2 c}{\partial x^2} - kcR_d$$

Solution Domain

$$0 \leq x \leq \infty$$

$$t \geq 0$$

Initial Condition (only used in GW1SBIC)

$$c(x,0) = C_{ico} + \sum_{j=1}^{N_{kj}} (C_{iej} - C_{ico}) \{H(x - x_{ONj}) - H(x - x_{OFFj})\}$$

where H(.) is the Heaviside unit step function

Boundary Conditions (used in both GW1S & GW1SBIC)

$$c(0,t) = C_{ico} + \sum_{j=1}^{N_{kj}} (C_{bej} - C_{ico}) \{H(t - t_{ONj}) - H(t - t_{OFFj})\}$$

$$\frac{\partial c}{\partial x}(\infty, t) = 0$$

**Solution ( $D > 0$ )**

$$\begin{aligned}
 c(x,t) = & C_{ico} + \frac{x}{2} \sqrt{\frac{R_d}{\pi D}} e^{\frac{Ux}{2D}} \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ico}) \int_{\tau=\text{Max}[0,t-t_{OFFj}]}^{\text{Max}[0,t-t_{ONj}]} \frac{e^{-\left(\frac{U^2}{4DR_d} + k\right)\tau} \frac{x^2 R_d}{4D\tau}}{\tau^{3/2}} d\tau \\
 & - \frac{k}{2} C_{ico} e^{\frac{Ux}{2D}} \int_{\tau=0}^{t^*} e^{-k\tau} \left\{ e^{\frac{-xU}{2D}} \text{erfc} \left( -x \sqrt{\frac{R_d}{4D\tau}} + U \sqrt{\frac{\tau}{4DR_d}} \right) - e^{\frac{xU}{2D}} \text{erfc} \left( x \sqrt{\frac{R_d}{4D\tau}} + U \sqrt{\frac{\tau}{4DR_d}} \right) \right\} d\tau \\
 & + \frac{e^{-kt^*}}{2} \sum_{j=1}^{N_{ic}} (C_{icj} - C_{ico}) \left[ e^{\frac{Ux}{D}} \text{erfc} \left( \frac{(x+x_{OFFj})}{2} \sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2} \sqrt{\frac{t^*}{DR_d}} \right) - \text{erfc} \left( \frac{-(x-x_{OFFj})}{2} \sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2} \sqrt{\frac{t^*}{DR_d}} \right) \right] \\
 & - \frac{e^{-kt^*}}{2} \sum_{j=1}^{N_{ic}} (C_{icj} - C_{ico}) \left[ e^{\frac{Ux}{D}} \text{erfc} \left( \frac{(x+x_{ONj})}{2} \sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2} \sqrt{\frac{t^*}{DR_d}} \right) - \text{erfc} \left( \frac{-(x-x_{ONj})}{2} \sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2} \sqrt{\frac{t^*}{DR_d}} \right) \right]
 \end{aligned}$$

$$x \geq 0$$

$$t \geq t_{ON1}$$

where

$$t^* = t - t_{ON1}$$

**Solution ( $D = 0$ )**

$$\begin{aligned}
 c(x,t) = & C_{ico} + C_{ico} \left\{ e^{-k \text{Min}[t-t_{ON1}, \tau_o]} - 1 \right\} + e^{-k(t-t_{ON1})} \sum_{j=1}^{N_{bc}} (C_{icj} - C_{ico}) \left[ H\{x-x_{1j}\} - H\{x-x_{2j}\} \right] \\
 & + e^{-k\tau_o} \sum_{j=1}^{N_{bc}} \left\{ C_{bcj} (t-t_{ON1}-\tau_o) - C_{ico} \right\} \left[ H\{\tau_o-t_{1j}\} - H\{\tau_o-t_{2j}\} \right]
 \end{aligned}$$

where

$$\tau_o = x R_d / U$$

$$t_{1j} = \text{Max} [0, t - t_{OFFj}]$$

$$t_{2j} = \text{Max} [0, t - t_{\text{ON}j}]$$

$$X_{1j} = (t - t_{\text{ON}j})U/R_d + X_{\text{ON}j}$$

$$X_{2j} = (t - t_{\text{ON}j})U/R_d + X_{\text{OFF}j}$$

Note the following indefinite integrals

$$\int \frac{e^{-a^2\tau - \frac{b^2}{\tau}}}{\tau^{3/2}} d\tau = \frac{\sqrt{\pi}}{2b} \left\{ e^{-2ab} \text{erf} \left( a\sqrt{\tau} - \frac{b}{\sqrt{\tau}} \right) - e^{2ab} \text{erf} \left( a\sqrt{\tau} + \frac{b}{\sqrt{\tau}} \right) \right\}$$

$$\int \frac{e^{-a^2\tau - \frac{b^2}{\tau}}}{\tau^{1/2}} d\tau = \frac{\sqrt{\pi}}{2a} \left\{ e^{-2ab} \text{erf} \left( a\sqrt{\tau} - \frac{b}{\sqrt{\tau}} \right) + e^{2ab} \text{erf} \left( a\sqrt{\tau} + \frac{b}{\sqrt{\tau}} \right) \right\}$$

# C

## MODEL GW2DSF

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Two Dimensional, Semi-Infinite Length and Finite Depth Domain

Mass Transport Equation

$$R_d \frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_z \frac{\partial^2 c}{\partial z^2} - kcR_d$$

Solution Domain

$$0 \leq x \leq \infty$$

$$0 \leq z \leq \infty$$

$$t \geq 0$$

Initial Condition

$$c(x, z, 0) = C_{ic}$$

Boundary Conditions

$$c(0, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic}) \{H(t - t_{ONj}) - H(t - t_{OFFj})\} \{H(z - z_{1j}) - H(z - z_{2j})\}$$

$$\frac{\partial c}{\partial x}(\infty, z, t) = 0$$

$$\frac{\partial c}{\partial z}(x, 0, t) = 0$$

$$\frac{\partial c}{\partial z}(x, B, t) = 0$$

where H(.) is the Heaviside unit step function.

**Solution ( $D_x > 0, D_z > 0$ )**

$$c(x, z, t) = C_{ic}$$

$$+ x \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sum_{j=1}^{N_{bc}} \int_{\tau=0}^{t^*} \frac{e^{-\left(\frac{V_x^2}{4R_d D_x} + k\right)\tau} \frac{X^2 R_d}{4D_x \tau}}{\tau^{3/2}} \left\{ C_{bcj}(t^* - \tau) - C_{ic} \right\} \sum_{m=0}^{\infty} L_m O_{mj} \cos(\psi_m z) e^{-\frac{\psi_m^2 D_z \tau}{R_d}} d\tau$$

$$- \frac{k}{2} C_{ic} \int_{\tau=0}^{t^*} e^{-k\tau} \left[ \operatorname{erfc} \left( -x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) - e^{\frac{xV_x}{D_x}} \operatorname{erfc} \left( x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) \right] d\tau$$

where  $t^* = t - t_{ON1}$   $t \geq t_{ON1}$

Define the following dimensionless coefficients

$$O_{mj} = \begin{cases} \frac{(z_{2j} - z_{1j})}{B} & \text{if } m = 0 \\ \left\{ \frac{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})}{\psi_m B} \right\} & \text{if } m = 1, 2, \dots \end{cases}$$

$$P_m = \begin{cases} 1 & \text{if } m = 0 \\ \left\{ \frac{\sin(\psi_m B)}{\psi_m B} \right\} & \text{if } m = 1, 2, \dots \end{cases}$$

$$L_m = \begin{cases} 1/2 & \text{if } m = 0 \\ 1 & \text{if } m = 1, 2, \dots \end{cases}$$

$$\psi_m = \frac{\pi m}{B} \quad m = 0, 1, 2, \dots$$

**Solution ( $D_x = 0, D_z > 0$ )**

$$\begin{aligned}
 c(x, z, t) = & C_{ic} \\
 & + 2 \sum_{m=0}^{\infty} L_m \cos(\psi_m z) e^{-\left(\frac{\psi_m^2 D_z}{R_d} + k\right) \tau_o} \sum_{j=1}^{N_{bc}} O_{mj} \left\{ C_{bcj} (t^* - \tau_o) - C_{ic} \right\} \left\{ H(\tau_o - t_{1j}) - H(\tau_o - t_{2j}) \right\} \\
 & + C_{ic} \left\{ e^{-k \text{Min}[t^*, \tau_o]} - 1 \right\}
 \end{aligned}$$

$$t \geq t_{ON1}$$

where

$$\tau_o = x R_d / V_x$$

$$t_{1j} = \text{Max} [0, t - t_{OFFj}]$$

$$t_{2j} = \text{Max} [0, t - t_{ONj}]$$

$$t^* = t - t_{ON1}$$

# D

## MODEL GW2DSS

---

Two Dimensional, Semi-Infinite Length, Semi-Infinite Depth Domain

Mass Transport Equation

$$R_d \frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_z \frac{\partial^2 c}{\partial z^2} - kcR_d$$

Solution Domain

$$0 \leq x \leq \infty$$

$$0 \leq z \leq \infty$$

$$t \geq 0$$

Initial Condition

$$c(x, z, 0) = C_{ic}$$

Boundary Conditions

$$c(0, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic}) \{H(t - t_{ONj}) - H(t - t_{OFFj})\} \{H(z - z_{1j}) - H(z - z_{2j})\}$$

where  $H(\cdot)$  is the Heaviside unit step function.

$$\frac{\partial c}{\partial x}(\infty, z, t) = 0$$

$$\frac{\partial c}{\partial z}(x, \infty, t) = 0$$

$$\frac{\partial c}{\partial z}(x, 0, t) = 0$$

**Solution ( $D_x > 0, D_z > 0$ )**

$$c(x, z, t) = C_{ic} + \frac{x}{4} \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sum_{j=1}^{N_{bc}} \int_{\tau=0}^{t^*} e^{-\left(\frac{V_x^2}{4R_d D_x} + k\right)\tau} \frac{x^2 R_d}{4D_x \tau^{\frac{3}{2}}} d\tau$$

$$\left\{ C_{bcj}(t - \tau) - C_{ic} \right\} \left[ \operatorname{erfc} \left\{ (z_{1j} + z) \sqrt{\frac{R_d}{4D_z \tau}} \right\} - \operatorname{erfc} \left\{ (z_{2j} + z) \sqrt{\frac{R_d}{4D_z \tau}} \right\} \right]$$

$$+ \operatorname{erfc} \left\{ (z_{1j} - z) \sqrt{\frac{R_d}{4D_z \tau}} \right\} - \operatorname{erfc} \left\{ (z_{2j} - z) \sqrt{\frac{R_d}{4D_z \tau}} \right\} d\tau$$

$$- \frac{k}{2} C_{ic} \int_{\tau=0}^{t^*} e^{-k\tau} \left[ \operatorname{erfc} \left\{ -x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right\} - e^{\frac{xV_x}{D_x}} \operatorname{erfc} \left\{ x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right\} \right] d\tau$$

where

$$t \geq t_{ON1}$$

$$t^* = t - t_{ON1}$$

**Solution ( $D_x = 0, D_z > 0$ )**

$$\begin{aligned}
 c(x, z, t) = & C_{ic} - C_{ic} \sum_{j=1}^{N_{bc}} \left\{ e^{-k \text{Max}[t_{1j}, \tau_o]} - e^{-k \text{Max}[t_{2j}, \tau_o]} \right\} \\
 & + \frac{e^{-k\tau_o}}{2} \sum_{j=1}^{N_{bc}} \left\{ C_{bcj} (t^* - \tau_o) - C_{ic} \right\} \left\{ H(\tau_o - t_{1j}) - H(\tau_o - t_{2j}) \right\} \cdot \\
 & \left[ \text{erfc} \left( (z_{1j} + z) \sqrt{\frac{R_d}{4D_z \tau}} \right) - \text{erfc} \left( (z_{2j} + z) \sqrt{\frac{R_d}{4D_z \tau}} \right) \right. \\
 & \left. + \text{erfc} \left( (z_{1j} - z) \sqrt{\frac{R_d}{4D_z \tau}} \right) - \text{erfc} \left( (z_{2j} - z) \sqrt{\frac{R_d}{4D_z \tau}} \right) \right]
 \end{aligned}$$

where

$$t \geq t_{ON1}$$

$$\tau_o = xR_d/V_x$$

$$t_{1j} = \text{Max} [0, t - t_{OFFj}]$$

$$t_{2j} = \text{Max} [0, t - t_{ONj}]$$

# *E*

## MODEL GW2SI

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Two Dimensional, Semi-Infinite Length and Infinite Width Domain

Mass Transport Equation

$$R_d \frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} - kcR_d$$

Solution Domain

$$0 \leq x \leq \infty$$

$$-\infty \leq y \leq \infty$$

$$t \geq 0$$

Initial Condition

$$c(x, y, 0) = C_{ic}$$

Boundary Conditions

$$c(0, y, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic}) \{H(t - t_{ONj}) - H(t - t_{OFFj})\} \{H(y - y_{1j}) - H(y - y_{2j})\}$$

where  $H(\cdot)$  is the Heaviside unit step function.

$$\frac{\partial c}{\partial x}(\infty, y, t) = 0$$

$$\frac{\partial c}{\partial y}(x, \infty, t) = 0$$

$$\frac{\partial c}{\partial y}(x, -\infty, t) = 0$$

**Solution ( $D_x > 0, D_y > 0$ )**

$$c(x, y, t) = c_{ic} + \frac{x}{4} \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{y_x x}{2D_x}} \int_{\tau=0}^{t^*} \frac{e^{-\frac{x^2 R_d}{4D_x \tau} - \left(\frac{y_y^2}{4R_d D_x} + k\right) \tau}}{\tau^{3/2}} U_{\tau} \bullet$$

$$\sum_{j=1}^{N_{bc}} \left\{ C_{bcj}(t^* - \tau) - C_{ic} \right\} \left[ -\operatorname{erfc}\left( (y_{2j} - y) \sqrt{\frac{R_d}{4D_y \tau}} \right) + \operatorname{erfc}\left( (y_{1j} - y) \sqrt{\frac{R_d}{4D_y \tau}} \right) \right] d\tau$$

$$- \frac{C_{ic}}{4} \left[ -2e^{-kt^*} \operatorname{erfc}\left( \sqrt{(a^2 + k)t^*} - \frac{b}{\sqrt{t^*}} \right) + 4 \right]$$

$$- e^{-2b\sqrt{a^2+k} - 2ba} \operatorname{erfc}\left( -a\sqrt{t^*} + \frac{b}{\sqrt{t^*}} \right) \left\{ \frac{\sqrt{a^2+k}}{a} + 1 \right\}$$

$$+ e^{-2b\sqrt{a^2+k} + 2ba} \operatorname{erfc}\left( a\sqrt{t^*} + \frac{b}{\sqrt{t^*}} \right) \left\{ \frac{\sqrt{a^2+k}}{a} - 1 \right\}$$

$$+ \frac{C_{ic}}{4} e^{\frac{xy_x}{D_x}} \left[ -2e^{-kt^*} \operatorname{erfc}\left( \sqrt{(a^2 + k)t^*} + \frac{b}{\sqrt{t^*}} \right) \right]$$

$$+ e^{-2b\sqrt{a^2+k} + 2ba} \operatorname{erfc}\left( a\sqrt{t^*} + \frac{b}{\sqrt{t^*}} \right) \left\{ \frac{\sqrt{a^2+k}}{a} + 1 \right\}$$

$$- e^{-2b\sqrt{a^2+k} - 2ba} \operatorname{erfc}\left( -a\sqrt{t^*} + \frac{b}{\sqrt{t^*}} \right) \left\{ \frac{\sqrt{a^2+k}}{a} - 1 \right\}$$

where  $t \geq t_{ON1}$

$$t^* = t - t_{ON1}$$

$$a^2 = \left( \frac{V_x^2}{4R_d D_x} + k \right)$$

$$b^2 = \left( \frac{x^2 R_d}{4D_x} \right)$$

$$U_{Tj} = \{H(t - \tau - t_{ONj}) - H(t - \tau - t_{OFFj})\}$$

**Solution ( $D_x = 0, D_y > 0$ )**

$$c(x, y, t) = C_{ic} + C_{ic} \sum_{j=1}^{N_{bc}} \{e^{-k \text{Max}[t_{2j}, \tau_o]} - e^{-k \text{Max}[t_{1j}, \tau_o]}\} \\ + \frac{1}{2} \sum_{j=1}^{N_{bc}} e^{-k\tau_o} \{C_{bcj}(t^* - \tau_o) - C_{ic}\} \{H(\tau_o - t_{1j}) - H(\tau_o - t_{2j})\} \cdot \\ \left\{ \text{erfc} \left( (y_{1j} - y) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) - \text{erfc} \left( (y_{2j} - y) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) \right\}$$

where

$$t \geq t_{ON1}$$

$$\tau_o = xR_d/V_x$$

$$t_{1j} = \text{Max}[0, t - t_{OFFj}]$$

$$t_{2j} = \text{Max}[0, t - t_{ONj}]$$

# F

## MODEL GW3SIF

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Three Dimensional, Semi-Infinite Length, Infinite Width, and Finite Depth Domain

Mass Transport Equation

$$R_d \frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} - kcR_d$$

Solution Domain

$$0 \leq x \leq \infty$$

$$-\infty \leq y \leq \infty$$

$$0 \leq z \leq B$$

$$t \geq 0$$

Initial Condition

$$c(x, y, z, 0) = C_{ic}$$

Boundary Conditions

$$c(0, y, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic}) \{H(t - t_{ONj}) - H(t - t_{OFFj})\} \cdot \\ \{H(y - y_{1j}) - H(y - y_{2j})\} \{H(z - z_{1j}) - H(z - z_{2j})\}$$

where  $H(\cdot)$  is the Heaviside unit step function.

$$\frac{\partial c}{\partial x}(\infty, y, z, t) = 0$$

$$\frac{\partial c}{\partial y}(x, +\infty, z, t) = 0$$

$$\frac{\partial c}{\partial y}(x, -\infty, z, t) = 0$$

$$\frac{\partial c}{\partial z}(x, y, 0, t) = 0$$

$$\frac{\partial c}{\partial z}(x, y, B, t) = 0$$

**Solution ( $D_x > 0, D_y > 0$ )**

$$c(x, y, z, t) = C_{ic} + \frac{x}{2} \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \cdot$$

$$\int_{\tau=0}^{t^*} e^{-\left(\frac{\psi_m^2 D_x}{R_d} + k + \frac{V_x^2}{4D_x R_d}\right) \tau - \frac{x^2 R_d}{4D_x \tau}} \left\{ \operatorname{erfc}\left( (y_{1j} - y) \sqrt{\frac{R_d}{4D_y \tau}} \right) - \operatorname{erfc}\left( (y_{2j} - y) \sqrt{\frac{R_d}{4D_y \tau}} \right) \right\} \cdot$$

$$\left\{ C_{bcj}(t^* - \tau) - C_{ic} \right\} \left\{ H(t - \tau - t_{ONj}) - H(t - \tau - t_{OFFj}) \right\} d\tau$$

$$- k C_{ic} \sum_{m=0}^{\infty} L_m P_m \cos(\psi_m z) \int_{\tau=0}^{t^*} e^{-\left(k + \frac{\psi_m^2 D_x}{R_d}\right) \tau} \left\{ \operatorname{erfc}\left( -x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) \right.$$

$$\left. - e^{\frac{x V_x}{D_x}} \operatorname{erfc}\left( x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) \right\} d\tau$$

where

$$t \geq t_{ON1}$$

$$t^* = t - t_{ON1}$$

Define the following coefficients

$$O_{mj} = \begin{cases} \frac{(z_{2j} - z_{1j})}{B} & \text{if } m = 0 \\ \left\{ \frac{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})}{\psi_m B} \right\} & \text{if } m = 1, 2, 3, \dots \end{cases}$$

$$P_m = \begin{cases} 1 & \text{if } m = 0 \\ \left\{ \frac{\sin(\psi_m B)}{\psi_m B} \right\} & \text{if } m = 1, 2, 3, \dots \end{cases}$$

$$\psi_m = \frac{\pi m}{B} \quad m = 0, 1, 2, \dots$$

**Solution ( $D_x = 0$ )**

$$c(x, y, z, t) = C_{ic} + \sum_{m=0}^{\infty} L_m \cos(\psi_m z) e^{-\left(\frac{\psi_m^2 D_x + k}{R_d}\right) \tau_o} \bullet$$

$$\sum_{j=1}^{N_{bc}} O_{mj} \{ C_{bcj} (t^* - \tau_o) - C_{ic} \{ H(\tau_o - t_{1j}) - H(\tau_o - t_{2j}) \} \} \bullet$$

$$\left\{ \operatorname{erfc} \left( (y_{1j} - y) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) - \operatorname{erfc} \left( (y_{2j} - y) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) \right\} + C_{ic} \{ e^{-k \operatorname{Min}[t^*, \tau_o]} - 1 \}$$

where

$$t \geq t_{ON1}$$

$$\tau_o = xR_d/V_x$$

# G

## MODEL GW3SIS

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Three Dimensional, Semi-Infinite Length, Infinite Width, and Semi-Infinite Depth Domain

Mass Transport Equation

$$R_d \frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} - kcR_d$$

Solution Domain

$$0 \leq x \leq \infty$$

$$-\infty \leq y \leq \infty$$

$$0 \leq z \leq \infty$$

$$t \geq 0$$

Initial Condition

$$c(x, y, z, 0) = C_{ic}$$

Boundary Conditions

$$c(0, y, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic}) \{H(t - t_{ONj}) - H(t - t_{OFFj})\} \cdot \\ \{H(y - y_{1j}) - H(y - y_{2j})\} \{H(z - z_{1j}) - H(z - z_{2j})\}$$

where  $H(\cdot)$  is the Heaviside unit step function.

$$\frac{\partial c}{\partial x}(\infty, y, z, t) = 0$$

$$\frac{\partial c}{\partial y}(x, \infty, z, t) = 0$$

$$\frac{\partial c}{\partial y}(x, -\infty, z, t) = 0$$

$$\frac{\partial c}{\partial z}(x, y, 0, t) = 0$$

$$\frac{\partial c}{\partial z}(x, y, \infty, t) = 0$$

**Solution ( $D_x > 0, D_y > 0, D_z > 0$ )**

$$c(x, y, z, t) = C_{ic} + \frac{x}{8} \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sum_{j=1}^{N_{bc}} \int_{\tau=0}^{t^*} \{C_{bcj}(t^* - \tau) - C_{ic}\} \cdot$$

$$\frac{e^{-\left(\frac{V_x^2}{4D_x R_d} + k\right)\tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{3/2}} \left\{ \operatorname{erfc}\left((y_{1j} - y) \sqrt{\frac{R_d}{4D_y \tau}}\right) - \operatorname{erfc}\left((y_{2j} - y) \sqrt{\frac{R_d}{4D_y \tau}}\right) \right\} \cdot$$

$$\left[ \operatorname{erfc}\left\{(z + z_{1j}) \sqrt{\frac{R_d}{4D_z \tau}}\right\} - \operatorname{erfc}\left\{(z + z_{2j}) \sqrt{\frac{R_d}{4D_z \tau}}\right\} \right]$$

$$+ \operatorname{erfc}\left\{(z_{1j} - z) \sqrt{\frac{R_d}{4D_z \tau}}\right\} - \operatorname{erfc}\left\{(z_{2j} - z) \sqrt{\frac{R_d}{4D_z \tau}}\right\} \right] d\tau$$

$$- \frac{kC_{ic}}{2} \int_{\tau=0}^{t^*} e^{-k\tau} \left[ \operatorname{erfc}\left\{-x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4R_d D_x}}\right\} - e^{\frac{V_x x}{D_x}} \operatorname{erfc}\left\{x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4R_d D_x}}\right\} \right] d\tau$$

$$t \geq t_{ON1}$$

**Solution ( $D_x = 0, D_y > 0, D_z > 0$ )**

$$\begin{aligned}
 c(x, y, z, t) = & C_c - C_{ic} \left\{ 1 - e^{-k \text{Min}[t^*, \tau_o]} \right\} \\
 & + \frac{e^{-kN_{bc}}}{4} \sum_{j=1}^{N_{bc}} \left\{ C_{bcj} (t^* - \tau_o) - C_{ic} \right\} \left\{ H(\tau_o - t_{1j}) - H(\tau_o - t_{2j}) \right\} \cdot \\
 & \left\{ \left[ \left( y_{1j} - y \right) \sqrt{\frac{R_d}{4D_y \tau_o}} - \text{erfc} \left( \left( y_{2j} - y \right) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) \right] \cdot \right. \\
 & \left[ \left( z_{1j} + z \right) \sqrt{\frac{R_d}{4D_z \tau_o}} - \text{erfc} \left( \left( z_{2j} + z \right) \sqrt{\frac{R_d}{4D_z \tau_o}} \right) \right. \\
 & \left. \left. + \left[ \left( z_{1j} - z \right) \sqrt{\frac{R_d}{4D_z \tau_o}} - \text{erfc} \left( \left( z_{2j} - z \right) \sqrt{\frac{R_d}{4D_z \tau_o}} \right) \right] \right] \right\}
 \end{aligned}$$

where

$$t \geq t_{ON1}$$

$$\tau_o = x/V_x$$

$$t_{1j} = \text{Max} [0, t - t_{OFFj}] \quad j = 1, 2, 3, \dots$$

$$t_{2j} = \text{Max} [0, t - t_{ONj}]$$

$$t^* = t - t_{ON1}$$

# H

## VERTICAL AVERAGING

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The vertical averaged concentration between depths  $z_a$  and  $z_b$  is determined as follows:

$$\int_{z'=z_a}^{z_b} \frac{c(x, y, z', t)}{(z_b - z_a)} dz' = \text{screen averaged conc.}$$

When the screen averaging option is selected, the analytical solution for the concentration from the appropriate model is integrated over the depths  $z_a$  and  $z_b$ , as shown above. Depth integration of the models is a straight forward, but tedious process. The final analytical solution will not be given for each of the transport models. However, all of the semi-infinite depth models require the integration of an Erfc(.) term and all finite-depth models require the integration of a Cosine(.) term, both of which are shown below.

Consider the following integrals that are applied to "point" concentration solutions:

$$\int \operatorname{erfc}(Az + B) dz = \left( z + \frac{B}{A} \right) \operatorname{erfc}(Az + B) - \frac{B}{A} - \frac{e^{-(Az+B)^2}}{A\sqrt{\pi}}$$

$$\int \operatorname{erfc}(-Az + B) dz = \left( z - \frac{B}{A} \right) \operatorname{erfc}(-Az + B) + \frac{B}{A} + \frac{e^{-(-Az+B)^2}}{A\sqrt{\pi}}$$

$$\int_{z'=z_a}^{z_b} \frac{\cos(\psi_m z')}{(z_b - z_a)} dz' = \frac{[\sin(\psi_m z_b) - \sin(\psi_m z_a)]}{\psi_m (z_b - z_a)}$$

$$= \frac{(z_b - z_a)}{(z_b - z_a)} = 1 \quad \text{if } \psi_m = 0$$

# I

## DETAILED DERIVATION OF MODEL GW3SIF

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Three Dimensional, Semi-Infinite Length, Infinite Width, and Finite Depth Domain

The three dimensional equation of mass transport for the case of dispersion, advection, first-order decay, and reversible sorption is given by:

$$1) \quad R_d \frac{\partial C}{\partial t} + V \frac{\partial C}{\partial x} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - kcR_d$$

$$0 \leq x \leq \infty$$

$$-\infty \leq y \leq \infty$$

$$0 \leq z \leq B$$

$$t \geq 0$$

with the initial condition

$$2) \quad C(x,y,z,0) = C_{ic} \text{ at } t = 0$$

and boundary conditions

$$3) \left\{ \begin{array}{ll} C, \frac{\partial C}{\partial y} = 0 & \text{at } y = \pm\infty \\ \frac{\partial C}{\partial z} = 0 & \text{at } z = 0 \\ \frac{\partial C}{\partial z} = 0 & \text{at } z = B \\ \frac{\partial C}{\partial x} = 0 & \text{at } x = +\infty \\ C(0, y, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} \{C_{bcj}(t) - C_{ic}\} \{H(y - y_{1j}) - H(y - y_{2j})\} \cdot & \text{at } x = 0 \\ \{H(z - z_{1j}) - H(z - z_{2j})\} \{H(t - t_{ONj}) - H(t - t_{OFFj})\} & \end{array} \right.$$

where  $H()$  are Heaviside unit step functions. The boundary condition at  $x=0$  is subdivided into  $N_{bc}$  boundary "patches". As given above, the  $j$ th source concentration on the  $x=0$  boundary is defined by the time varying function  $C_{bcj}(t)$ . However, this source is spatially uniform between coordinates  $y_{1j}$  and  $y_{2j}$  of the Y-axis,  $z_{1j}$  and  $z_{2j}$  of the Z-axis between the time interval  $t_{ONj}$  and  $t_{OFFj}$ . An initial, uniform concentration of  $C_{ic}$  is given as the initial condition.

The Heaviside step function is defined as follows:

$$4) H(x - a) = \begin{cases} 0 & \text{if } x < a \\ \frac{1}{2} & \text{if } x = a \\ 1 & \text{if } x > a \end{cases}$$

We will transform out the velocity and decay terms in the mass transport equation. In order to do this, the following new variable,  $\hat{C}$ , will be defined, where  $\hat{C}$  is related to  $C$  by the expression:

$$5) C = \hat{C} \exp \left\{ \frac{V_x x}{2D_x} - \left( \frac{V_x^2}{4D_x R_d} + k \right) t \right\} + C_{ic}$$

Differentiate Eq. (5) to get the following expressions:

$$6) \quad \begin{cases} \frac{\partial C}{\partial x} = \frac{\partial \hat{C}}{\partial x} e^A + \frac{V_x}{2D_x} \hat{C} e^A \\ \frac{\partial^2 C}{\partial x^2} = \frac{\partial^2 \hat{C}}{\partial x^2} e^A + \frac{V_x}{D_x} \frac{\partial \hat{C}}{\partial x} e^A + \left( \frac{V_x}{2D_x} \right)^2 \hat{C} e^A \\ \frac{\partial C}{\partial t} = - \left( \frac{V_x^2}{4D_x R_d} + k \right) \hat{C} e^A + \frac{\partial \hat{C}}{\partial t} e^A \end{cases}$$

where the symbol "A" is defined as:

$$7) \quad A = \left\{ \frac{V_x x}{2D_x} - \left( \frac{V_x^2}{4D_x R_d} + k \right) t \right\}$$

Upon substitution of the derivatives of Eq. (6) into Eqs. (1), (2), (3), the mass transport equation reduces to the diffusion equation.

$$8) \quad R_d \frac{\partial \hat{C}}{\partial t} = D_x \frac{\partial^2 \hat{C}}{\partial x^2} + D_y \frac{\partial^2 \hat{C}}{\partial y^2} + D_z \frac{\partial^2 \hat{C}}{\partial z^2} - k R_d C_{ic} e^{\left\{ \frac{V_x x}{2D_x} + \left( \frac{V_x^2}{4D_x R_d} + k \right) t \right\}}$$

subject to the initial condition:

$$9) \quad \hat{C}(x, y, z, 0) = 0 \quad \text{at } t = 0$$

and boundary conditions

$$\left. \begin{aligned}
 & \frac{\partial \hat{C}}{\partial y} = 0 && \text{at } y = \pm\infty \\
 & \frac{\partial \hat{C}}{\partial z} = 0 && \text{at } z = 0 \\
 & \frac{\partial \hat{C}}{\partial z} = 0 && \text{at } z = B \\
 & C, \frac{\partial \hat{C}}{\partial x} = 0 && \text{at } x = +\infty \\
 & \hat{C}(0, y, z, t) = e^{\left(\frac{v^2}{4D_x R_d} + k\right)t} \sum_{j=1}^{N_{bc}} \{C_{bcj}(t) - C_{ic}\} \cdot \\
 & \quad \left\{ H(y - y_{1j}) - H(y - y_{2j}) \right\} \left\{ H(z - z_{1j}) - H(z - z_{2j}) \right\} \cdot \\
 & \quad \left\{ H(t - t_{ONj}) - H(t - t_{OFFj}) \right\} \\
 \end{aligned} \right\} 10)$$

If we use the integral transform technique to solve the partial differential equation, we will need to know the kernels for second type boundary conditions in a finite domain. Ozisik (1968) gives these kernels as follows:

$$11) \quad \left\{ \begin{aligned}
 & K_z(\Psi_m, z) = \left(\frac{2}{B}\right)^{\frac{1}{2}} \cos(\Psi_m z) \quad \text{for } \Psi_m = \frac{\pi m}{B} \quad m = 1, 2, \dots \\
 & K_z(0, z) = \left(\frac{1}{B}\right)^{\frac{1}{2}} \quad \text{for } m = 0
 \end{aligned} \right.$$

where  $\Psi_m$  is the eigenvalue of the corresponding Sturm-Liouville problem.

For semi-infinite domain problems with first type boundary conditions, Ozisik (1968) gives the kernel as:

$$12) \quad K_x(\beta, x) = \sqrt{\frac{2}{\pi}} \sin(\beta x)$$

The kernel for infinite domain problems is given by Ozisik (1968) as

$$13) \quad K_y(v, y) = e^{ivy}$$

We will first eliminate the  $x$  variation in our partial differential equation. Multiply Eq. (8) by the kernel  $K_x(\beta, x)$  and then apply the following definition of an integral transform.

$$14) \quad \bar{C}(\beta, y, z, t) = \int_{x'=0}^{\infty} K_x(\beta, x') \hat{C}(x', y, z, t) dx'$$

In order to eliminate the y and z variation from the partial differential equation, we will apply the following two integral transformations:

$$15) \quad \bar{\bar{C}}(\beta, v, z, t) = \int_{y'=-\infty}^{\infty} K_y(v, y') \bar{C}(\beta, y', z, t) dy'$$

$$16) \quad \bar{\bar{\bar{C}}}(\beta, v, \psi_m, t) = \int_{z'=0}^B K_z(\psi_m, z') \bar{\bar{C}}(\beta, v, z', t) dz'$$

where  $K_y(v, y')$  is the kernel of Eq. (13) and  $K_z(\psi_m, z')$  is the kernel of Eq. (11).

Multiply Eq (8) by  $K_x(\beta, x')$  and then integrate  $x'$  from 0 to  $+\infty$ , using integration-by-parts twice to evaluate the following:

$$17) \quad \int_{x'=0}^{\infty} K_x(\beta, x') \frac{\partial^2 \hat{C}}{\partial x'^2} dx' = \left\{ K_x(\beta, x) \frac{\partial \hat{C}}{\partial x} - \hat{C} \frac{\partial K_x}{\partial x} \right\} \Big|_{x=0}^{\infty} + \int_{x'=0}^{\infty} \hat{C} \frac{\partial^2 K_x}{\partial x'^2} dx'$$

The curl bracketed term of Eq. (17) goes to zero at the  $x = \infty$  boundary. Replace the last integral term in Eq. (17) with the transform definition of Eq. (14) to get:

$$18) \quad \int_{x'=0}^{\infty} K_x(\beta, x') \frac{\partial^2 \hat{C}}{\partial x'^2} dx' = \left\{ \frac{\partial K_x}{\partial x}(\beta, 0) \hat{C}(0, y, z, t) \right\}_{\text{at } x=0} - \beta^2 \bar{C}(\beta, y, z, t)$$

where the kernel  $K_x$  of Eq. (12) was evaluated at  $x = 0$ .

In a similar manner, we will multiply Eq. (8) by the kernels  $K_y(v, y')$  and then  $K_z(\psi_m, z')$  and then integrate-by-parts to get the following:

$$19) \quad \int_{y'=-\infty}^{\infty} K_y(v, y') \frac{\partial^2 \bar{C}}{\partial y'^2} dy' = -v^2 \bar{\bar{C}}(\beta, v, z, t)$$

$$20) \quad \int_{z'=0}^B K_z(\psi_m, z') \frac{\partial^2 \bar{\bar{C}}}{\partial z'^2} dz' = -\psi_m^2 \bar{\bar{\bar{C}}}(\beta, v, \psi_m, t)$$

where the boundary condition of Eq. (10) where used.

The final triple transformed solution of Eq. (8) is:

$$\begin{aligned}
 R_d \frac{d\bar{\bar{C}}}{dt} = & -\beta^2 D_x \bar{\bar{C}} - v^2 D_y \bar{\bar{C}} - \psi_m^2 D_z \bar{\bar{C}} \\
 & + \int_{y'=-\infty}^{\infty} \int_{z'=0}^B D_x \left\{ \frac{\partial K_x}{\partial x} \hat{C}(0, y', z', t) \right\}_{\text{at } x=0} K_y K_z dy' dz' \\
 & - k R_d C_{ic} e^{\left( \frac{V_x^2}{4D_x R_d} + k \right) t} \int_{x'=0}^{\infty} K_x e^{\frac{-V_x x'}{2D_x}} \int_{y'=-\infty}^{\infty} K_y \int_{z'=0}^B K_z dx' dy' dz'
 \end{aligned}
 \tag{21}$$

with the initial condition:

$$\bar{\bar{C}}(\beta, v, \psi_m, 0) = 0 \quad \text{at } t=0
 \tag{22}$$

Note that our problem of Eq. (21) has been reduced to that of an ordinary-differential, first-order equation as a function of time.

Integrate the first-order ordinary differential equation of Eq. (21) with respect to time to get:

$$\begin{aligned}
 \bar{\bar{C}}(\beta, v, \psi_m, t) = & \frac{D_x}{R_d} \beta \sqrt{\frac{2}{\pi}} e^{-\left( \beta^2 D_x + v^2 D_y + \psi_m^2 D_z \right) \frac{t}{R_d}} \bullet \\
 & \sum_{j=1}^{N_{bc}} \int_{t'=0}^t e^{\left( \beta^2 D_x + v^2 D_y + \psi_m^2 D_z \right) \frac{t'}{R_d} + \left( k + \frac{V_x^2}{4D_x R_d} \right) t'} \int_{z'=z_{1j}}^{z_{2j}} \int_{y'=y_{1j}}^{y_{2j}} K_z(\psi_m, z') K_y(v, y') \bullet \\
 & (C_{bcj} - C_{ic}) dy' dz' dt' \\
 & - k C_{ic} \int_{t'=0}^t e^{-\left( \beta^2 D_x + v^2 D_y + \psi_m^2 D_z \right) \frac{(t-t')}{R_d} + \left( k + \frac{V_x^2}{4D_x R_d} \right) t'} \bullet \\
 & \int_{x'=0}^{\infty} K_x e^{\frac{-V_x x'}{2D_x}} \int_{y'=-\infty}^{\infty} K_y \int_{z'=0}^B K_z dx' dy' dz' dt'
 \end{aligned}
 \tag{23}$$

where the  $x = 0$  boundary condition of Eq. (10) was used to get

$$\left\{ \frac{\partial K_x}{\partial x} \hat{C} \right\} = \beta \sqrt{\frac{2}{\pi}} e^{\left( k + \frac{V_x^2}{4D_x R_d} \right) t} \sum_{j=1}^{N_{bc}} \left\{ C_{bcj}(t') - C_{ic} \right\} \left\{ H(y - y_{1j}) - H(y - y_{2j}) \right\} \cdot \left\{ H(z - z_{1j}) - H(z - z_{2j}) \right\} \left\{ H(t' - t_{ONj}) - H(t' - t_{OFFj}) \right\}$$

24)

The three inverse transforms are defined as follows:

$$\bar{\bar{C}}(\beta, v, z, t) = \sum_{m=0}^{\infty} K_z(\psi_m, z) \bar{\bar{C}}(\beta, v, \psi_m, t)$$

25)

$$\bar{C}(\beta, y, z, t) = \frac{1}{2\pi} \int_{v=-\infty}^{\infty} K_y(-v, y) \bar{\bar{C}}(\beta, v, z, t) dv$$

26)

$$\hat{C}(x, y, z, t) = \int_{\beta=0}^{\infty} K_x(\beta, x) \bar{C}(\beta, y, z, t) d\beta$$

27)

Apply the three inverse transforms of Eqs. (25), (26), and (27) by first multiplying Eq. (23) by  $K_z(\Psi_m, z)$  then multiplying by  $K_y(-v, y)$  and finally multiplying by  $K_x(\beta, x)$ .

The end result of applying the three inverse transforms to Eq. (23) is as follows:

$$\hat{C}(x, y, z, t) = \frac{D_x e^{\left( \frac{V_x^2}{4D_x R_d} + k \right) t}}{\pi R_d \sqrt{2\pi}} \sum_{m=0}^{\infty} K_z(\psi_m, z) \int_{v=-\infty}^{\infty} K_y(-v, y) \int_{\beta=0}^{\infty} K_x(\beta, x) \beta \cdot \sum_{j=1}^{N_{bc}} \int_{t'=0}^t e^{-\left( \frac{\beta^2 D_x + v^2 D_y + \psi_m^2 D_z}{R_d} \right) (t-t')} - \left( k + \frac{V_x^2}{4D_x R_d} \right) (t-t')} \cdot \int_{z'=z_{1j}}^{z_{2j}} \int_{y'=y_{1j}}^{y_{2j}} K_z(\psi_m, z') K_y(v, y') \left\{ C_{bcj}(t') - C_{ic} \right\} dy' dz' dt' d\beta dv$$

$$- \frac{k C_{ic}}{2\pi} e^{\left( k + \frac{V_x^2}{4D_x R_d} \right) t} \sum_{m=0}^{\infty} K_z(\psi_m, z) \int_{v=-\infty}^{\infty} K_y(-v, y) \int_{\beta=0}^{\infty} K_x(\beta, x) \cdot \int_{t'=0}^t e^{-\left( \beta^2 D_x + v^2 D_y + \psi_m^2 D_z \right) \frac{(t-t')}{R_d}} - \left( k + \frac{V_x^2}{4D_x R_d} \right) (t-t')} \int_{x'=0}^{\infty} K_x e^{\frac{-V_x x'}{2D_x}} \int_{y'=-\infty}^{\infty} K_y \int_{z'=0}^B K_z dy' dx' dz' dt' d\beta dv$$

28)

Define the following coefficient

$$29) \quad L_m = \begin{cases} \frac{1}{2} & \text{if } m = 0 \\ 1 & \text{if } m = 1, 2, 3, \dots \end{cases}$$

Substitute the  $K_x$ ,  $K_y$ ,  $K_z$  kernels of Eqs. (11), (12), and (13) and the  $L_m$  coefficient of Eq. (29) into Eq. (28) to get:

$$\begin{aligned} \hat{C}(x, y, z, t) = & \frac{2D_x e^{\left(\frac{V_x^2}{4D_x R_d} + k\right)t}}{B\pi^2 R_d} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \bullet \\ & \sum_{j=1}^{N_{bc}} \int_{t'=0}^t e^{-\left(\frac{\psi_m^2 D_z}{R_d} + k + \frac{V_x^2}{4D_x R_d}\right)(t-t')} \int_{\beta=0}^{\infty} \beta \sin(\beta x) e^{-\frac{\beta^2 D_x}{R_d}(t-t')} \bullet \\ & \int_{z'=z_{1j}}^{z_{2j}} \cos(\psi_m z') \int_{y'=y_{1j}}^{y_{2j}} \int_{v=-\infty}^{\infty} e^{-iv(y-y') - \frac{v^2 D_y}{R_d}(t-t')} (C_{bcj}(t') - C_{ic}) dt' dv dy' dz' d\beta \\ & - \frac{2kC_{ic} e^{\left(k + \frac{V_x^2}{4D_x R_d}\right)t}}{B\pi^2} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \int_{y'=-\infty}^{\infty} \int_{z'=0}^B \cos(\psi_m z') \bullet \\ & \int_{t'=0}^t e^{-\left(\frac{\psi_m^2 D_z}{R_d} + k + \frac{V_x^2}{4D_x R_d}\right)(t-t')} \int_{v=-\infty}^{\infty} e^{-\frac{v^2 D_y}{R_d}(t-t') - iv(y-y')} dv \bullet \\ 30) \quad & \int_{\beta=0}^{\infty} \sin(\beta x) e^{-\frac{\beta^2 D_x}{R_d}(t-t')} \int_{x'=0}^{\infty} \sin(\beta x') e^{-\frac{V_x x'}{2D_x}} dx' d\beta dt' dz' dy' \end{aligned}$$

However, we can evaluate the following five integrals

$$31) \quad \int_{z'=z_{1j}}^{z_{2j}} \cos(\psi_m z') dz' = \begin{cases} (z_{2j} - z_{1j}) & \text{if } m = 0 \\ \left\{ \frac{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})}{\psi_m} \right\} & \text{if } m > 0 \end{cases}$$

$$32) \quad \int_{\beta=0}^{\infty} \beta \sin(\beta x) e^{-\left(\frac{\beta^2 D_x}{R_d}\right)(t-t')} d\beta = \frac{x\sqrt{\pi} e^{-\frac{x^2 R_d}{4D_x(t-t')}}}{4\left(D_x \frac{(t-t')}{R_d}\right)^{\frac{3}{2}}}$$

$$33) \quad \int_{v=-\infty}^{\infty} e^{-iv(y-y') - \frac{v^2 D_y}{R_d}(t-t')} dv = \sqrt{\frac{\pi R_d}{D_y(t-t')}} e^{-\frac{(y-y')^2 R_d}{4D_y(t-t')}}$$

$$34) \quad \int_{z'=0}^H \cos(\psi_m z') dz' = \begin{cases} B & \text{if } m = 0 \\ \frac{\sin(\psi_m B)}{\psi_m} & \text{if } m = 1, 2, 3, \dots \end{cases}$$

$$35) \quad \int_{x'=0}^{\infty} \sin(\beta x') e^{-\frac{V_x x'}{2D_x}} dx' = \frac{\beta}{\left(\frac{V_x^2}{4D_x^2} + \beta^2\right)}$$

Define the following dimensionless coefficients

$$36) \quad O_{mj} = \begin{cases} \frac{(z_{2j} - z_{1j})}{B} & \text{if } m = 0 \\ \frac{\{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})\}}{\psi_m B} & \text{if } m > 0 \end{cases}$$

$$37) \quad P_m = \begin{cases} 1 & \text{if } m = 0 \\ \frac{\sin(\psi_m B)}{\psi_m B} & \text{if } m = 1, 2, \dots \end{cases}$$

Substitute the integrals of Eqs. (31-35) into Eq. (30) and use Eqs. (36) and 37) to get:

$$\begin{aligned}
 \hat{C}(x, y, z, t) &= \frac{xR_d e^{\left(k + \frac{V_x^2}{4D_x R_d}\right)t}}{2\pi\sqrt{D_x D_y}} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \cdot \\
 &\int_{t'=0}^t \frac{e^{-\left(\frac{\psi_m^2 D_x + k + \frac{V_x^2}{4D_x R_d}\right)(t-t') - \frac{x^2 R_d}{4D_x(t-t')}}}{(t-t')^2} \int_{y'=y_{1j}}^{y_{2j}} e^{-\frac{(y-y')^2 R_d}{4D_y(t-t')}} dy' \cdot \\
 &(C_{bcj}(t') - C_{ic}) dt' \\
 &- \frac{2kC_{ic}}{\pi^2} \sqrt{\frac{\pi R_d}{D_y}} e^{\left(k + \frac{V_x^2}{4D_x R_d}\right)t} \sum_{m=0}^{\infty} L_m P_m \cos(\psi_m z) \cdot \\
 &\int_{t'=0}^t \frac{e^{-\left(\frac{V_x^2}{4D_x R_d} + k + \frac{\psi_m^2 D_x}{R_d}\right)(t-t')}}{\sqrt{t-t'}} \int_{y'=-\infty}^{\infty} e^{-\frac{(y-y')^2 R_d}{4D_y(t-t')}} \cdot \\
 &\int_{\beta=0}^{\infty} \frac{\beta \sin(\beta x) e^{-\frac{\beta^2 D_x(t-t')}{R_d}}}{\left(\beta^2 + \frac{V_x^2}{4D_x^2}\right)} d\beta dy' dt'
 \end{aligned}$$

38)

Note the following three integrals:

$$\int_{y'=y_{1j}}^{y_{2j}} e^{-\frac{(y-y')^2 R_d}{4D_y(t-t')}} dy' = \sqrt{\frac{\pi D_y(t-t')}{R_d}} \left\{ \operatorname{erfc} \left( \frac{(y_{1j} - y)}{\sqrt{4D_y(t-t')}} \frac{R_d}{R_d} \right) - \operatorname{erfc} \left( \frac{(y_{2j} - y)}{\sqrt{4D_y(t-t')}} \frac{R_d}{R_d} \right) \right\}$$

39)

$$\int_{y'=-\infty}^{\infty} e^{-\frac{(y-y')^2 R_d}{4D_y(t-t')}} dy' = 2\sqrt{\frac{\pi D_y(t-t')}{R_d}}$$

40)

$$\int_{\beta=0}^{\infty} \frac{\beta \sin(\beta x) e^{-\frac{\beta^2 D_x(t-t')}{R_d}}}{\left(\beta^2 + \frac{V_x^2}{4D_x^2}\right)} d\beta = \frac{\pi e^{-\frac{V_x^2(t-t')}{4D_x R_d}}}{4} \left\{ e^{-\frac{xV_x}{2D_x}} \operatorname{erfc} \left( -\frac{x}{2} \sqrt{\frac{R_d}{D_x(t-t')}} + \frac{V_x}{2} \sqrt{\frac{t-t'}{D_x R_d}} \right) \right. \\
 \left. - e^{\frac{xV_x}{2D_x}} \operatorname{erfc} \left( \frac{x}{2} \sqrt{\frac{R_d}{D_x(t-t')}} + \frac{V_x}{2} \sqrt{\frac{t-t'}{D_x R_d}} \right) \right\}$$

41)

Substitute the integrals of Eqs. (39-41) into Eq. (38) and rearrange to get:

$$\begin{aligned}
 \hat{C}(x, y, z, t) = & \frac{x}{2} \sqrt{\frac{R_d}{\pi D_x}} e^{\left(k + \frac{V_x^2}{4D_x R_d}\right)t} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \cdot \\
 & \int_{t'=0}^t e^{\frac{\left(\frac{\psi_m^2 D_z}{R_d} + k + \frac{V_x^2}{4D_x R_d}\right)(t-t') - \frac{x^2 R_d}{4D_x(t-t')}}}{(t-t')^{\frac{3}{2}}} \left\{ \operatorname{erfc} \left( \frac{(y_{1j} - y)}{\sqrt{\frac{4D_y(t-t')}{R_d}}} \right) \right. \\
 & \left. - \operatorname{erfc} \left( \frac{(y_{2j} - y)}{\sqrt{\frac{4D_y(t-t')}{R_d}}} \right) \right\} (C_{bcj}(t') - C_{ic}) dt' \\
 & - k C_{ic} e^{\left(k + \frac{V_x^2}{4D_x R_d}\right)t} \sum_{m=0}^{\infty} L_m P_m \cos(\psi_m z) \int_{t'=0}^t e^{-\left(k + \frac{\psi_m^2 D_z}{R_d}\right)(t-t')} \cdot \\
 & \left\{ e^{\frac{xV_x}{2D_x}} \operatorname{erfc} \left( -\frac{x}{2} \sqrt{\frac{R_d}{D_x(t-t')}} + \frac{V_x}{2} \sqrt{\frac{t-t'}{D_x R_d}} \right) \right. \\
 & \left. - e^{\frac{xV_x}{2D_x}} \left( \frac{x}{2} \sqrt{\frac{R_d}{D_x(t-t')}} + \frac{V_x}{2} \sqrt{\frac{t-t'}{D_x R_d}} \right) \right\} dt'
 \end{aligned}$$

42)

Note the following integral relationships:

$$43) \quad \int_{\tau=0}^t f(\tau) H(t - \tau - t_{on}) d\tau = \int_{\tau=0}^{\max\{0, t-t_{on}\}} f(\tau) d\tau$$

$$44) \quad \int_{\tau=0}^t f(\tau) \{H(t - \tau - t_{on}) - H(t - \tau - t_{off})\} d\tau = \int_{\tau=\max\{0, t-t_{off}\}}^{\max\{0, t-t_{on}\}} f(\tau) d\tau$$

$$45) \quad \int_{\tau=0}^t f(\tau)H(t-\tau-t_{off})d\tau = \int_{\tau=0}^{\max[0,t-t_{off}]} f(\tau)d\tau$$

Use the transform of Eq. (5) and the integrals of Eqs. (43-45) in Eq. (42) to obtain the final solution to the concentration:

$$46) \quad C(x, y, z, t) = C_{ic} + \frac{x}{2} \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \cdot$$

$$\int_{\tau=0}^{t^*} \frac{e^{-\left(k + \frac{V_x^2}{4D_x R_d} + \frac{\psi_m^2 D_z}{R_d}\right)\tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{\frac{3}{2}}} \left\{ \operatorname{erfc}\left(y_{1j} - y\right) \sqrt{\frac{R_d}{4D_y \tau}} - \operatorname{erfc}\left(y_{2j} - y\right) \sqrt{\frac{R_d}{4D_y \tau}} \right\} \cdot$$

$$\left\{ C_{bcj}(t^* - \tau) - C_{ic} \right\} \left\{ H(t - \tau - t_{ONj}) - H(t - \tau - t_{OFFj}) \right\} d\tau$$

$$- k C_{ic} \sum_{m=0}^{\infty} L_m P_m \cos(\psi_m z) \int_{\tau=0}^{t^*} e^{-\left(k + \frac{\psi_m^2 D_z}{R_d}\right)\tau} \left\{ \operatorname{erfc}\left(-x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}}\right) \right.$$

$$\left. - e^{\frac{x V_x}{D_x}} \operatorname{erfc}\left(x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}}\right) \right\} d\tau$$

where the eigenvalue  $\Psi_m = \frac{\pi m}{B}$  and  $t^* = t - t_{ON1}$ .

$t \geq t_{ON1}$

Note the following indefinite integral:

$$47) \quad \int e^{(M\tau+N)} \operatorname{erfc}\left(a\sqrt{\tau} + \frac{b}{\sqrt{\tau}}\right) d\tau = \frac{e^{(m\tau+N)}}{M} \operatorname{erfc}\left(a\sqrt{\tau} + \frac{b}{\sqrt{\tau}}\right)$$

$$+ \frac{e^{-2ab+N+2b\sqrt{a^2-M}}}{2M} \operatorname{erf}\left(\sqrt{\tau(a^2-M)} + \frac{b}{\sqrt{\tau}}\right) \left(\frac{a}{\sqrt{a^2-M}} + 1\right)$$

$$+ \frac{e^{-2ab+N-2b\sqrt{a^2-M}}}{2M} \operatorname{erf}\left(\sqrt{\tau(a^2-M)} - \frac{b}{\sqrt{\tau}}\right) \left(\frac{a}{\sqrt{a^2-M}} - 1\right)$$

In addition, note that all of the  $P_m$  terms vanish except for the  $m=0$  case. Upon substitution the  $\Psi_m$  eigenvalues from Eq. 11), we find that:

$$48) \quad \sin(\Psi_m B) = \sin(\pi m) = 0 \quad m=0,1,\dots$$

Hence, the  $P_m$  coefficient reduces to:

$$49) \quad P_m = \begin{cases} 1 & \text{if } m = 0 \\ 0 & \text{if } m = 1,2,\dots \end{cases}$$

Our solution in Eq. 46) reduces to the following:

50)

$$C(x, y, z, t) = C_{ic} + \frac{x}{2} \sqrt{\frac{R_d}{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sum_{m=0}^{\infty} L_m \cos(\Psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \cdot$$

$$\int_{\tau=0}^{t^*} \frac{e^{-\frac{x^2 R_d}{4D_x \tau} - \left(k + \frac{V_x^2}{4D_x R_d} + \frac{\Psi_m^2 D_z}{R_d}\right) \tau}}{\tau^{\frac{3}{2}}} \left\{ \operatorname{erfc} \left( (y_{1j} - y) \sqrt{\frac{R_d}{4D_y \tau}} \right) - \operatorname{erfc} \left( (y_{2j} - y) \sqrt{\frac{R_d}{4D_y \tau}} \right) \right\} \cdot$$

$$\left\{ C_{bcj} (t^* - \tau) - C_{ic} \right\} \left\{ H(t - \tau - t_{ONj}) - H(t - \tau - t_{OFFj}) \right\} d\tau$$

$$- k C_{ic} \int_{\tau=0}^t e^{-k\tau} \left\{ \operatorname{erfc} \left( -x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) - e^{\frac{xV_x}{D_x}} \operatorname{erfc} \left( x \sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) \right\} d\tau$$

$$\text{where } \Psi_m = \frac{\pi m}{B}, \quad t^* = t - t_{ON1} \quad t \geq t_{ON1}$$

### Special Case: Fully Penetrating Source

To get a single fully penetrating source set  $N_{bc}=1$  and  $z_1$  and  $z_2$  as follows:

$$51) \quad \begin{cases} z_1 = 0 \\ z_2 = B \end{cases}$$

The solution of Eq. (50) now reduces to the 2-D solution (Cleary and Ungs, 1978; Javandel et al., 1984; EPRI, 1989):

$$52) \quad C(x, y, z, t) = \frac{C_{ic} x \sqrt{R_d} e^{\left(\frac{V_x x}{2D_x} - \gamma\right)}}{4\sqrt{\pi D_x}} \int_{\tau=0}^t \frac{e^{-\left(k - \gamma + \frac{V_x^2}{4D_x R_d}\right) \tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{\frac{3}{2}}} \cdot \left\{ \operatorname{erfc} \left( \frac{(y_1 - y)}{\sqrt{\frac{4D_y \tau}{R_d}}} \right) - \operatorname{erfc} \left( \frac{(y_2 - y)}{\sqrt{\frac{4D_y \tau}{R_d}}} \right) \right\} d\tau$$

### Special Case: Infinite Width Source

An infinite source width problem of a single source is found by setting  $N_{bc} = 1$ , and  $y_1$  and  $y_2$  as follows:

$$53) \quad \begin{cases} y_1 = -\infty \\ y_2 = +\infty \end{cases}$$

$$54) \quad C(x, y, z, t) = \frac{C_o x \sqrt{R_d} e^{\left(\frac{V_x x}{2D_x}\right)}}{\sqrt{\pi D_x}} \sum_{m=0}^{\infty} L_m O_m \cos(\psi_m z) \cdot \int_{\tau=0}^t \frac{e^{-\left(\frac{\psi_m^2 D_x}{R_d} + k + \frac{V_x^2}{4D_x R_d}\right) \tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{\frac{3}{2}}} d\tau$$

which upon integration reduces to

$$55) \quad C(x, y, z, t) = C_o e^{\left(\frac{V_x x}{2D_x}\right)} \sum_{m=0}^{\infty} L_m O_m \cos(\psi_m z) \cdot \left\{ e^{\sqrt{\frac{\alpha R_d}{D_x}}} \operatorname{erfc} \left( \frac{x}{\sqrt{\frac{4D_x t^*}{R_d}}} + \sqrt{\alpha t^*} \right) - e^{-\sqrt{\frac{\alpha R_d}{D_x}}} \operatorname{erfc} \left( \frac{x}{\sqrt{\frac{4D_x t^*}{R_d}}} - \sqrt{\alpha t^*} \right) \right\}$$

where the coefficient  $\alpha$  is defined as

$$56) \quad \alpha = \left\{ \frac{\psi_m^2 D_z}{R_d} + k + \frac{V_x^2}{4D_x R_d} \right\}$$

### Special Case: Steady-state Mass Flux

The steady-state mass flux at location  $x$  of the  $x$ -axis is found by evaluating both the advective and dispersive components of flux :

$$57) \quad \dot{m}(x) = \theta V_x \int_{y'=-\infty}^{\infty} \int_{z'=0}^B C(x, y', z', \infty) dy' dz' - \theta D_x \int_{y'=-\infty}^{\infty} \int_{z'=0}^B \frac{\partial C}{\partial x}(x, y', z', \infty) dy' dz'$$

where  $\theta$  is the porosity of the aquifer.

The steady-state concentration  $C(x, y, z, \infty)$  is found by setting  $t = \infty$  in Eq. (50).

In order to evaluate Eq. (57), we will need the following integral:

$$58) \quad \int_{z'=0}^B \cos(\psi_m z') dz' = \left\{ \frac{\sin(\psi_m z')}{\psi_m} \right\} \Big|_0^B = \begin{cases} B & \text{if } m = 0 \\ 0 & \text{if } m > 0 \end{cases}$$

Hence, only the  $m = 0$  term of Eq. (50) need be considered when evaluating Eq. (57). The only  $y$  term in Eq. (57) is found by:

$$59) \quad \int_{y'=-\infty}^{\infty} \left\{ \operatorname{erfc} \left( \frac{(y_1 - y')}{\sqrt{\frac{4D_y \tau}{R_d}}} \right) - \operatorname{erfc} \left( \frac{(y_2 - y')}{\sqrt{\frac{4D_y \tau}{R_d}}} \right) \right\} dy' = 2(y_2 - y_1)$$

Substitute the integrals of Eqs. (58) and (59) and the steady-state solution of Eq. (50) into the first integral of Eq. (57):

$$60) \quad \int_{y'=-\infty}^{\infty} \int_{z'=0}^B C(x, y', z', \infty) dy' dz' = C_{ic} \frac{x(z_2 - z_1)(y_2 - y_1)}{2\sqrt{\pi D_x}} e^{\frac{V_x x}{2D_x}} \sqrt{R_d} \cdot \int_{\tau=0}^{\infty} \frac{e^{-\left(k + \frac{V_x^2}{4D_x R_d}\right)\tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{\frac{3}{2}}} d\tau$$

The right-hand side integral of Eq. (60) can be evaluated as follows:

$$61) \quad b \int_{\tau=0}^{\infty} \frac{e^{-a^2 \tau - \frac{b^2}{\tau}}}{\tau^{\frac{3}{2}}} d\tau = \sqrt{\pi} e^{-2ab}$$

Substitute Eq. (61) into Eq. (60) and let  $b = x \sqrt{\frac{R_d}{4D_x}}$

$$62) \quad \int_{y'=-\infty}^{\infty} \int_{z'=0}^B C(x, y', z', \infty) dy' dz' = C_{ic} (z_2 - z_1)(y_2 - y_1) e^{x \left\{ \frac{V_x}{2D_x} - \sqrt{\frac{kR_d}{D_x} + \frac{V_x^2}{4D_x^2}} \right\}}$$

Differentiate Eq. (62) with respect to x

$$63) \quad \int_{y'=-\infty}^{\infty} \int_{z'=0}^B \frac{\partial C}{\partial x} (x, y', z', \infty) dy' dz' = C_{ic} (z_2 - z_1)(y_2 - y_1) \cdot \left\{ \frac{V_x}{2D_x} - \sqrt{\frac{kR_d}{D_x} + \frac{V_x^2}{4D_x^2}} \right\} e^{x \left\{ \frac{V_x}{2D_x} - \sqrt{\frac{kR_d}{D_x} + \frac{V_x^2}{4D_x^2}} \right\}}$$

We will now evaluate Eq. (57) at  $x = 0$ .

$$64) \quad \dot{m}(x=0) = \theta V_x \int_{y'=-\infty}^{\infty} \int_{z'=0}^B C(0, y', z', \infty) dy' dz' - \theta D_x \int_{y'=-\infty}^{\infty} \int_{z'=0}^B \frac{\partial C}{\partial x} (0, y', z', \infty) dy' dz'$$

Substitute Eqs. (62) and (63) into Eq. (64) for  $x = 0$  to give the total mass flux as:

$$65) \quad \dot{m}(x=0, t=\infty) = \theta C_o (z_2 - z_1)(y_2 - y_1) \frac{V_x}{2} \left\{ 1 + \sqrt{1 + \frac{k4R_d D_x}{V_x^2}} \right\}$$

**References**

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Attachment 5

**Attachment 5**

**Input Data for MYGRT Model Runs**

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 1-1**  
(Reference Figures 1 and 2)

All elevations and thickness values in feet.

**Volumetric Moisture Content of Soil:**  
Estimated from Table 6, Ref. 4      25%

**Depth to Water Table:**

	Source	MS-11 Outside of Footprint	MS-7	B-6	B-5 Outside of Footprint	MS-2 Outside of Footprint
Approximate Elevation of Excavation	-		828	822		
Estimated Seasonal High Groundwater Elevation (NAVD 88)	Figure 3 of 7, Ref. 4	N/A	819.53	817.00	N/A	N/A
Thickness of Unsaturated Zone	-		8.47	5		

**Hydraulic Gradient for Section:**

Approximate Seasonal High GW elevation:	
at edge of MS-11	829.6
at 2L Compliance Boundary	807
Hydraulic Gradient (ft/ft)	0.01

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 1-1**

(Reference Figures 1 and 2)

All elevations and thickness values in feet.

**Hydraulic Conductivity for Section:**

	Source	MS-11	MS-7	B-6	B-5	MS-2
Hydraulic Conductivity (ft/day)	See Table 5, Reference 4	5.0E-01	8.7E-01	4.4E-01	6.4E-01	6.4E-01
Hydraulic Conductivity (ft/year)	See Table 5, Reference 4	182.5	317.6	160.6	233.6	233.6
Geometric Mean ( ft/yr)	219.4					

**Effective Porosity for Section:**

	Source	MS-11	MS-7	B-6	B-5	MS-2
Depth of Sample	See Table 4, Reference 4	No Sample	18.5' to 20'	43' to 45'	33.5' to 35'	No Sample
Effective Porosity Values (vol/vol)	See Table 4, Reference 4	No Sample	0.27	0.31	0.25	No Sample
Geometric Mean (vol/vol)	0.28					

**Thickness of Aquifer:**

	Source	MS-11	MS-7	B-6	B-5	MS-2
Minimum Measured Groundwater Elevation (NAVD 88)	Measured Water Levels	828.62	814.04	810.01	805.34	799.58
Top of Bedrock	Table 1, Ref. 4	797.87	796.34	761.59	763.27	784.67
Thickness of Aquifer		30.75	17.7	48.42	42.07	14.91
Geometric Mean Thickness	27.8					

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 2-2**  
(Reference Figures 1 and 2)

(All elevations and thickness values in feet)

**Volumetric Moisture Content of Soil:**

Estimated from Table 6, Ref. 4      25%

**Thickness of Unsaturated Zone:**

	Source	MS-10 Outside of Footprint	B-2 828	B-1 Outside of Footprint
Approximate Elevation of Excavation	-			
Estimated Seasonal High Groundwater Elevation (NAVD 88)	Figure 3 of 7, Ref. 4	836.07	819.5	802.52
Thickness of Unsaturated Zone	-		8.5	

**Hydraulic Gradient for Section:**

Approximate Seasonal High GW elevation: at MS-10	836.1
at 2L Compliance Boundary	805
Hydraulic Gradient (ft/ft)	0.03

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 2-2**

(Reference Figures 1 and 2)

(All elevations and thickness values in feet)

**Hydraulic Conductivity for Section:**

	Source	MS-10	B-2	B-1
Hydraulic Conductivity (ft/day)	See Table 5, Reference 4	4.0E-01	5.0E-01	6.4E-01
Hydraulic Conductivity (ft/year)	See Table 5, Reference 4	146.0	182.5	233.6
Geometric Mean ( ft/yr)	183.9			

Note: As described in Table 5 of Reference 4, values for hydraulic conductivity are estimated from similar soil types for wells MS-10 and B-1.

**Effective Porosity for Section:**

	Source	MS-10	B-2	B-1
Depth of Sample	See Table 4, Reference 4	No Sample	48.5 to 50'	No Sample
Effective Porosity Values (vol/vol)	See Table 5, Reference 4	0.30	0.26	0.26
Geometric Mean (vol/vol)	0.27			

Note: As described in Table 5 of Reference 4, values for effective porosity are estimated from similar soil types for wells MS-10 and B-1.

**Thickness of Aquifer**

	Source	MS-10	B-2	B-1
Minimum Measured Groundwater Elevation (NAVD 88)	Measured Water Levels	835.56	813.16	801.22
Top of Bedrock	Table 1, Ref. 4	804.29	787.85	783.09
Thickness of Aquifer	-	31.27	25.31	18.13
Geometric Mean Thickness	24.3			

**MARSHALL STEAM STATION  
FGD SCRUBBER LANDFILL - GROUNDWATER WELLS WATER LEVELS (feet)**

Well	TOC Elevation (ft)	Minimum Water Level Measured	2/6/03	2/13/03	2/21/03	2/25/03	3/28/03	4/29/03	5/28/03	6/30/03	8/8/03	11/20/03	2/11/04
B-1	811.57	801.22	801.22	na	na	801.52	801.78	802.11	802.54	802.14	802.06	801.72	801.82
B-2	860.76	813.16	813.16	na	na	813.38	813.99	814.99	815.77	816.90	817.69	818.14	817.82
B-3	859.34	808.89	808.89	na	na	809.10	809.81	811.04	812.10	813.40	814.17	814.05	813.36
B-4	861.47	806.46	806.46	na	na	806.79	807.50	808.84	810.12	811.18	812.02	812.76	812.92
B-5	844.07	805.34	805.34	na	na	805.57	806.27	808.15	810.02	812.59	813.74	813.15	812.44
B-6	854.50	810.01	810.01	na	na	810.21	810.88	811.89	812.77	814.01	815.04	815.82	815.27
B-7	854.55	805.25	805.25	na	na	805.26	805.68	806.61	807.53	809.03	810.60	812.04	811.62
MS-1	816.32	802.03	802.03	na	na	803.47	804.77	806.39	808.62	806.82	806.44	804.38	805.12
MS-2	823.18	799.58	799.58	na	na	799.89	800.75	801.45	801.63	801.44	801.17	800.51	800.85
MS-3	814.53	799.11	799.11	na	na	799.50	800.02	800.50	800.93	800.69	800.68	799.99	800.31
MS-4	847.68	805.56	805.56	na	na	805.74	806.26	807.14	808.01	809.33	810.59	811.21	810.56
MS-5	843.04	808.86	808.86	na	na	809.00	809.63	810.72	811.58	812.73	813.05	812.47	811.70
MS-6	841.90	812.07	812.07	na	na	812.96	814.30	815.51	816.41	816.25	815.29	813.80	813.79
MS-7	836.18	814.04	814.04	na	na	814.24	815.68	817.41	818.95	819.30	819.53	817.62	817.64
MS-8	851.42	821.52	821.52	na	na	821.72	822.42	823.44	824.37	825.26	825.85	825.72	825.72
MS-9	868.04	822.57	822.57	na	na	822.74	823.31	824.65	825.87	827.60	828.68	829.61	829.65
MS-10	851.29	835.56	na	na	na	na	na	na	na	na	836.07	835.56	836.10
MS-11	859.78	828.62	na	na	na	na	na	na	na	na	829.83	828.62	828.74
OW-1	842.50	821.57	na	na	821.88	821.57	822.34	823.39	824.39	825.11	825.72	825.43	825.50
OW-2	836.36	815.93	na	na	816.05	815.93	817.10	818.78	820.28	820.76	821.17	819.56	819.56
OW-3	835.66	812.61	na	na	812.61	812.78	814.57	816.45	818.22	817.66	816.89	815.16	815.14

**Attachment 5**

**Input Data for MYGRT Model Runs**

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 1-1**  
(Reference Figures 1 and 2)

All elevations and thickness values in feet.

**Volumetric Moisture Content of Soil:**  
Estimated from Table 6, Ref. 4      25%

**Depth to Water Table:**

	Source	MS-11 Outside of Footprint	MS-7	B-6	B-5 Outside of Footprint	MS-2 Outside of Footprint
Approximate Elevation of Excavation	-		828	822		
Estimated Seasonal High Groundwater Elevation (NAVD 88)	Figure 3 of 7, Ref. 4	N/A	819.53	817.00	N/A	N/A
Thickness of Unsaturated Zone	-		8.47	5		

**Hydraulic Gradient for Section:**

Approximate Seasonal High GW elevation:	
at edge of MS-11	829.6
at 2L Compliance Boundary	807
Hydraulic Gradient (ft/ft)	0.01

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 1-1**  
(Reference Figures 1 and 2)

All elevations and thickness values in feet.

**Hydraulic Conductivity for Section:**

	Source	MS-11	MS-7	B-6	B-5	MS-2
Hydraulic Conductivity (ft/day)	See Table 5, Reference 4	5.0E-01	8.7E-01	4.4E-01	6.4E-01	6.4E-01
Hydraulic Conductivity (ft/year)	See Table 5, Reference 4	182.5	317.6	160.6	233.6	233.6
Geometric Mean ( ft/yr)	219.4					

**Effective Porosity for Section:**

	Source	MS-11	MS-7	B-6	B-5	MS-2
Depth of Sample	See Table 4, Reference 4	No Sample	18.5' to 20'	43' to 45'	33.5' to 35'	No Sample
Effective Porosity Values (vol/vol)	See Table 4, Reference 4	No Sample	0.27	0.31	0.25	No Sample
Geometric Mean (vol/vol)	0.28					

**Thickness of Aquifer:**

	Source	MS-11	MS-7	B-6	B-5	MS-2
Minimum Measured Groundwater Elevation (NAVD 88)	Measured Water Levels	828.62	814.04	810.01	805.34	799.58
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Thickness of Aquifer		30.75	17.7	48.42	42.07	14.91
Geometric Mean Thickness	27.8					

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 2-2**  
(Reference Figures 1 and 2)

(All elevations and thickness values in feet)

**Volumetric Moisture Content of Soil:**  
Estimated from Table 6, Ref. 4      25%

**Thickness of Unsaturated Zone:**

	Source	MS-10 Outside of Footprint	B-2	B-1 Outside of Footprint
Approximate Elevation of Excavation	-		828	
Estimated Seasonal High Groundwater Elevation (NAVD 88)	Figure 3 of 7, Ref. 4	836.07	819.5	802.52
Thickness of Unsaturated Zone	-		8.5	

**Hydraulic Gradient for Section:**

Approximate Seasonal High GW elevation:	
at MS-10	836.1
at 2L Compliance Boundary	805
Hydraulic Gradient (ft/ft)	0.03

**Marshall Steam Station  
FGD Residue Landfill  
Properties Used in MYGRT**

**Cross Section 2-2**  
(Reference Figures 1 and 2)

(All elevations and thickness values in feet)

**Hydraulic Conductivity for Section:**

	Source	MS-10	B-2	B-1
Hydraulic Conductivity (ft/day)	See Table 5, Reference 4	4.0E-01	5.0E-01	6.4E-01
Hydraulic Conductivity (ft/year)	See Table 5, Reference 4	146.0	182.5	233.6
Geometric Mean ( ft/yr)	183.9			

Note: As described in Table 5 of Reference 4, values for hydraulic conductivity are estimated from similar soil types for wells MS-10 and B-1.

**Effective Porosity for Section:**

	Source	MS-10	B-2	B-1
Depth of Sample	See Table 4, Reference 4	No Sample	48.5 to 50'	No Sample
Effective Porosity Values (vol/vol)	See Table 5, Reference 4	0.30	0.26	0.26
Geometric Mean (vol/vol)	0.27			

Note: As described in Table 5 of Reference 4, values for effective porosity are estimated from similar soil types for wells MS-10 and B-1.

**Thickness of Aquifer**

	Source	MS-10	B-2	B-1
Minimum Measured Groundwater Elevation (NAVD 88)	Measured Water Levels	835.56	813.16	801.22
Top of Bedrock	Table 1, Ref. 4	804.29	787.85	783.09
Thickness of Aquifer	-	31.27	25.31	18.13
Geometric Mean Thickness	24.3			

MARSHALL STEAM STATION  
 FGD SCRUBBER LANDFILL - GROUNDWATER WELLS WATER LEVELS (feet)

Well	TOC Elevation (ft)	Minimum Water Level Measured	2/6/03	2/13/03	2/21/03	2/25/03	3/28/03	4/29/03	5/28/03	6/30/03	8/8/03	11/20/03	2/11/04
B-1	811.57	801.22	801.22	na	na	801.52	801.78	802.11	802.54	802.14	802.06	801.72	801.82
B-2	860.76	813.16	813.16	na	na	813.38	813.99	814.99	815.77	816.90	817.69	818.14	817.82
B-3	859.34	808.89	808.89	na	na	809.10	809.81	811.04	812.10	813.40	814.17	814.05	813.36
B-4	861.47	806.46	806.46	na	na	806.79	807.50	808.84	810.12	811.18	812.02	812.76	812.92
B-5	844.07	805.34	805.34	na	na	805.57	806.27	808.15	810.02	812.59	813.74	813.15	812.44
B-6	854.50	810.01	810.01	na	na	810.21	810.88	811.89	812.77	814.01	815.04	815.82	815.27
B-7	854.55	805.25	805.25	na	na	805.26	805.68	806.61	807.53	809.03	810.60	812.04	811.62
MS-1	816.32	802.03	802.03	na	na	803.47	804.77	806.39	808.62	806.82	806.44	804.38	805.12
MS-2	823.18	799.58	799.58	na	na	799.89	800.75	801.45	801.63	801.44	801.17	800.51	800.85
MS-3	814.53	799.11	799.11	na	na	799.50	800.02	800.50	800.93	800.69	800.68	799.99	800.31
MS-4	847.68	805.56	805.56	na	na	805.74	806.26	807.14	808.01	809.33	810.59	811.21	810.56
MS-5	843.04	808.86	808.86	na	na	809.00	809.63	810.72	811.58	812.73	813.05	812.47	811.70
MS-6	841.90	812.07	812.07	na	na	812.96	814.30	815.51	816.41	816.25	815.29	813.80	813.79
MS-7	836.18	814.04	814.04	na	na	814.24	815.68	817.41	818.95	819.30	819.53	817.62	817.64
MS-8	851.42	821.52	821.52	na	na	821.72	822.42	823.44	824.37	825.26	825.85	825.72	825.72
MS-9	868.04	822.57	822.57	na	na	822.74	823.31	824.65	825.87	827.60	828.68	829.61	829.65
MS-10	851.29	835.56	na	na	na	na	na	na	na	na	836.07	835.56	836.10
MS-11	859.78	828.62	na	na	na	na	na	na	na	na	829.83	828.62	828.74
OW-1	842.50	821.57	na	na	821.88	821.57	822.34	823.39	824.39	825.11	825.72	825.43	825.50
OW-2	836.36	815.93	na	na	816.05	815.93	817.10	818.78	820.28	820.76	821.17	819.56	819.56
OW-3	835.66	812.61	na	na	812.61	812.78	814.57	816.45	818.22	817.66	816.89	815.16	815.14

Attachment 6

**Attachment 6**

**MYGRT Model  
Input Data and Results**

**MYGRT Analysis  
Input and Results**

**Cross Section 1-1  
Sulfate**

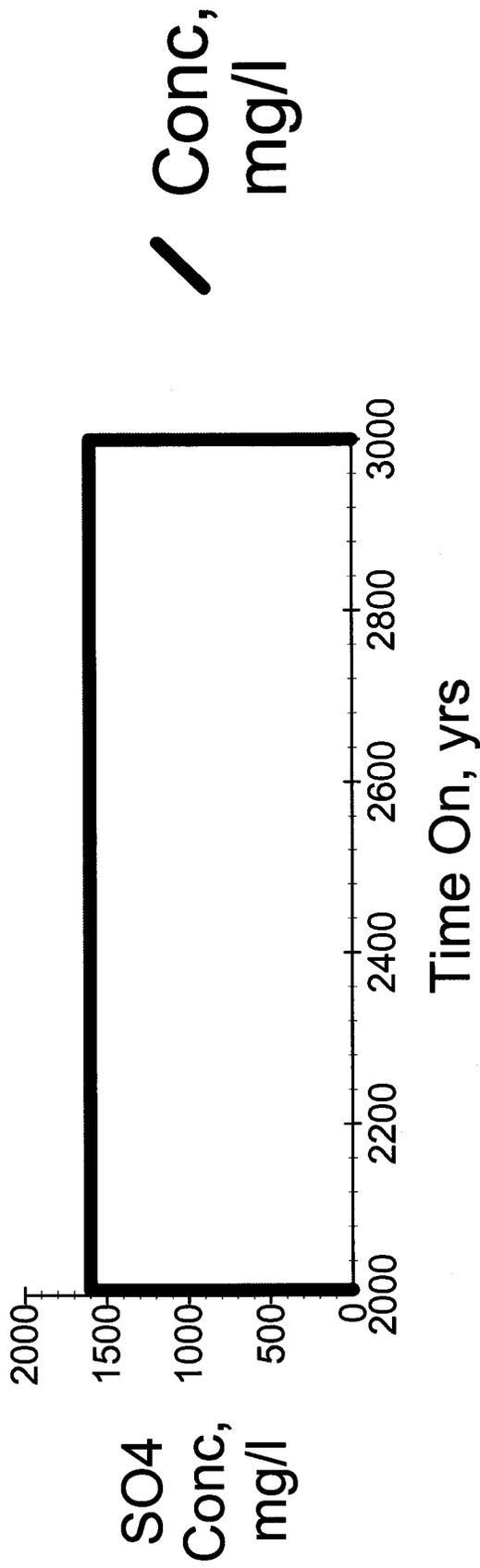
Input Parameters

Description	Units	Value	Note
General Parameters			
Site		MSS FGD Landfill - Cross Section 1-1	
Description		X Sect 1-1 Cap @End of Year	
Notes		Put your notes here.	
Solute Name		SO4	
Organic		No	
Zones Simulated		Unsat/Sat	
Source Location		Unsat	
Saturated Zone Dimension		Sat_3d	
Point or Depth Averaged		Point	
Aquifer Thickness		Finite	
Number of Sat Down Gradient Zones		One	
Unsaturated Zone Parameters			
Unsat Infiltration Rate used in Sat		Yes	
Unsat Infiltration Rate	ft/yr	0.78	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2011	
Unsat Infiltration After Switch	ft/yr	0.0001	
Unsat Moisture Content	ft3/ft3	0.25	
Unsat Dispersion Coeff in Z	ft2/yr	1.25	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		1	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	1440	
Source Length	ft	1300	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	196	
Dispersion along Y	ft2/yr	1.96	
Dispersion along Z	ft2/yr	1.96	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	27.8	
Seepage Velocity	ft/yr	7.84	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.28	
Hydraulic Gradient	ft/ft	0.01	
Hydraulic Conductivity	ft/yr	219.4	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	27.8	Calc'd
Source Penetration Depth After	ft	25.8	Calc'd
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			

Input Parameters

Description	Units	Value	Note
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.6	
pH		7	
Rd (inorganic)		1	Calc'd
Partition Coeff, Kd	ml/g	0	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	16.4042	

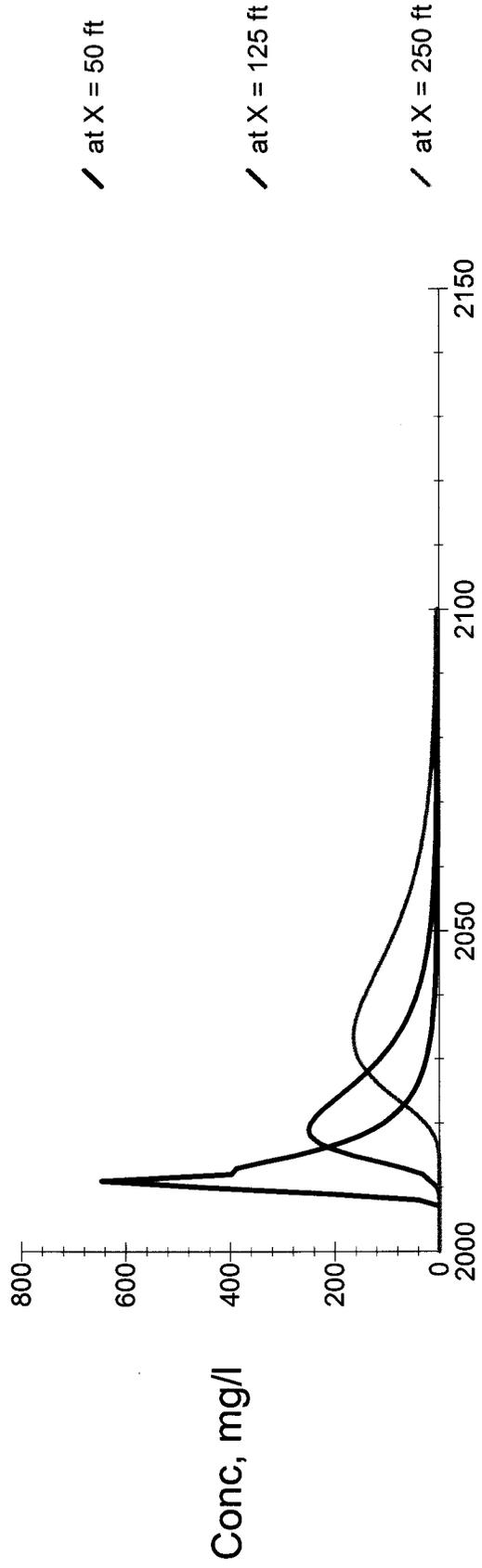
# Source Concentration



Source Concentration

	Time On, yrs	Conc, mg/l
1	2006.000	1600.000
2	2007.000	1600.000
3	2008.000	1600.000
4	2009.000	1600.000
5	2010.000	1600.000
6	3000.000	0.000

# SO4 Concentrations vs Time



Time, yrs, Saturated Zone, 3D, Y: 0 ft, Z: 27.8 ft

SO4 Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
1	2000	0	0	0
2	2001	0	0	0
3	2002	0	0	0
4	2003	0	0	0
5	2004	0	0	0
6	2005	0	0	0
7	2006	0	0	0
8	2007	0.102417	0	0
9	2008	38.9357	0.00349101	0
10	2009	214.562	0.175169	0
11	2010	443.416	3.38919	1.30102E-6
12	2011	646.569	18.2632	5.85453E-5
13	2012	397.84	32.4923	0.00166168
14	2013	387.599	69.3706	0.021533
15	2014	331.53	117.471	0.142206
16	2015	274.028	166.337	0.598729
17	2016	224.946	206.056	1.84407
18	2017	185.057	232.534	4.52032
19	2018	153.205	246.454	9.30924
20	2019	127.602	249.965	16.6964
21	2020	106.99	245.954	26.8169
22	2021	90.2703	236.79	39.3938
23	2022	76.5824	224.304	53.8156
24	2023	65.3522	210.085	69.3396
25	2024	56.074	195.122	85.1634
26	2025	48.3268	179.973	100.503
27	2026	41.8252	165.12	114.736
28	2027	36.3846	151.048	127.526
29	2028	31.7739	137.743	138.477
30	2029	27.8547	125.324	147.429
31	2030	24.5101	113.825	154.339
32	2031	21.6453	103.248	159.267
33	2032	19.2	93.6459	162.429
34	2033	17.0896	84.8747	163.87
35	2034	15.2656	76.8979	163.774
36	2035	13.6861	69.6664	162.351
37	2036	12.3142	63.117	159.779
38	2037	11.1189	57.188	156.231
39	2038	10.0807	51.8602	151.98
40	2039	9.17187	47.0423	147.083
41	2040	8.37667	42.7009	141.726
42	2041	7.67951	38.7894	136.034

## SO4 Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
43	2042	7.06696	35.2639	130.107
44	2043	6.52834	32.0899	124.057
45	2044	6.05333	29.228	117.942
46	2045	5.63355	26.6456	111.823
47	2046	5.26436	24.3312	105.832
48	2047	4.93701	22.2409	99.934
49	2048	4.64715	20.3582	94.1935
50	2049	4.38979	18.6592	88.6233
51	2050	4.16175	17.1309	83.2729
52	2051	3.95938	15.7551	78.1524
53	2052	3.77916	14.513	73.2509
54	2053	3.61875	13.3931	68.5865
55	2054	3.47582	12.3829	64.1592
56	2055	3.34848	11.4723	59.9746
57	2056	3.23467	10.6494	56.0157
58	2057	3.13306	9.90689	52.2881
59	2058	3.04229	9.23688	48.7868
60	2059	2.96109	8.63176	45.501
61	2060	2.88842	8.08513	42.4226
62	2061	2.8233	7.59095	39.5412
63	2062	2.76504	7.14513	36.8557
64	2063	2.71271	6.74141	34.345
65	2064	2.66577	6.37649	32.0066
66	2065	2.62361	6.04616	29.8276
67	2066	2.58565	5.74667	27.7958
68	2067	2.55164	5.47648	25.9151
69	2068	2.52112	5.23243	24.1735
70	2069	2.49359	5.01082	22.5523
71	2070	2.46882	4.81023	21.0505
72	2071	2.44651	4.62851	19.6589
73	2072	2.42641	4.46383	18.3702
74	2073	2.40829	4.31459	17.1779
75	2074	2.39194	4.17909	16.073
76	2075	2.37723	4.05666	15.0559
77	2076	2.36391	3.94523	14.1121
78	2077	2.35194	3.84457	13.2445
79	2078	2.34111	3.75304	12.4415
80	2079	2.33132	3.66999	11.7005
81	2080	2.32247	3.59461	11.0169
82	2081	2.31448	3.52619	10.3865
83	2082	2.30726	3.46409	9.80563
84	2083	2.30072	3.40767	9.27001

SO4 Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
85	2084	2.2948	3.35639	8.77598
86	2085	2.28943	3.30973	8.32017
87	2086	2.28459	3.26745	7.90165
88	2087	2.28021	3.22909	7.51694
89	2088	2.27623	3.19413	7.16168
90	2089	2.27263	3.16232	6.83449
91	2090	2.26936	3.13342	6.53358
92	2091	2.2664	3.10714	6.25664
93	2092	2.26372	3.08322	6.00183
94	2093	2.26128	3.06147	5.76742
95	2094	2.25907	3.04168	5.55191
96	2095	2.25706	3.02364	5.35323
97	2096	2.25525	3.00729	5.17153
98	2097	2.2536	2.99237	5.00396
99	2098	2.2521	2.97879	4.84992
100	2099	2.25074	2.96642	4.70829
101	2100	2.2495	2.95516	4.57812

**MYGRT Analysis  
Input and Results**

**Cross Section 1-1  
Fluoride**

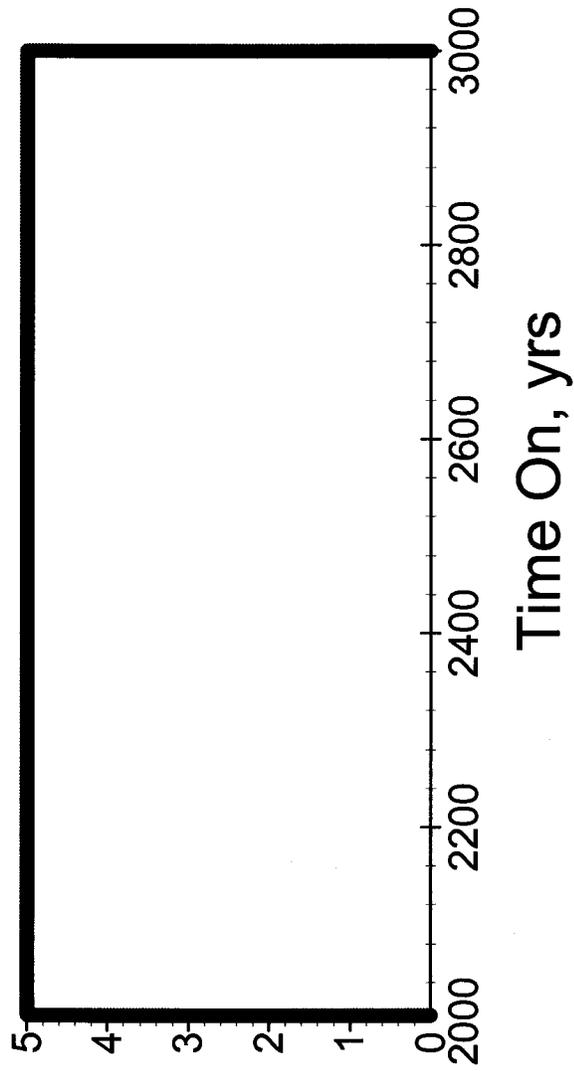
Input Parameters

Description	Units	Value	Note
General Parameters			
Site		MSS FGD Landfill - Cross Section 1-1	
Description		X Sect 1-1 Cap @End of Year 5	
Notes		Put your notes here.	
Solute Name		Fluoride	
Organic		No	
Zones Simulated		Unsat/Sat	
Source Location		Unsat	
Saturated Zone Dimension		Sat_3d	
Point or Depth Averaged		Point	
Aquifer Thickness		Finite	
Number of Sat Down Gradient Zones		One	
Unsaturated Zone Parameters			
Unsat Infiltration Rate used in Sat		Yes	
Unsat Infiltration Rate	ft/yr	0.78	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2011	
Unsat Infiltration After Switch	ft/yr	0.0001	
Unsat Moisture Content	ft3/ft3	0.25	
Unsat Dispersion Coeff in Z	ft2/yr	1.25	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		1	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	1440	
Source Length	ft	1300	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	196	
Dispersion along Y	ft2/yr	19.6	
Dispersion along Z	ft2/yr	1.96	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	27.8	
Seepage Velocity	ft/yr	7.84	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.28	
Hydraulic Gradient	ft/ft	0.01	
Hydraulic Conductivity	ft/yr	219.4	
Horizontal Velocity calculated		Yes	
Source Penetration Depth	ft	27.8	Calc'd
Source Penetration Depth After :	ft	25.8	Calc'd
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			

Input Parameters

Description	Units	Value	Note
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.6	
pH		7	
Rd (inorganic)		1	Calc'd
Partition Coeff, Kd	ml/g	0	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	16.4042	

# Source Concentration, Fluoride



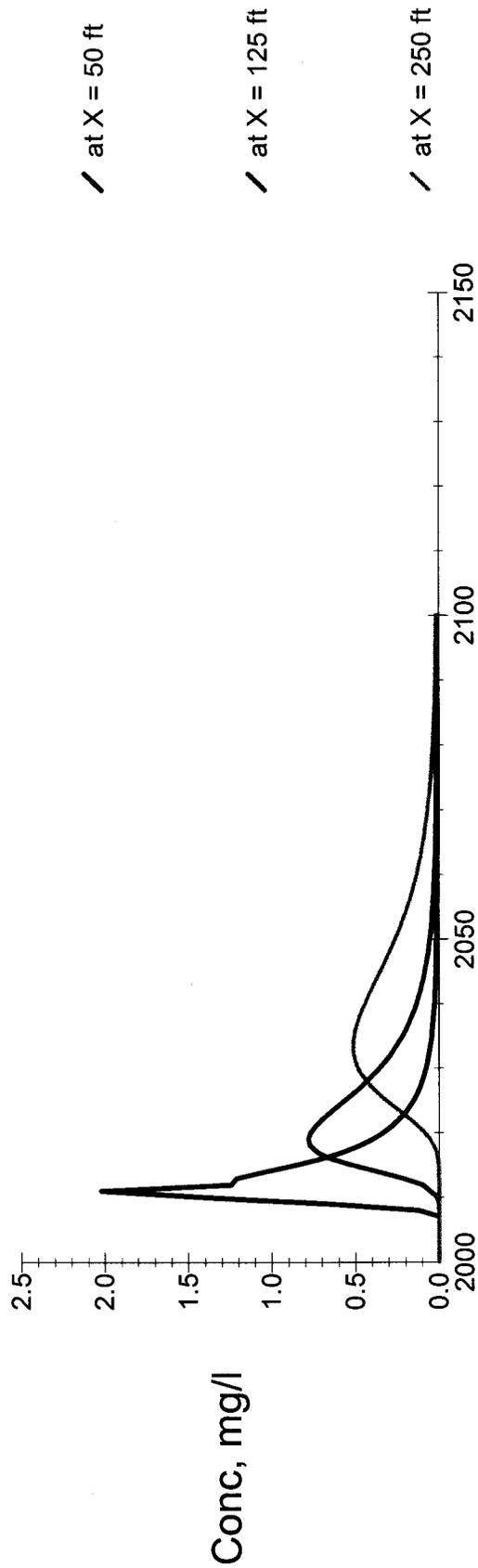
Conc,  
mg/l

Conc,  
mg/l

Source Concentration

	Time On, yrs	Conc, mg/l
1	2006.000	5.000
2	2007.000	5.000
3	2008.000	5.000
4	2009.000	5.000
5	2010.000	5.000
6	3000.000	0.000

# Fluoride Concentrations vs Time



Time, yrs, Saturated Zone, 3D, Y: 0 ft, Z: 27.8 ft

Fluoride Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
1	2000	0	0	0
2	2001	0	0	0
3	2002	0	0	0
4	2003	0	0	0
5	2004	0	0	0
6	2005	0	0	0
7	2006	0	0	0
8	2007	0.00320054	0	0
9	2008	0.121674	1.09094E-6	0
10	2009	0.670506	0.00547404	0
11	2010	1.38568	0.0105912	1.06569E-9
12	2011	2.02053	0.0570724	2.14204E-7
13	2012	1.24325	0.101538	5.19276E-6
14	2013	1.21125	0.216783	5.72905E-5
15	2014	1.03603	0.367098	0.000444393
16	2015	0.856338	0.519804	0.00187103
17	2016	0.702957	0.643924	0.00576272
18	2017	0.578304	0.726668	0.014126
19	2018	0.478765	0.770168	0.0290914
20	2019	0.398757	0.781142	0.0521763
21	2020	0.334345	0.768606	0.083803
22	2021	0.282095	0.739968	0.123106
23	2022	0.23932	0.70095	0.168174
24	2023	0.204226	0.656515	0.216686
25	2024	0.175231	0.609757	0.266136
26	2025	0.151021	0.562415	0.314071
27	2026	0.130704	0.516002	0.358549
28	2027	0.113702	0.472024	0.398519
29	2028	0.0992935	0.430447	0.43274
30	2029	0.0870461	0.391637	0.460717
31	2030	0.0765939	0.355704	0.48231
32	2031	0.0676414	0.322649	0.497711
33	2032	0.06	0.292643	0.507592
34	2033	0.0534049	0.265233	0.512094
35	2034	0.047705	0.240306	0.511795
36	2035	0.0427691	0.217708	0.507346
37	2036	0.0384818	0.197241	0.499308
38	2037	0.0347465	0.178713	0.488222
39	2038	0.0315023	0.162063	0.474938
40	2039	0.0286621	0.147007	0.459634
41	2040	0.0261771	0.133441	0.442895
42	2041	0.0239985	0.121217	0.425106

Fluoride Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
43	2042	0.0220843	0.1102	0.406585
44	2043	0.0204011	0.100281	0.387678
45	2044	0.0189167	0.0913377	0.368568
46	2045	0.0176048	0.0832674	0.349447
47	2046	0.0164511	0.0760349	0.330726
48	2047	0.0154282	0.0695028	0.312294
49	2048	0.0145224	0.0636194	0.294355
50	2049	0.0137181	0.05831	0.276948
51	2050	0.0130055	0.053534	0.260228
52	2051	0.0123731	0.0492348	0.244226
53	2052	0.0118099	0.0453531	0.228909
54	2053	0.0113086	0.0418535	0.214333
55	2054	0.0108619	0.0386967	0.200498
56	2055	0.010464	0.0358511	0.187421
57	2056	0.0101083	0.0332795	0.175049
58	2057	0.00979079	0.0309591	0.1634
59	2058	0.00950715	0.0288653	0.152459
60	2059	0.00925342	0.0269743	0.142191
61	2060	0.00902632	0.0252661	0.132571
62	2061	0.00882282	0.0237218	0.123567
63	2062	0.00864075	0.0223286	0.115174
64	2063	0.00847723	0.021067	0.107328
65	2064	0.00833055	0.0199266	0.100021
66	2065	0.00819878	0.0188943	0.0932112
67	2066	0.00808015	0.0179584	0.0868621
68	2067	0.00797387	0.017114	0.0809847
69	2068	0.00787849	0.0163514	0.0755424
70	2069	0.00779246	0.0156589	0.0704762
71	2070	0.00771505	0.015032	0.0657829
72	2071	0.00764534	0.0144641	0.0614342
73	2072	0.00758253	0.0139495	0.0574071
74	2073	0.00752592	0.0134831	0.053681
75	2074	0.0074748	0.0130597	0.0502284
76	2075	0.00742885	0.0126771	0.0470498
77	2076	0.00738723	0.0123289	0.0441003
78	2077	0.00734982	0.0120143	0.0413893
79	2078	0.00731596	0.0117283	0.0388798
80	2079	0.00728537	0.0114688	0.0365642
81	2080	0.00725774	0.0112332	0.0344281
82	2081	0.00723274	0.0110194	0.032458
83	2082	0.00721016	0.0108253	0.0306427
84	2083	0.00718973	0.010649	0.0289689

Fluoride Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
85	2084	.00717125	0.0104887	0.027425
86	2085	.00715448	0.0103429	0.0260006
87	2086	.00713935	0.0102108	0.0246927
88	2087	.00712566	0.010091	0.0234906
89	2088	.00711323	.00998169	0.0223804
90	2089	.00710196	0.0098823	0.0213579
91	2090	.00709176	.00979199	0.0204175
92	2091	.00708251	.00970984	0.0195521
93	2092	.00707411	.00963511	0.0187558
94	2093	.00706651	.00956713	0.0180233
95	2094	0.0070596	.00950529	0.0173498
96	2095	.00705333	.00944889	0.0167289
97	2096	.00704766	.00939782	0.0161611
98	2097	0.0070425	0.0093512	0.0156375
99	2098	.00703782	.00930876	0.0151561
100	2099	.00703356	0.0092701	0.0147135
101	2100	0.0070297	.00923491	0.0143067

**MYGRT Analysis  
Input and Results**

**Cross Section 2-2  
Sulfate**

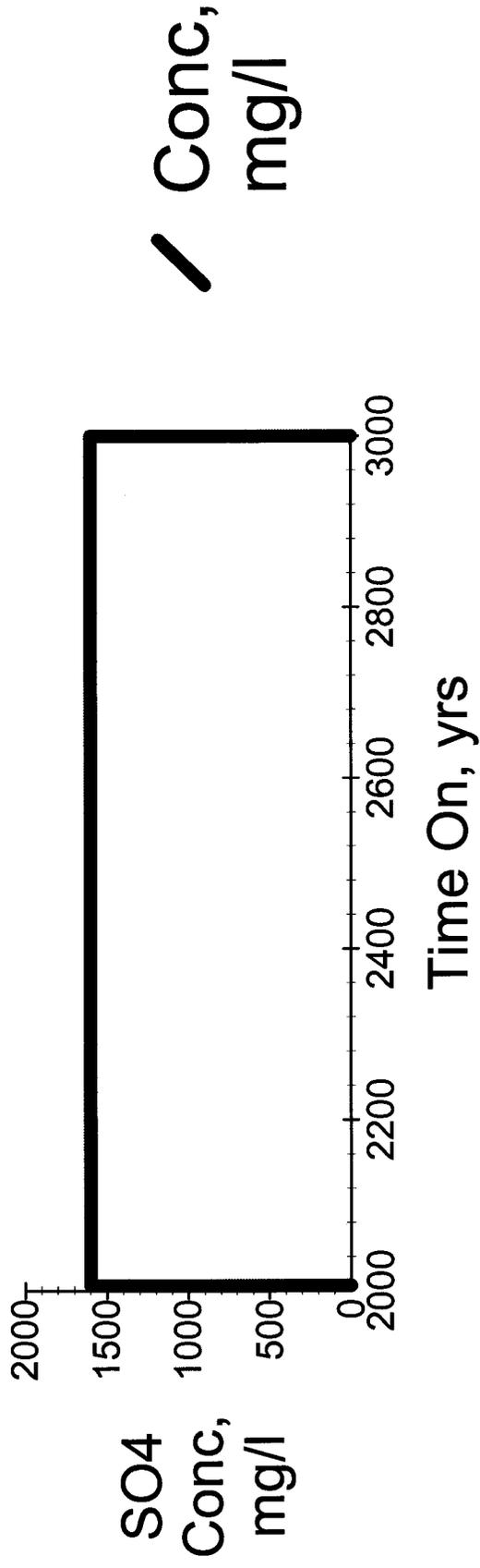
Input Parameters

Description	Units	Value	Note
General Parameters			
Site		MSS FGD Landfill - Cross Section 2-2	
Description		X Sect 2-2 Cap @End of Year	
Notes		Put your notes here.	
Solute Name		Sulfate	
Organic		No	
Zones Simulated		Unsat/Sat	
Source Location		Unsat	
Saturated Zone Dimension		Sat_3d	
Point or Depth Averaged		Point	
Aquifer Thickness		Finite	
Number of Sat Down Gradient Zones		One	
Unsaturated Zone Parameters			
Unsat Infiltration Rate used in Sat		Yes	
Unsat Infiltration Rate	ft/yr	0.78	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2011	
Unsat Infiltration After Switch	ft/yr	0.0001	
Unsat Moisture Content	ft3/ft3	0.25	
Unsat Dispersion Coeff in Z	ft2/yr	1.87	Calc'd
Depth to water table	ft	6	
Unsat Retardation Coeff		1	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	1440	
Source Length	ft	760	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	510	
Dispersion along Y	ft2/yr	51	
Dispersion along Z	ft2/yr	5.1	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	24.3	
Seepage Velocity	ft/yr	20.4	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.27	
Hydraulic Gradient	ft/ft	0.03	
Hydraulic Conductivity	ft/yr	183.9	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	24.3	Calc'd
Source Penetration Depth After	ft	19.9	Calc'd
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			

Input Parameters

Description	Units	Value	Note
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.6	
pH		7	
Rd (inorganic)		1	Calc'd
Partition Coeff, Kd	ml/g	0	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	16.4042	

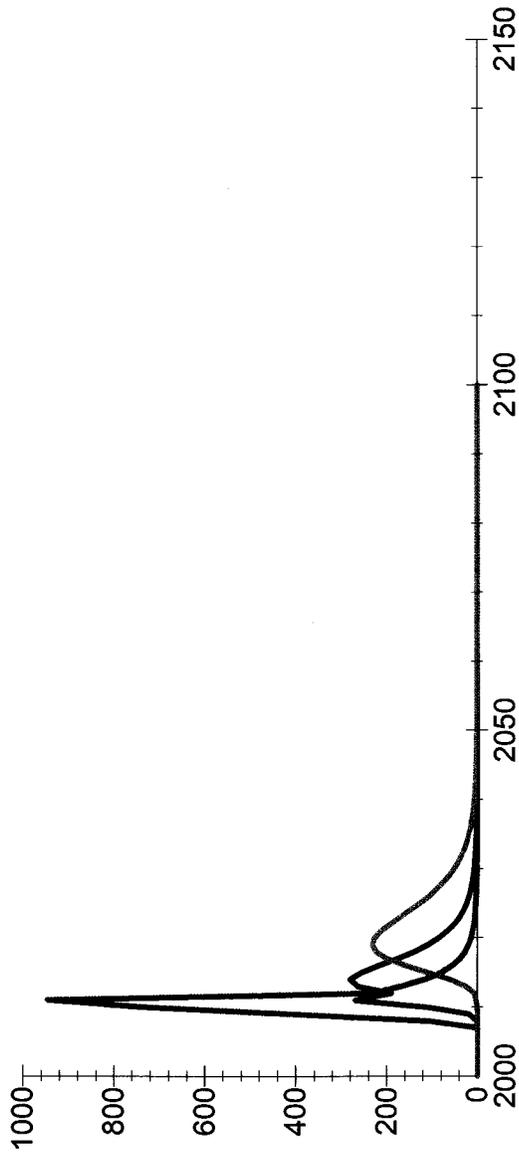
# Source Concentration



Source Concentration

	Time On, yrs	Conc, mg/l
1	2006.000	1600.000
2	2007.000	1600.000
3	2008.000	1600.000
4	2009.000	1600.000
5	2010.000	1600.000
6	3000.000	0.000

# Sulfate Concentrations vs Time



Time, yrs, Saturated Zone, 3D, Y: 0 ft, Z: 24.3 ft

/ at X = 50 ft

/ at X = 125 ft

/ at X = 250 ft

## Sulfate Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
1	2000	0	0	0
2	2001	0	0	0
3	2002	0	0	0
4	2003	0	0	0
5	2004	0	0	0
6	2005	0	0	0
7	2006	0	0	0
8	2007	0.685173	.79925E-6	0
9	2008	105.738	0.470171	.41337E-7
10	2009	426.947	19.9163	0.0018809
11	2010	737.021	108.903	0.20237
12	2011	946.57	269.294	2.95565
13	2012	229.11	189.967	7.93709
14	2013	168.079	263.437	26.2578
15	2014	114.815	280.505	60.6897
16	2015	78.5606	256.383	108.489
17	2016	54.492	216.761	158.528
18	2017	38.356	175.9	198.928
19	2018	27.3719	139.6	223.499
20	2019	19.7792	109.444	231.918
21	2020	14.4511	85.2055	227.085
22	2021	10.6719	66.1281	213.142
23	2022	7.95591	51.2303	193.694
24	2023	5.99235	39.7106	171.864
25	2024	4.55751	30.8084	149.648
26	2025	3.50163	23.9406	128.392
27	2026	2.71972	18.6452	108.868
28	2027	2.13821	14.5677	91.4896
29	2028	1.70294	11.4211	76.3104
30	2029	1.37586	8.99247	63.2767
31	2030	1.12897	7.11502	52.216
32	2031	0.942098	5.66362	42.9361
33	2032	0.800033	4.5389	35.1996
34	2033	0.691824	3.66734	28.8008
35	2034	0.609115	2.99065	23.5314
36	2035	0.545746	2.46473	19.2119
37	2036	0.49706	2.05532	15.6818
38	2037	0.459615	1.73663	12.8096
39	2038	0.430737	1.48811	10.4765
40	2039	0.408423	1.29406	8.58514
41	2040	0.391169	1.14258	7.05657
42	2041	0.377795	1.0241	5.82189

Sulfate Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
43	2042	0.367413	0.931326	4.82573
44	2043	0.35934	0.858614	4.02276
45	2044	0.353057	0.801589	3.37634
46	2045	0.348166	0.756874	2.85692
47	2046	0.344351	0.721752	2.43943
48	2047	0.341373	0.694141	2.104
49	2048	0.339046	0.672428	1.83473
50	2049	0.337227	0.655343	1.61871
51	2050	0.335803	0.641879	1.44529
52	2051	0.334691	0.631291	1.3065
53	2052	0.333819	0.622936	1.19512
54	2053	0.333136	0.616344	1.10581
55	2054	0.332602	0.61114	1.03422
56	2055	0.332183	0.607032	0.976835
57	2056	0.331855	0.603788	0.930865
58	2057	0.331599	0.601227	0.894038
59	2058	0.331399	0.599204	0.864545
60	2059	0.331243	0.597606	0.840929
61	2060	0.331122	0.596344	0.822008
62	2061	0.331028	0.595347	0.806841
63	2062	0.330956	0.59456	0.794708
64	2063	0.3309	0.593939	0.784981
65	2064	0.330857	0.593449	0.77719
66	2065	0.330825	0.59306	0.770944
67	2066	0.330802	0.592761	0.765958
68	2067	0.330785	0.592523	0.761961
69	2068	0.330772	0.592337	0.758761
70	2069	0.330764	0.592192	0.7562
71	2070	0.330759	0.59208	0.754151
72	2071	0.330756	0.591993	0.752512
73	2072	0.330755	0.591927	0.751203
74	2073	0.330756	0.591877	0.750157
75	2074	0.330757	0.59184	0.749321
76	2075	0.33076	0.591813	0.748656
77	2076	0.330763	0.591793	0.748125
78	2077	0.330767	0.59178	0.747703
79	2078	0.330771	0.591772	0.747368
80	2079	0.330775	0.591768	0.747103
81	2080	0.330779	0.591766	0.746893
82	2081	0.330784	0.591768	0.746729
83	2082	0.330788	0.591771	0.7466
84	2083	0.330793	0.591775	0.746499

Sulfate Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
85	2084	0.330797	0.591781	0.746422
86	2085	0.330802	0.591787	0.746363
87	2086	0.330807	0.591794	0.746318
88	2087	0.330811	0.591801	0.746286
89	2088	0.330815	0.591809	0.746262
90	2089	0.330819	0.591816	0.746246
91	2090	0.330823	0.591825	0.746236
92	2091	0.330828	0.591833	0.74623
93	2092	0.330832	0.591841	0.746229
94	2093	0.330836	0.591848	0.74623
95	2094	0.33084	0.591856	0.746233
96	2095	0.330843	0.591864	0.746238
97	2096	0.330848	0.591872	0.746245
98	2097	0.330851	0.59188	0.746253
99	2098	0.330854	0.591888	0.746261
100	2099	0.330857	0.591893	0.746266
101	2100	0.330861	0.591902	0.746279

**MYGRT Analysis  
Input and Results**

**Cross Section 2-2  
Fluoride**

Input Parameters

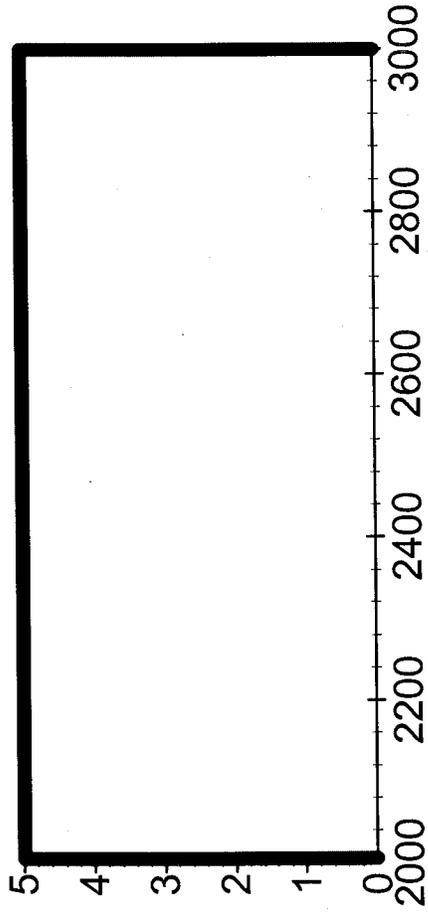
Description	Units	Value	Note
General Parameters			
Site		MSS FGD Landfill - Cross Section 2-2	
Description		X Sect 2-2 Cap @End of Year	
Notes			
Solute Name		Fluoride	
Organic		No	
Zones Simulated		Unsat/Sat	
Source Location		Unsat	
Saturated Zone Dimension		Sat_3d	
Point or Depth Averaged		Point	
Aquifer Thickness		Finite	
Number of Sat Down Gradient Zones		One	
Unsaturated Zone Parameters			
Unsat Infiltration Rate used in Sat		Yes	
Unsat Infiltration Rate	ft/yr	0.78	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2011	
Unsat Infiltration After Switch	ft/yr	0.0001	
Unsat Moisture Content	ft3/ft3	0.25	
Unsat Dispersion Coeff in Z	ft2/yr	1.87	Calc'd
Depth to water table	ft	6	
Unsat Retardation Coeff		1	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	1440	
Source Length	ft	760	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	510	
Dispersion along Y	ft2/yr	51	
Dispersion along Z	ft2/yr	5.1	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	24.3	
Seepage Velocity	ft/yr	20.4	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.27	
Hydraulic Gradient	ft/ft	0.03	
Hydraulic Conductivity	ft/yr	183.9	
Horizontal Velocity calculated		Yes	
Source Penetration Depth	ft	24.3	Calc'd
Source Penetration Depth After	ft	19.9	Calc'd
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			

Input Parameters

Description	Units	Value	Note
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.6	
pH		7	
Rd (inorganic)		1	Calc'd
Partition Coeff, Kd	ml/g	0	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	16.4042	

# Source Concentration

Fluoride  
Conc,  
mg/l



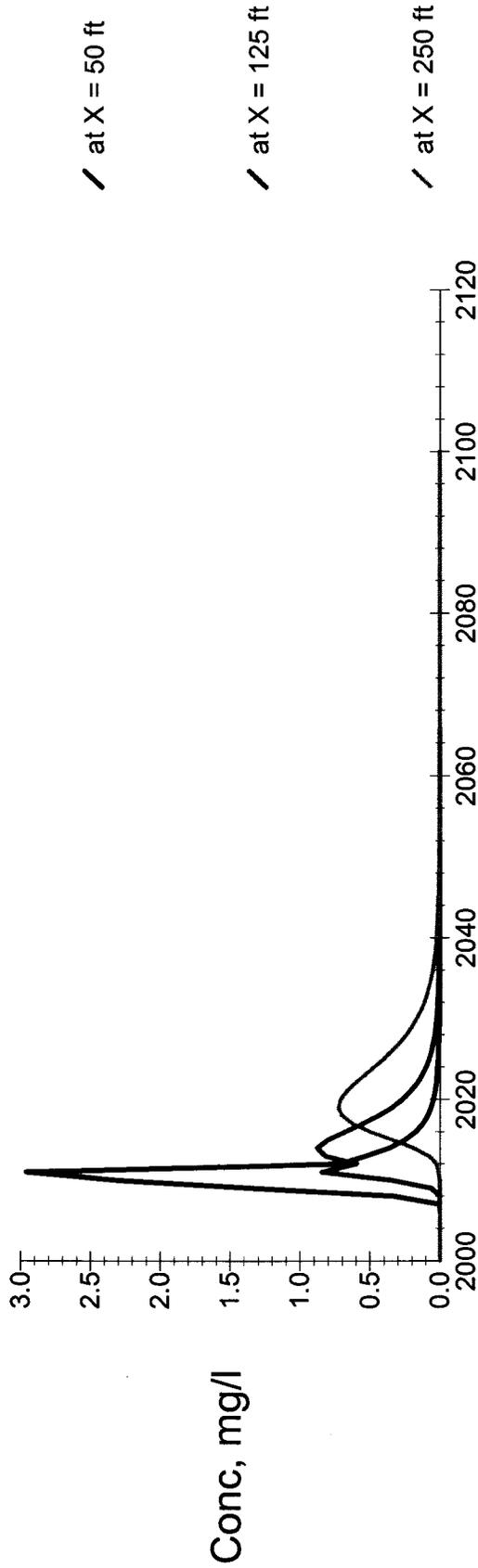
Conc,  
mg/l

Time On, yrs

Source Concentration

	Time On, yrs	Conc, mg/l
1	2006.000	5.000
2	2007.000	5.000
3	2008.000	5.000
4	2009.000	5.000
5	2010.000	5.000
6	3000.000	0.000

# Fluoride Concentrations vs Time



Time, yrs, Saturated Zone, 3D, Y: 0 ft, Z: 24.3 ft

Fluoride Concentrations vs Time

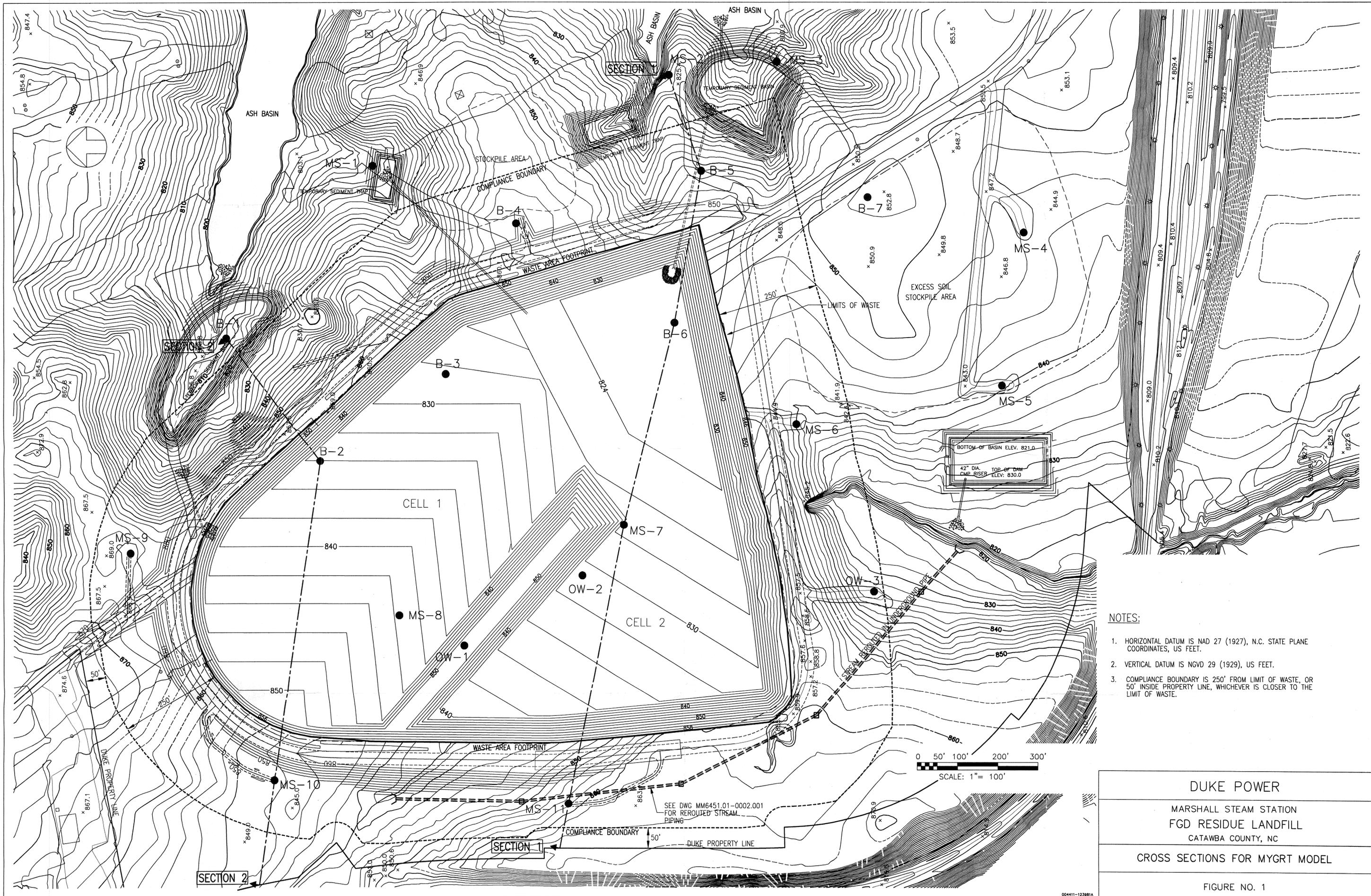
	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
1	2000	0	0	0
2	2001	0	0	0
3	2002	0	0	0
4	2003	0	0	0
5	2004	0	0	0
6	2005	0	0	0
7	2006	0	0	0
8	2007	0.002141178	7.74765E-9	0
9	2008	0.3304330	0.00146928	41679E-10
10	2009	1.33421	0.0622384	5.87781E-6
11	2010	2.30319	0.340322	000632406
12	2011	2.95803	0.841544	0.0092364
13	2012	0.71597	0.593647	0.0248034
14	2013	0.525248	0.82324	0.0820557
15	2014	0.358797	0.87658	0.189655
16	2015	0.245502	0.801196	0.339029
17	2016	0.170288	0.677377	0.4954
18	2017	0.119862	0.549687	0.621649
19	2018	0.0855372	0.43625	0.698434
20	2019	0.0618101	0.342014	0.724743
21	2020	0.0451596	0.266267	0.70964
22	2021	0.0333497	0.20665	0.666069
23	2022	0.0248622	0.160095	0.605294
24	2023	0.0187261	0.124096	0.537076
25	2024	0.0142422	0.0962764	0.467649
26	2025	0.0109426	0.0748145	0.401224
27	2026	0.00849912	0.0582662	0.340212
28	2027	0.00668191	0.0455239	0.285905
29	2028	0.00532168	0.0356909	0.23847
30	2029	0.00429957	0.0281015	0.19774
31	2030	0.00352802	0.0222344	0.163175
32	2031	0.00294406	0.0176988	0.134175
33	2032	0.00250008	0.014184	0.109998
34	2033	0.00216195	0.0114604	0.0900024
35	2034	0.00190348	0.00934578	0.0735355
36	2035	0.00170546	0.00770228	0.0600371
37	2036	0.00155331	0.00642288	0.0490056
38	2037	0.0014363	0.00542698	0.0400299
39	2038	0.00134605	0.00465033	0.0327391
40	2039	0.00127632	0.00404395	0.0268286
41	2040	0.0012224	0.00357056	0.0220518
42	2041	0.00118061	0.0032003	0.0181934

Fluoride Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
43	2042	.00114817	.00291039	0.0150804
44	2043	.00112294	.00268317	0.0125711
45	2044	.00110329	.00250492	0.010551
46	2045	.00108802	.00236523	.00892786
47	2046	0.0010761	.00225547	.00762323
48	2047	.00106679	.00216919	0.006575
49	2048	.00105952	.00210134	.00573355
50	2049	.00105383	.00204795	.00505848
51	2050	.00104938	.00200587	.00451653
52	2051	.00104591	.00197278	.00408281
53	2052	.00104317	.00194663	.00373465
54	2053	.00104105	.00192607	.00345567
55	2054	.00103938	.00190981	.00323194
56	2055	.00103807	.00189697	.00305261
57	2056	.00103705	.00188684	.00290895
58	2057	.00103625	.00187883	.00279387
59	2058	.00103562	.00187251	0.0027017
60	2059	.00103513	.00186752	0.0026279
61	2060	.00103476	.00186357	.00256877
62	2061	.00103446	.00186046	.00252138
63	2062	.00103424	0.001858	.00248346
64	2063	.00103406	.00185606	.00245307
65	2064	.00103393	.00185453	.00242872
66	2065	.00103383	.00185331	0.0024092
67	2066	.00103376	.00185238	.00239362
68	2067	0.0010337	.00185164	.00238113
69	2068	.00103366	.00185105	.00237113
70	2069	.00103364	0.0018506	.00236313
71	2070	.00103362	.00185025	.00235672
72	2071	.00103361	.00184998	0.0023516
73	2072	.00103361	.00184977	.00234751
74	2073	.00103361	.00184962	.00234424
75	2074	.00103362	0.0018495	.00234163
76	2075	.00103362	.00184941	.00233955
77	2076	.00103363	.00184935	.00233789
78	2077	.00103364	.00184929	.00233652
79	2078	.00103366	.00184929	.00233553
80	2079	.00103367	.00184927	0.0023347
81	2080	.00103368	.00184927	.00233404
82	2081	0.0010337	.00184927	.00233353
83	2082	.00103371	.00184928	.00233312
84	2083	.00103373	0.0018493	.00233281

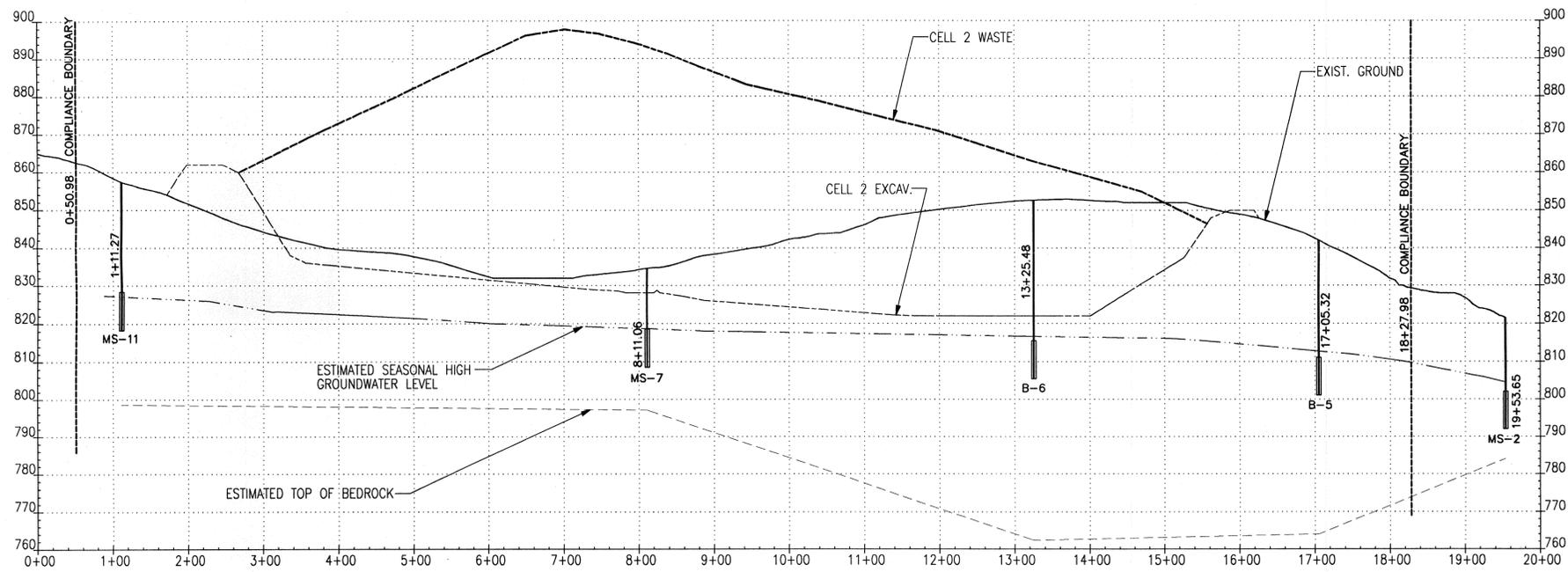
Fluoride Concentrations vs Time

	Time, yrs	Conc, mg/l at X = 50 ft	Conc, mg/l at X = 125 ft	Conc, mg/l at X = 250 ft
85	2084	0.00103374	0.00184931	0.00233257
86	2085	0.00103376	0.00184933	0.00233238
87	2086	0.00103377	0.00184936	0.00233224
88	2087	0.00103379	0.00184938	0.00233214
89	2088	0.0010338	0.0018494	0.00233207
90	2089	0.00103381	0.00184943	0.00233202
91	2090	0.00103382	0.00184945	0.00233199
92	2091	0.00103384	0.00184948	0.00233197
93	2092	0.00103385	0.0018495	0.00233196
94	2093	0.00103386	0.00184953	0.00233197
95	2094	0.00103387	0.00184955	0.00233198
96	2095	0.00103389	0.00184958	0.002332
97	2096	0.0010339	0.0018496	0.00233202
98	2097	0.00103391	0.00184962	0.00233204
99	2098	0.00103392	0.00184965	0.00233207
100	2099	0.00103393	0.00184966	0.00233208
101	2100	0.00103394	0.00184969	0.00233212

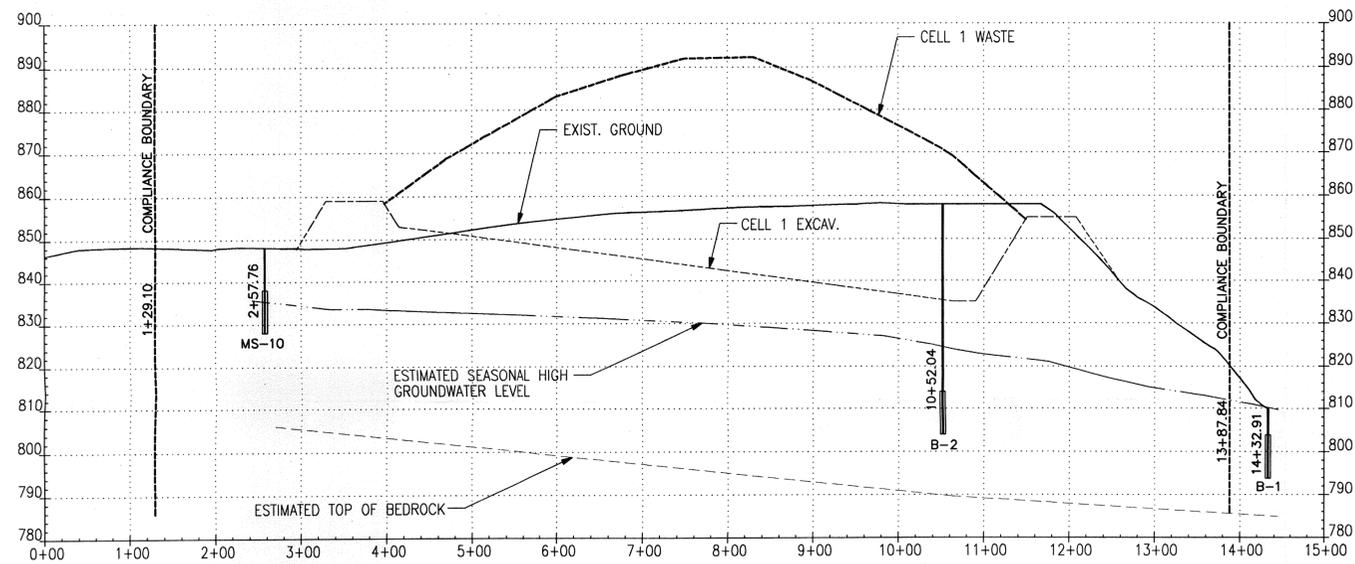


- NOTES:**
1. HORIZONTAL DATUM IS NAD 27 (1927), N.C. STATE PLANE COORDINATES, US FEET.
  2. VERTICAL DATUM IS NGVD 29 (1929), US FEET.
  3. COMPLIANCE BOUNDARY IS 250' FROM LIMIT OF WASTE, OR 50' INSIDE PROPERTY LINE, WHICHEVER IS CLOSER TO THE LIMIT OF WASTE.

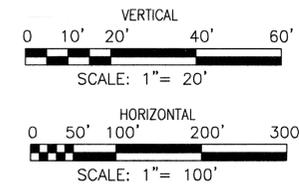
<p><b>DUKE POWER</b></p> <p>MARSHALL STEAM STATION FGD RESIDUE LANDFILL CATAWBA COUNTY, NC</p>
<p><b>CROSS SECTIONS FOR MYGRT MODEL</b></p>
<p>FIGURE NO. 1</p>



SECTION 1-1



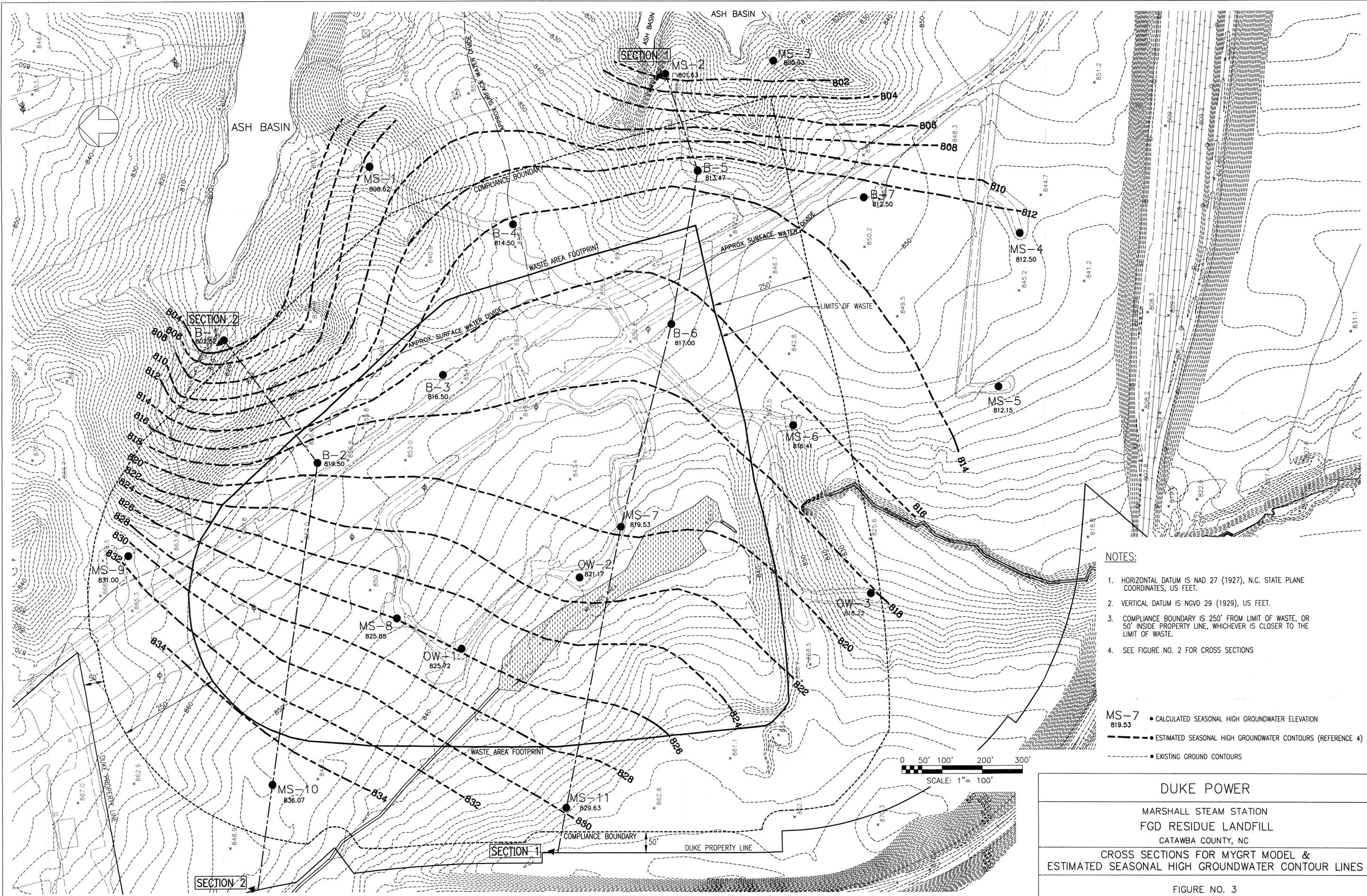
SECTION 2-2



NOTES:

1. HORIZONTAL DATUM IS NAD 27 (1927), N.C. STATE PLANE COORDINATES, US FEET.
2. VERTICAL DATUM IS NGVD 29 (1929), US FEET.
3. ESTIMATED SEASONAL HIGH GROUNDWATER LEVEL AND TOP OF BEDROCK FROM REFERENCE 4.

DUKE POWER
MARSHALL STEAM STATION FGD RESIDUE LANDFILL CATAWBA COUNTY, NC
CROSS SECTIONS FOR MYGRT MODEL
FIGURE NO. 2



- NOTES:**
1. HORIZONTAL DATUM IS NAD 27 (1927), N.C. STATE PLANE COORDINATES, US FEET.
  2. VERTICAL DATUM IS NGVD 29 (1929), US FEET.
  3. COMPLIANCE BOUNDARY IS 250' FROM LIMIT OF WASTE, OR 50' INSIDE PROPERTY LINE, WHICHEVER IS CLOSER TO THE LIMIT OF WASTE.
  4. SEE FIGURE NO. 2 FOR CROSS SECTIONS
- MS-7 819.53 • CALCULATED SEASONAL HIGH GROUNDWATER ELEVATION  
 - - - ESTIMATED SEASONAL HIGH GROUNDWATER CONTOURS (REFERENCE 4)  
 - - - EXISTING GROUND CONTOURS

**DUKE POWER**  
 MARSHALL STEAM STATION  
 FGD RESIDUE LANDFILL  
 CATAWBA COUNTY, NC  
 CROSS SECTIONS FOR MYGRT MODEL &  
 ESTIMATED SEASONAL HIGH GROUNDWATER CONTOUR LINES  
 FIGURE NO. 3