85-03

APPROVED
DIVISION OF WASTE MANAGEMENT
SOLID WASTE SECTION
DATE 12-20-02 BY EL

Carmen Johnson
Fac/Permit/Co ID# 85-03
Date 5/10/12
Doc ID# DIN

Duke Energy

Belews Creek Steam Station

Stokes County, NC

Landfill Permit Application

.0503(2)(d)(ii)(A) Compliance Demonstration Report

January 18, 2002

Duke Energy
PO Box 1006
Charlotte, NC 28201-1006

Duke Power
A Duke Energy Company

Duke Power Company
Fossil and Hydro Generation Departmen
P.O. Box 1006
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February 14, 2002

North Carolina Department of
Environment and Natural Resources
Division of Waste Management
Solid Waste Section
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Raleigh, NC 27699-1646

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Received
Solid Waste
Section

Attention: Ms. Ellen Lorscheider
Hydrogeologist, Solid Waste Section

Subject: Duke Energy – Belews Creek Steam Station
Industrial Landfill Permit Application
Permit Number 85-03, Stokes County

Dear Ms. Lorscheider:

Please reference the attached groundwater modeling report as required per 15A NCAC 13B .0503 (2) (d) (ii). This report is intended to supplement the site suitability portion of the industrial landfill permit application that was submitted to your office on October 4, 2001.

If additional information is needed to ensure a timely response, please contact me at (704) 382-4309.

Sincerely,

Allen Stowe

Allen Stowe, Scientist
North American Support

Attachments

cc: James Coffey – NC DENR, Solid Waste Section
Randy Price – Belews Creek Steam Station

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SOLID WASTE SECTION
DATE 12-20-02 BY EL.

Prepared by:

NORTH CAROLINA PROFESSIONAL SEAL 17661 ENGINEER WILLIAM M. MILLER

William M. Miller, PE
January 18, 2002

Duke Energy
PO Box 1006
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Executive Summary

This report provides the demonstration that the conceptual design for the Belews Creek ash landfill presented will ensure that 2L groundwater standards are not exceeded. This conclusion was reached by review of the site-specific conditions and by the use of groundwater modeling that including site-specific adsorptive properties. The design proposed in this demonstration ensures that the ground water standards established under 15A NCAC 2L will not be exceeded.

This design proposed in this demonstration calls for:
1. the active landfill will receive ash for a 5 year period.
2. an engineered cover will be placed on the competed landfill at the end of the 5 year period.

The engineered cover will consist of a textured 40 mil very flexible polyethylene (VFPE) 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 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.

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.

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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-ml 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 X 10^{-7}cm/sec. FML components consisting of high density polyethylene (HDPE) shall be at least 60-ml 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 Energy Belews Creek Steam Station Landfill Permit Application – Siting Package, October 2, 2001 [Reference 1] will ensure that the ground 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 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 250 feet from the footprint of the proposed landfill to the nearest property boundary, a distance of 250 feet from the footprint will be used to evaluate compliance with 2L groundwater standards.

2.0 Description of Conceptual Design

The conceptual design for the proposed ash landfill is shown on Figure .0504-4, in Reference 1. The landfill will consist of an ash monofill, utilizing ash produced at the Belews Creek Steam Station. The ash will be transported to the landfill by truck, where it will be placed and compacted.

Laboratory analysis of the ash leachate has been performed. This analytical information and infiltration modeling (HELP) was used in a groundwater fate and transport model (MYGRT) to evaluate compliance with T15A NCAC 2L Groundwater Standards. The results of this modeling show that a landfill design, utilizing an engineered cap system to minimize infiltration into the landfill, will allow the landfill to met 2L standards.

The engineered cap will consist of a textured 40 mil very flexible polyethylene (VFPE) 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.

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.

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.

3.0 Description of Demonstration Approach

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

Step 1.	Develop conceptual groundwater flow model of site.
Step 2.	Determine if ash leachate constituents exceed the NCAC T15A 2L standards.
Step 3.	Determine the attenuation capacities of the site soils.
Step 4.	Determine the volume of leachate that will infiltrate into the soil beneath the landfill with use of HELP model.
Step 5.	Determine the groundwater concentrations of the leachate at various distances from the ash landfill over time with use of the MYGRT model.
Step 6.	Compare the modeled groundwater concentrations to NCAC T15A 2L standards.

4.0 Site Conceptual Hydrogeologic Model

4.1 Site Climatic Information

The site is located in southeastern Stokes County. The climatic information provided in this section is taken from Soil Survey of Stokes County, North Carolina, United States Department of Agriculture [Reference 2].

Stokes 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.

	Average Daily Temperature (°F)	Average Monthly Precipitation (inches)
January	46.2	3.25
February	49.7	3.49
March	58.7	4.33
April	69.6	3.74
May	76.9	3.86
June	83.3	3.82
July	86.8	4.23
August	85.8	4.03
September	80.4	3.83
October	70.5	3.76
November	60.7	3.15
December	50.4	3.47
Annual Average	68.3	44.96

The growing season is fairly long, with the last freezing temperature occurring (5 years out of 10) later than April 21. The first freezing temperature typically occurs (5 years out of 10) earlier than October 16.

4.2 Site Geology

The site geology is described in Volume 2 of Reference 1.

4.3 Site Hydrogeology

The site hydrogeology is described in Volume 2 of Reference 1.

4.4 Site Conceptual Hydrogeologic Model

As described in Volume 2 of Reference 1, the geology and groundwater flow at the site are consistent with the conceptual groundwater model of the Piedmont region as described by Legrand [Reference 3]. 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 3, 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 3, page 325]

As the topographic lines on Figure 1 show, Pine Hall Road is located along a surface water divide. Surface water (and rainfall recharge) flows to the north of Pine Hall Road drains northward into the Belews Creek Ash Basin. Surface water (and rainfall recharge) flows to the south of Pine Hall Road drains southward into the Belews Lake.

Consistent with the conceptual model of groundwater flow in the Piedmont region, the groundwater flow from the area of the landfill expansion will be northward, towards the Belews Creek Ash Basin. The ash basin is a permitted NPDES treatment facility. The northward portion of the groundwater system beneath the landfill will be separated into three sub-basins. Consistent with the LeGrand conceptual model, the boundaries of the sub-basins are delineated by the existing surface water drainage basins. These sub-basins are shown on Figure 1 as Area 1, Area 2, and Area 3.

During placement of the ash and prior to placement of the VFPE cover, the pore space in the ash will begin to retain rainwater infiltrating through the ash. However as shown by the HELP model runs described in Section 8.0, much of the rainfall is lost to runoff and evaporation. The amount of rainfall that infiltrates is not sufficient to raise the groundwater table high enough to cause groundwater to flow to the south (across Pine Hall Rd.) Once the VFPE cover is placed, the infiltration will be essentially eliminated, causing a corresponding reduction in groundwater levels underneath the landfill.

no flow across Rd only to pond

As described in Volume 2 of Reference 1, the material in the subsurface at the site is divided into four layers:

1. Layer 1 – Residual soil and saprolite consisting primarily of sandy silts (ML) and silty sands (SM) with a Standard Penetration Resistance of N≤30. It ranges in thickness from 10.6 to 43.3 feet with an average thickness of 25.24 feet (Volume 2 of Reference 1, Figure 4).

Soil at least 10.6' thick?

2. Layer 2 – Saprolite and weathered rock consisting of sandy silts (ML) and silty sands (SM) with layers of moderately to very severely weathered rock. It has Standard Penetration Resistance of N>30. Its thickness ranges from 1.2 feet to 30.0 feet with an average thickness of 17.64 feet (Volume 2 of Reference 1, Figure 4).
3. Weathered rock/fractured rock – consists of very severely weathered to slightly weathered rock and fractured rock. This layer is defined as the material below auger refusal and rock with Recovery of less than 90% and Rock Quality Designation (RQD) of less than 50%. The weathered rock/fractured rock layer below auger refusal ranges from 0 feet (in one borehole MW2-3) up to 40 feet in thickness. The thickness of weathered rock above auger refusal (in Layer 2) is estimated at 5 to 11 feet based on site and local boring data.
4. Sound Rock – defined as rock with Recovery $\geq$ 90 and RQD $\geq$ 50.

5.0 Waste Characteristics

The physical and chemical properties of the fly ash were obtained by tests performed on ash taken from the existing portion of the landfill, located adjacent to the proposed expansion.

5.1 Physical Properties

The physical properties of the ash were obtained from borings at three locations in the existing ash landfill. Five bag samples were collected in these borings. Lab analyses were performed on these samples to determine grain size analyses, void ratio, porosity, specific gravity, unit weight, and saturated hydraulic conductivity (performed on Shelby tube samples).

The results of the lab analyses on the samples collected from these borings is found in the report, Fly and Bottom Ash Testing Results, Belews Creek Ash Landfill, Duke Power Belews Creek Station, Stokes County, North Carolina, S&ME Project No. 1264-00-157C. A copy of this report is included as Appendix 1.

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

5.2 SPLP Analyses Performed on Composite Ash Samples

5.2.1 Composite Ash Samples

Composite ash samples were collected to determine which constituents, if any, would produce leachate concentrations exceeding the NCAC T15A 2L Groundwater Standards.

Flyash was sampled per the procedure outlined in the EPA publication, Guidance for the Sampling and Analysis of Municipal Waste Combustion Ash for the Toxicity Characteristic (June 1995, EPA Pub. No.: EPA530-R-95-036), with a minor exception that was previously approved by NC DENR Division of Solid Waste.[1] The samples were acquired at the mill hoppers and composited daily over an eight hour period. Overall, seven composite samples were obtained. These samples were analyzed using the Synthetic Precipitation Leaching Procedure (SPLP). These results were evaluated using the statistical methods prescribed in the forenamed guidance document.

5.2.2 Results of Leaching Analyses Performed on Composite Ash Samples

The composite ash samples (7 samples) were subjected to the SPLP (Synthetic Precipitation Leaching Procedure) leaching analyses to determine the concentrations of the following constituents the leachate: As, Ba, Cd, Cr, Fe, Pb, Mn, Hg, Se, and Ag. The results for the SPLP analyses are presented in Table 5-1.

The concentrations for SO_4 were determined by Ion Chromatography analyses. The results for these analyses are presented in Table 5-2.

[1] The guidance document specified two weeks of composite sampling. One week of composite samples were collected for this study. Bill Hocutt, NCDENR, Solid Waste Section, approved this change.
OK.

5.2.3 Comparison of Results of 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 5-3. As this table shows, the mean concentrations of Cd and Se exceeded the NCAC T15A 2L Groundwater Standards. The mean concentrations for the other constituents were equal to or below the 2L standards. Therefore, only Cd and Se will require further evaluation in this demonstration.

modeled modeled

Table 5-1 Results of SPLP Analyses in Composite Ash Samples

Sample	Date /Time	As ug/L	Ba mg/L	Cd ug/L	Cr ug/L	Fe mg/L		Pb ug/L	Mn ug/L		Hg ug/L	Se ug/L		Ag ug/L
				2L 5µL	2L 50µL	-3			15	50	11	50		
20005529	2/14/00 8:00 AM	15.1	0.240	8.03	66.44	1.110		6.75	88	<	1.00	33.9	<	5
20005530	2/15/00 8:00 AM	22.5	0.231	5.46	34.18	0.253		3.05	48	<	1.00	136.0	<	5
20005531	2/16/00 8:00 AM	3.9	0.248	7.24	6.59	0.133	<	2.00	77	<	1.00	32.3	<	5
20005532	2/17/00 8:00 AM	23.6	0.315	7.83	57.44	0.300		3.69	40	<	1.00	102.4	<	5
20005567	2/21/00 8:00 AM	27.3	0.274	6.70	47.02	0.230		4.26	35	<	1.00	126.5	<	5
20005568	2/22/00 8:00 AM	20.6	0.262	8.11	58.46	0.310		5.52	44	<	1.00	102.8	<	5
20005569	2/24/00 8:00 AM	2.0	0.223	3.19 <	1.00	0.014	<	2.00	45	<	1.00	26.0	<	5.0
Percent Non-Detects		14.3%	0.0%	0.0%	14.3%	0.0%		28.6%	0.0%		100.0%	0.0%		100.0%

Non-Detects Replaced with 1/2 LOD

Sample	Date /Time	As ug/L	Ba mg/L	Cd ug/L	Cr ug/L	Fe mg/L	Sqrt(Fe)	Pb ug/L	Mn mg/L		Hg ug/L	Se ug/L		Ag ug/L
20005529	2/14/00 8:00 AM	15.1	0.240	8.03	66.44	1.110	1.054	6.75	88	<	1.00	33.9	<	5.0
20005530	2/15/00 8:00 AM	22.5	0.231	5.46	34.18	0.253	0.503	3.05	48	<	1.00	136.0	<	5.0
20005531	2/16/00 8:00 AM	3.9	0.248	7.24	6.59	0.133	0.365	1.00	77	<	1.00	32.3	<	5.0
20005532	2/17/00 8:00 AM	23.6	0.315	7.83	57.44	0.300	0.548	3.69	40	<	1.00	102.4	<	5.0
20005567	2/21/00 8:00 AM	27.3	0.274	6.70	47.02	0.230	0.480	4.26	35	<	1.00	126.5	<	5.0
20005568	2/22/00 8:00 AM	20.6	0.262	8.11	58.46	0.310	0.557	5.52	44	<	1.00	102.8	<	5.0
20005569	2/24/00 8:00 AM	1.0	0.223	3.19	0.50	0.014							<	5.0
	Mean	16.29	0.26	6.65	38.66	0.34							<	5.00
	units	ug/L	mg/L	ug/L	ug/L	mg/L								ug/L

Ash samples
SPLP

Table 5-2 Results of Analyses in Composite Ash Samples for SO_4

Sample ID	Date /Time	SO_4 mg/L
20005521	2/14/00 8:00 AM	171.27
20005523	2/15/00 8:00 AM	121.98
20005524	2/16/00 8:00 AM	150.03
20005525	2/17/00 8:00 AM	123.80
20005526	2/21/00 8:00 AM	99.49
20005527	2/22/00 8:00 AM	128.06
20005528	2/24/00 8:00 AM	66.53
Percent Non-Detects		0.0%
	Mean	123.02
	units	mg/L

Table 5-3 Comparison of SPLP Results to NCAC 2L Groundwater Standards

	Results from Composite Ash Samples Leaching Analyses (Mean Values)	NCAC 2L .0202 Groundwater Quality Standards	
Analyte	**mg/L**	**mg/L**	
As	0.01629	0.05	
Ba	0.26	2.0	
Cd	**0.00665**	**0.005**	Note 1
Cr	0.03866	0.05	
Fe	0.34	0.3	Note 2
Pb	0.00361	0.015	
Mn	0.05386	0.05	Note 2
Hg	< 0.001	0.0011	
Se	**0.07999**	**0.05**	Note 1
Ag	0.005	0.018	
SO_4	123.0	250	

Notes:
1. Constituent concentrations shown in bold exceed 2L standards.
2. Rounding of the analytical results to the number of significant figures consistent with those used in 2L for the corresponding constituent provides concentrations that are equal to, but not in excess of the 2 L standard.

6.0 Site Soil Characteristics

The site soils are classified in Soil Survey of Stokes County, North Carolina [Reference 2] as Pacolet-Rion. Two sets of analyses were performed on samples from the site. The soil samples were analyzed to determine the adsorptive capacity for selected constituents. The results of these analyses are presented in Site-Specific Chemical Attenuation Parameters of Selected Constituents for Proposed Belews Creek Ash Landfill. A copy of this report is included as Appendix 2. Additional analyses were performed to determine typical geotechnical properties. The results of these analyses are found in Volume 2 of Reference 1 and in the Soil Sample Laboratory Report. A copy of this report is included as Appendix 3.

The results of various analyses performed on eleven samples of site soil are discussed in detail in Site-Specific Chemical Attenuation Parameters of Selected Constituents for Proposed Belews Creek Ash Landfill [Appendix 2]. Analyses were performed on the soil samples to determine the following:

- Cation exchange capacity (CEC)
- Anion exchange capacity (AEC)
- Extractable amounts of Fe and Mn
- Soil pH
- Particle size
- Types of clay present
- Carbon analyses (total organic carbon)
- Adsorption properties for selected constituents

These samples were selected to be representative of the various soil conditions at the site. The samples are from borings BC-3, BC-6, MW2-1, MW2-1, and MW-6.

These analyses indicate that the soils from the Belews Creek site are predominately fine sandy loam textured with very little organic matter. The soils are acidic with a pH range of about 5 to 6.3. A significant amount of extractable iron is present in the soils, although the amount varied form sample to sample. The soils were found to be primarily kaolintic with substantial amounts of vermiculite or hydroxy-interlayered vermiculite.

6.1 Physical Properties

The physical properties of the site soils are discussed in Section 8.0 HELP Model Description and Results.

6.2 Adsorption Properties

The adsorption properties of the site soils are provided in Appendix 2. The reader should refer to this reference for detail on the specific procedures used in these analyses. These analyses were conducted using a batch equilibrium approach in which a solution containing the constituents of interest, at a range of known concentrations, is equilibrated with the site soil for some designated time followed by analyses of the constituents remaining in solution. Using this approach adsorption isotherms were constructed by measuring the solutions concentrations of the constituents of interest at equilibrium and estimating the amount lost to the soil.

Adsorption tests were performed separately for three constituent groups as follows:
1. As (V), Se (VI), and Mn (II)
2. Cr (VI) and Cd (II)
3. Fe (III)

The adsorptive capacity of the soil is expressed by the parameter K_d, the linear distribution coefficient. This term, K_d, is defined as the parameter that describes the linear partitioning between leachate constituents and the soil material at equilibrium.

It is defined as: $K_d = C_S/C_W$
C_S = the amount of sorbed mass of constituent per mass of soil at equilibrium.
C_W = the equilibrium concentration of the constituents in solution.

The K_d terms are used in the MYGRT analyses.

6.2.1 Adsorption of As (V), Cr (VI), Se (VI) and Cd (II) on Site Soils

A summary of the results of the analyses is found below.

Table 6-1 Summary of Results of Adsorption Analyses of Site Soils

Sample ID	Depth Below Ground Surface	As (V) K_d	Cr (VI) K_d	Se(VI) K_d	Cd(II) K_d
	(ft)	(L/kg)	(L/kg)	(L/kg)	(L/kg)
BC-3	0 – 10	7600	13.5	43.6	14.9
BC-3	40 – 50	1630	12.8	9.5	15.5
BC-3	50 – 60	4000	501.4	27.2	6.3
BC-6	0 – 10	9900	325.6	145.9	7.1
BC-6	10 – 20	>11000	131.5	59.6	5.5
BC-6	20 –24	>11000	400	21.6	8.5
MW2-2	30 – 40	2440	11.5	8.3	46.7
MW2-1	35 – 45	3300	41.0	18.7	34.2
MW-6	28 – 38	2460	41.0	20.8	9.4
MW-6	38 - 48	4200	128.9	43.8	14.9

Note: Section 6.2.2 discusses adsorption tests performed on Mn and Fe.

Refer to Table 7 of Appendix 2 for additional information on these results and to this appendix for discussions on comparison of these results to published literature.

In general, these soils show an extremely strong capacity to adsorb As, consistent with the high concentration of iron oxides/hydroxides found in these soils. The adsorptive capacities for the other constituents show variability across the site area and in depth, even at the same boring location.

6.2.2 Adsorption of Mn and Fe on Site Soils

As discussed in Appendix 2, complete attenuation of Mn (II) and Fe (III) by the soil occurred. Therefore K_d values could not be calculated and are meaningless for these soil conditions. Due to the significant amounts of Mn and Fe oxides, the behavior of Mn and Fe in these soils is controlled by the precipitation-dissolution reactions of these naturally occurring solid phases. The report in Appendix 2 further concludes that added amounts of Mn (II) and Fe (III) are quickly attenuated to those levels that would be in the soil naturally.

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,[2] (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 Post-Operational Period,[3] after the placement of the engineered cover.

2) The MYGRT model was used to predict the concentrations of Cd and Se during the Operational Period and during the Post-Operational Period. As described in Section 5.2.3, Cd and Se were the only constituents whose SPLP results exceeded the 2L groundwater standards.

[2] The Operational Period refers to the 5 year period of landfill operation prior to the placement of the engineered cover.

[3] The Post-Operational 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 Model

The 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 4]

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.

The HELP model used for this demonstration is HELP, Hydrologic Evaluation of Landfill Performance, IGWMC FOS32, Version 3.04, April 1995 [Reference 5].

8.2 HELP Model Inputs:

Inputs for the HELP model can be described as input into the following two types of data; (1) weather data and (2) soil and landfill design data.

Weather Data

The HELP model contains default values for growing season, average annual wind speed, average quarterly relative humidities, normal mean monthly temperatures, maximum leaf area index, evaporative zone depth and latitude for Greensboro. These values were used in the analyses. The average monthly temperature values from the Stokes County Soil Survey [Reference 2] were used to improve the accuracy of the synthetic weather generated by HELP.

Soil and Landfill Design Data

The soil and ash properties that are used by HELP were developed from analyses on site soil and ash. These values are shown in Table 8-1, Table 8-2 and Table 8-4.

Properties for Soil Layer Beneath the Landfill

The soil properties from undisturbed samples are used to calculate porosity, field capacity, wilting point, and hydraulic conductivity parameters for the soil layer beneath the landfill. These values are shown in Table 8-1. These represent the soil properties for the soil layer beneath the landfill.

The hydraulic conductivity calculated in this table compares well with the mean value for Layer 1, from Table 8, Volume 2, Reference 1. The mean hydraulic conductivity in this reference for Layer 1 is 9.1E-05 cm/sec. A description of Layer 1 is found on in Section 4.4.

Properties for Vegetative Soil Layer

The soil properties from remolded samples taken from borings located within the landfill footprint and are used to calculate porosity, field capacity, wilting point, and hydraulic conductivity parameters for the vegetative soil layer. These values are shown in Table 8-2. This layer will be constructed of soil that is excavated from the landfill footprint area and compacted as the vegetative cover layer. Therefore, the remolded samples reflect the properties for this layer.

Since the soil properties were user defined, the hydraulic conductivity in the top half of the evaporative zone was calculated (adjusted) by using Eqn. A-10 in the HELP manual. These calculations are found in Table 8-3. An 18" thick evaporative zone was used. Therefore, the adjusted hydraulic conductivity was used on the upper 9" layer.

Properties for Ash Layer

The properties from the ash samples are used to calculate average values for porosity, field capacity, wilting point, and hydraulic conductivity parameters for the ash layer. These values are shown in Table 8-4. These properties are taken from Appendix 1.

Table 8-1 Site Soils – Properties Used in Help Model – Undisturbed Samples

This table presents the information from undisturbed soil samples [Appendix 3] and calculates values for the site soil used in the HELP analyses.
HELP Layers: Soil beneath the landfill in the Operational and Post Operational Conditions

Depth to Base Gr	Sample ID and UD Number	Depth of Sample (ft)	USCS Classification	Natural Moisture (%)	Porosity	Per Cent Sand 0.05 - 2.0mm (USDA Soil Classification)	Per Cent Clay <0.002 mm (USDA Soil Classification)	Hydraulic Conductivity, k (cm/sec)
0	MW 2-1 UD#2	9.5 - 11.5	CH	30.7%	0.64	30%	3%	2.80E-06
0	MW 2-2 UD#3	24.1 - 25.5	ML	18.0%	0.46	34%	3%	1.81E-04
0	MW 2-2 UD#5	34.1 - 36.1	ML	33.1%	0.49	40%	3%	6.63E-05
15'	MW 2-3 UD#4	29.0 - 30.6	ML	17.5%	0.45	41%	2%	5.58E-05
19'	MW 2-4 UD#2	19.0 – 21.0	ML	21.1%	0.51	37%	3%	Bad Sample
22	BC-4 UD-1	5.0 - 6.7	ML	16.1%	0.53	47%	2%	2.51E-04
6.8	BC-5 UD-1	9.5 - 11.5	ML	23.4%	0.56	50%	7%	3.61E-04

OK! only sample take @ grade

	Natural Moisture (%)	Porosity	Per Cent Sand 0.05 - 2.0mm	Per Cent Clay <0.002 mm	Hydraulic Conductivity, k (cm/sec)
Mean Values	22.8%	0.52	40%	3%	1.53E-04

The Field Capacity and Wilting Capacity are calculated from the mean values above.
The equations used for these calculations are found in the HELP Users Manual, Appendix A.
See Table 8-3 Vegetated, Saturated Hydraulic Conductivity for adjusted hydraulic conductivity for this soil when used in the preexisting conditions HELP Model.

Field Capacity (HELP Eqn A-3)	Wilting Point (HELP Eqn A-4)
0.196	0.061

Table 8-2 Site Soils – Properties Used in Help Model – Remolded Samples

This table presents the information from the soil borings and lab tests [Appendix 3] and calculates values for the site soil used in the HELP analyses.

HELP Layers: Vegetative Layer in Post Operational Condition

Sample ID	Depth of Sample (ft)	USCS Classification	Natural Moisture (%)	Porosity	Per Cent Sand 0.05 - 2.0mm (USDA Soil Classification)	Per Cent Clay <0.002 mm (USDA Soil Classification)	Hydraulic Conductivity, k (cm/sec)
BC-1	0'-10'	ML	17.6%	0.44	42%	14%	5.64E-05
BC-3	0'-10'	SM	11.9%	0.37	53%	6%	3.47E-04
BC-4	0'-10'	ML	14.9%	0.42	47%	10%	5.54E-05
BC-5	0'-10'	ML	18.3%	0.44	49%	17%	6.47E-05
BC-6	0'-10'	ML	23.2%	0.49	40%	20%	5.31E-05

0-22 cut
0-9 cut

	Natural Moisture (%)	Porosity	Per Cent Sand 0.05 - 2.0mm	Per Cent Clay <0.002 mm	Hydraulic Conductivity, k (cm/sec)
Mean Values	17.2%	0.43	46%	13%	1.15E-04

The Field Capacity and Wilting Capacity are calculated from the mean values above.
The equations used for these calculations are found in the HELP Users Manual, Appendix A.
See Table 8-3 Vegetated, Saturated Hydraulic Conductivity for adjusted hydraulic conductivity for this soil.

Field Capacity (HELP Eqn A-3)	Wilting Point (HELP Eqn A-4)
0.206	0.098

Table 8-3 Vegetated, Saturated Hydraulic Conductivity

Since the soil properties are not default HELP soil properties, the saturated hydraulic conductivity in the top half of the evaporative zone must be adjusted.

LAI = Leaf Area Index
LAI = 2

K_s =Saturated hydraulic conductivity in vegetative layer soil, cm/sec

$(K_s)_v$ =Saturated hydraulic conductivity in top half of evaporative zone, cm/sec

Eqn. A-10 HELP Manual
K_{sv} =(1.0 + 0.5966*LAI + 0.132659 *(LAI)^2 + 0.1123454*(LAI)^3 - 0.04777627 (LAI)^4 +0.004325035 (LAI)^5*) K_s

Ksv for Remolded Soil

K_s =1.15E-04 cm/sec
K_{sv} =3.46E-04cm/sec

Ksv for Site Soil for Pre-Operational Period HELP Model

K_s = 1.53E-04 cm/sec
K_{sv} =3.05E-04 cm/sec

These values will be used in the top half of the evaporative zone.

Table 8-4 Site Ash – Properties Used in Help Model

This table presents the information from the ash borings and lab tests [Appendix 1] and calculates values used for the site ash in the HELP analyses.

The percent sand and clay are based on USDA Soil Classification parameters.
HELP Layers: Ash layers in Operational and Post-Operational Conditions

Sample ID	Depth of Sample (ft)	Sample Type	USCS Classification	Natural Moisture (%)	Porosity	Per Cent Sand 0.05 - 2.0mm	Per Cent Clay <0.002 mm	Hydraulic Conductivity, k (cm/sec)	Confining Pressure (psi)
A-1	13.5 - 15.5	UD	NA	13.1%	0.39	22%	2.9%	3.10E-05	2.5
A-1								2.32E-05	4.0
A-2	13.5 - 15.2	UD	NA	18.1%	0.47	13.5%	0.6%	8.30E-05	2.5
A-2								9.03E-05	4.0
A-3	13.5 - 15.5	UD	NA	12.1%	0.48	16.3%	0.2%	1.09E-04	2.5
A-3								1.64E-04	4.0
A-3	28.5 - 30.5	UD	NA	22.3%	0.45	13.8%	0.6%	2.36E-04	2.5
A-3								1.02E-04	8.0

	Natural Moisture (%)	Porosity	Per Cent Sand 0.05 - 2.0mm	Per Cent Clay <0.002 mm	Hydraulic Conductivity, k (cm/sec)
Mean Values	16.4%	0.45	16.4%	1.1%	1.05E-04

The Field Capacity and Wilting Capacity are calculated from the mean values above.
The equations used for these calculations are found in the HELP Users Manual, Appendix A.

Field Capacity (HELP Eqn A-3)	Wilting Point (HELP Eqn A-4)
0.215	0.057

8.3 HELP Model Results

Three phases were modeled with HELP. These phases are:

- Pre-Operational period – models the infiltration that occurs prior to ash placement.
- Operational Period – models the infiltration that occurs during the period of ash placement.
- Post-Operational Period – models the infiltration that occurs after placement of the engineered cover.

8.3.1 Pre-Operational Period

A HELP run using a 4 foot thickness of site soil was made to estimate the percolation rate through the site soil prior to ash placement. The results from this run will be compared to the percolation rates during the operational period. The properties for the soil beneath the landfill (Table 8-1) were used for this run. The HELP model results are that the average annual infiltration prior to ash placement is 16 inches.

8.3.2 Operational Period

The landfill was modeled during the operational period (the 5 year period of ash placement) to:

1. determine the quantity of infiltration that would pass through the ash, becoming leachate.
2. determine the effect of infiltration on groundwater levels beneath the landfill footprint.

The landfill was divided into three areas for HELP modeling. As described in Section 4.3 Site Hydrogeology, the boundaries of the sub-basins are delineated by the existing surface water drainage basins. These sub-basins are shown on Figure 1 as Area 1, Area 2, and Area 3. The areas, elevations, ash thickness, and average slope information is presented on Figure 2.

The HELP model for the operational period consists of two layers. The upper layer is the average depth of ash placed in the particular area (Area 1, Area 2, or Area 3). Beneath this is a 4 foot thick layer of site soil. Depths to groundwater beneath the landfill greatly exceed 4 feet.

The site soils are in the Pacolet-Rion group, Hydrologic Group B. In these HELP runs, a Curve Number of 72 (Dirt Road, Hydrologic Group A) was conservatively used. These runs also conservatively ignore the surface slopes. Use of these conditions will produce more percolation through the ash in the model than would occur at the site.

The amount of percolation through the three areas, along with the thickness of ash in the three areas, is shown below.

Table 8-5 HELP Model Results – Operational Period

	Area (acres)	Mean Depth of Ash (feet)	Average Annual Percolation Through Ash (inches per year)
Area 1	19.6	67.2	2.72
Area 2	27.5	82.3	1.05
Area 3	5.3	35.9	7.48

Comparison of the pre-operational period percolation rate of 16 inches to the percolation rates for the rates for Area 1, Area 2, and Area 3 shows that the percolation rate for the 5 year period of operation is less than the Pre-Operational rate. The difference in the percolation rates is due to losses to storage in the ash layers. The higher percolation through Area 3 is due to the smaller depth of ash and the corresponding smaller amount of storage.

Since the percolation rate(s) into the soil during the Operational Period is less than the percolation rate(s) during the Pre-Operational Period, there would be only small changes in the groundwater table elevations and groundwater flow between these two periods. Therefore, the existing groundwater profile can be used in the MYGRT model to reflect the groundwater flow during the operational period.

Copies of the outputs for the HELP model runs are located in Appendix 4.

8.3.3 Description of HELP Model for Landfill – Post-Operational Period

The landfill was modeled during the Post-Operational Period (after placement of engineered cover) to determine the quantity of leachate.

The engineered cover will consist of a textured 40 mil very flexible polyethylene (VFPE) 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.

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.

As described in the previous section, the landfill was divided into three areas for HELP modeling. As described in 4.3 Site Hydrogeology, the boundaries of the sub-basins are delineated by the existing surface water drainage basins. These three sub-basins are shown on Figure 1. The areas, elevations, ash thickness, and average slope information is presented on Figure 2. There would be no change in these boundaries due to placement of the ash.

The landfill modeled for the Post-Operational Period consisted of the following layers.

Table 8-6 HELP Layers for Post-Operational Period Model

Layer Description	Thickness of Layer (inches)	HELP Model Layer Number
Vegetative Soil	24	1 and 2
GEONET Drainage Layer	0.20	3
VFPE (40 mil very flexible polyethylene)	0.04	4
Ash	– Varies with Area –	5
Existing Site Soil	48	6

The specific properties for the site soil and ash are found in Table 8-1, Table 8-2, Table 8-3, and Table 8-4. The VFPE layer modeled has a hydraulic conductivity of 2.0E-13 cm/sec. The assumed placement quality for the VFPE cover is good. This will be assured through a QA/QC program developed in coordination with the manufacture and NCDENR. Note that in the HELP runs, the default values for HDPE were used for this layer.

The assumed number of holes in the cover used in the HELP analyses are: very low

- pinhole density is 1 hole/acre 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.

8.3.4 Results of HELP Models for Operational Period

The percolation rates through the engineered cover, and through the bottom of the landfill, is shown in Table 8-7. These results indicate the effectiveness of the engineered cover to reduce infiltration through the landfill.

Table 8-7 HELP Model Results – Post-Operational Period

	Area (acres)	Mean Depth of Ash (feet)	Average Annual Percolation Through Ash (inches per year)
Area 1	19.6	67.2	0.0154
Area 2	27.5	82.3	0.0154
Area 3	5.3	35.9	0.0154

Copies of these HELP runs are located in Appendix 4.

9.0 MYGRT Model Description and 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 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.

MYGRT Version 3.0 was used for these analyses [Reference 6]. A copy of the MYGRT manual is included as Appendix 5.

9.1 Description of Model Runs

MYGRT has the capability to change the infiltration rate at a specified time, so the Operational and the Post-Operational conditions can be modeled in the same model run.

As with the HELP runs, separate MYGRT runs were made for each of the three drainage areas. MYGRT requires each constituent of concern (Cd, Se) to be in a separate model run. A separate model run was performed for each constituent to simulate fate and transport within each of the groundwater flow basins (Area 1, Area 2, and Area 3). Therefore, a total of six model runs were performed.

9.2 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. The unsaturated/saturated modeling scenario was used. The model calculated the concentrations of Cd and Se after the constituents pass through the unsaturated zone, underneath the landfill, and through the saturated zone. The source location is modeled in the unsaturated zone. Table 9-2 provides the input values for the key parameters.

The minimum K_d values for the site are used for the MYGRT analyses.

<u>Modeling Period</u>
The period of time for modeling was selected as 10,005 years. The landfill was modeled with infiltration representative of the operational period (uncovered) for 5 years. After placement of the cover , at the end of the 5 year period, the infiltration rate is decreased to represent the infiltration that will occur during the post operational period. Due to the extremely small infiltration rate of the engineered cover, the time required for a pore volume of water to pass through the column of ash is calculated to be 11,324 years [See Appendix 6].

Since the period of time for exchange of even one pore volume is so long, a period of 10,000 years was deemed to be sufficient to determine compliance with 2L standards. Therefore, the results from the SPLP analyses for Cd and Se were used as the input concentrations, modified as

described in the following section. Therefore, the 5 year operational period, added to the 10,000 year period results in the 10,005 year modeling period.

Adjustment of Input Concentrations

As described on pages A-8 through A-9 of the MYGRT manual, and as shown on Figure A-2 of the MYGRT manual, MYGRT assumes the landfill to be located so that there is an upgradient source of groundwater that flows underneath the landfill. This assumption is not valid at the site of the proposed Belews Creek landfill.

MYGRT calculates the initial concentrations beneath the landfill, based on this assumed upgradient flow. These calculations result in an initial concentration that is lower than would actually exist at the base of the landfill. This was verified by making MYGRT runs with a retardation factor of 1 and inspecting the results at a location immediately (1') below the landfill.

To obtain the correct initial concentrations, the SPLP concentrations for Cd and Se are factored up for use in MYGRT. As shown on page A-8, the term for source area is included in the MYGRT calculation for initial concentration. Therefore, a separate correction factor is computed for Area1, Area 2, and Area 3. These calculations are shown in Appendix 6. The adjusted concentrations are presented in Table 9-1.

Cd, Mean Concentration from SPLP Analysis	0.00665 mg/l
Se, Mean Concentration from SPLP Analysis	0.07999 mg/l

Table 9-1 Adjusted Cd and Se Concentrations

	Adjustment Factor	Cd Concentration Used in MYGRT (mg/l)	Se Concentration Used in MYGRT (mg/l)
Area 1	1.03	0.00675	0.0824
Area 2	1.01	0.00672	0.0808
Area 3	1.01	0.00672	0.0808

Table 9-2 MYGRT Model – Key Input Parameters

Input Parameter	Units	Source of Input	Area 1	Area 2	Area 3
Unsaturated Zone Parameters					
Area	acres	Figure 2	19.6	27.5	5.3
Width of Source	ft	Note 1	620	645	375
Length of Source Parallel with Aquifer Flow Direction	ft	Figure 2	1380	1550	615
Input Source Concentration, Cd	mg/l	Note 2	0.00675	0.00672	0.00672
Input Source Concentration, Se	mg/l	Note 2	0.0824	0.0808	0.0808
Infiltration Rate - Operational Period Years 2003 to 2007	In/year	HELP	2.72	1.05	7.48
Infiltration Rate – Post-Operational Period Years 2008 to 12,008	In/year	HELP	0.0154	0.0154	0.0154
Volumetric Moisture Content of Soil (Unsaturated)	vol/vol	Table 5-1	22.8	22.8	22.8
Depth to water table below source	ft	Note 3	4	4	4
Rd, Unsaturated layer, Cd		See Note 4	32.6	32.6	32.6
Rd, Unsaturated layer, Se		See Note 4	48.7	48.7	48.7
Saturated Zone Parameters					
Uppermost groundwater elevation for section	ft	Figure 2	BC-1A 809.56	C/L Haul Road 817.6	C/L Haul Road 810
Lowermost groundwater elevation for section	ft	Figure 2	MW2-2 754.08	Ash Basin 750.8	Ash Basin 750.8
Hydraulic Gradient	ft/ft		0.040	0.043	0.096
Hydraulic Conductivity	ft/yr	k is from Table 8, Vol. 2, Reference 1, for Layer 1.	14.5	14.5	14.5
n_e, effective porosity		Reference 7 Note 4	0.15	0.15	0.15
Scale Distance for Dispersion Calculation	ft	See Note 5	250	250	250
Aquifer Thickness	ft	Appendix 6	15.0	2.9	8.3
Solute Plume Properties					
Bulk Density	g/ml	Appendix 6	1.31	1.31	1.31
K_d for Cadmium	ml/g	Note 6	5.5	5.5	5.5
K_d for Selenium	m/g	Note 7	8.3	8.3	8.3

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Table 9-2 MYGRT Model – Key Input Parameters

Notes:

1. Width of source is determined by dividing area by the length.
2. As described in Section 9.2, the SPLP results are factored-up to account for dilution flow assumed by MYGRT.
3. A four foot depth to groundwater underneath the landfill is conservatively assumed.
4. The retardation factor, Rd is calculated by MYGRT as:
   For unsaturated soil, Rd = 1 + [K_d *dry bulk density]/moisture content.
   For saturated soil, Rd = 1 + [K_d *dry bulk density]/effective porosity.
   See Appendix 6.
5. The scale distance for dispersion calculations used is 250 feet. The horizontal, transverse, and vertical coefficients are calculated by MYGRT as follows:

Horizontal Dispersion Coefficient	1/10th of scale distance multiplied by the seepage velocity
Transverse Dispersion Coefficient	1/10th of horizontal dispersion coefficient
Vertical Dispersion Coefficient	1/100th horizontal dispersion coefficient

6. The units for K_d as noted in Table 6-1 are L/kg. This is equivalent to ml/g. The minimum K_d for Cd is conservatively used. The K_d values for Cd ranged from 5.5 to 46.7 L/kg.
7. The units for K_d as noted in Table 6-1 are L/kg. This is equivalent to ml/g. The minimum K_d for Se is conservatively used. The K_d values for Se ranged from 8.3 to 145.9 L/kg.

10.0 MYGRT Model Results and Comparison to 2L Standards

The results from the MYGRT runs are located in Appendix 7. The results are summarized in the table below. As described in Section 1.0 Regulatory Requirements, it is greater than 250 feet from the footprint of the proposed landfill to the nearest property boundary, and a distance of 250 feet from the footprint will be used to evaluate compliance with 2L groundwater standards.

Table 10-1 MYGRT Model Results – Minimum K_d Used

	NCAC 2L Standards(mg/l)	Area 1	Area 2	Area 3
Maximum Concentration of Cadmium at 250' (mg/l)	0.005	<0.0012	<0.003	<0.0005
Maximum Concentration of Selenium at 250' (mg/l)	0.05	<0.012	<0.027	<0.006

Note that these results are based on use of the minimum K_d terms for the site. As shown in Table 6-1 Summary of Results of Adsorption Analyses of Site Soils, the K_d values for cadmium range from a minimum of 5.5 L/kg to a maximum of 46.7 L/kg, with an average value of 16.3 L/kg. Similarly, for selenium, the K_d terms range from a minimum of 8.3 L/kg to a maximum of 145.9 L/kg, with the average value of 39.9 L/kg. As shown in Table 10-1, even when the minimum K_d terms for the site are used, the 2L standards are not exceeded with the proposed design.

11.0 Conclusions

As shown in Table 10-1, even when the minimum K_d terms for the site are used, the 2L standards are not exceeded with the proposed design. Therefore, the design proposed in this demonstration ensures that the ground water standards established under 15A NCAC 2L will not be exceeded.

This design proposed in this demonstration calls for:

3. the active landfill will receive ash for a 5 year period.
4. an engineered cover will be placed on the competed landfill at the end of the 5 year period.

The engineered cover will consist of a textured 40 mil very flexible polyethylene (VFPE) 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 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.

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. 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.

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 Energy Belews Creek Steam Station, Stokes County, NC, Landfill Permit Application – Siting Package, October 2, 2001, Volumes 1 and 2.

2 Soil Survey of Stokes County, North Carolina, United States Department of Agriculture, Issued October 1995.

3 *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.

4 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.

5 HELP, Hydrologic Evaluation of Landfill Performance, International Ground Water Modeling Center FOS32, Version 3.04, April 1995.

6 *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. See Appendix 5.

7 North Carolina Risk Analysis Framework, DRAFT, December 1996.

Drawings Under Seperate Cover

Appendices

Appendix 1

Fly and Bottom Ash Testing Results
Belews Creek Ash Landfill
Duke Power Belews Creek Station
Stokes County, North Carolina
S&ME Project No. 1264-00-157C

FLY AND BOTTOM ASH
TESTING RESULTS

BELEWS CREEK ASH LANDFILL
DUKE POWER BELEWS CREEK STATION
STOKES COUNTY, NORTH CAROLINA
S&ME PROJECT NO. 1264-00-157C

Prepared For:

DUKE POWER
MAIL CODE EC12ZB
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April 2001

April 27, 2001

Mr. William (Bill) Miller, P.E.
Duke Power
Mail Code EC12ZB
Post Office Box 1006
Charlotte, North Carolina 28201-1006

Reference: **FLY AND BOTTOM ASH TESTING RESULTS**
Belews Creek Ash Landfill
Duke Power Belews Creek Steam Station
Stokes County, North Carolina
S&ME Project No. 1264-00-157C

Dear Mr. Miller:

S&ME, Inc. is pleased to present the results of our fly and bottom ash testing for the Belews Creek Steam Station Ash Landfill. This report includes a brief summary of the project; supporting Boring Logs and laboratory testing sheets are included in the Appendices.

Project Information

Duke Power operates a landfill for disposal of fly ash at their Belews Creek Steam Station in Stokes County, North Carolina. The landfill is under consideration for expansion. Negotiations with the North Carolina Department of Environment and Natural Resources are ongoing regarding whether the expansion will have to include bottom and/or top liner system(s). As part of the negotiations, Duke Power is conducting technical evaluation of the landfill, including characteristics of the disposed fly ash and a separate, coarser material termed "bottom ash". As such, Duke Power desired S&ME to assist with three aspects of the evaluation, namely:

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- Drilling borings into previously disposed fly ash to (1) conduct in-situ field conductivity tests and (2) obtain fly ash samples for laboratory testing;
- Secure bottom ash samples for laboratory testing; and,
- Conduct selected characteristic laboratory tests on the collected fly and bottom ash samples.

This report presents a summary of these activities and the results.

Drilling and Sampling

On March 12 and 13, 2001, S&ME drilled four auger borings into the fly ash landfill at locations specified by Duke Power personnel using a truck-mounted Diedrich D-120 drill rig. Auger boring B-1 was terminated at a depth of 10 feet as no fly ash was encountered. Auger borings A-1, A-2, and A-3 were drilled to depths of 18.5, 32, and 32 feet, respectively, through fly ash. Borings A-1 and A-3 were terminated within the fly ash; boring A-2, as later revealed by the lowermost Shelby tube, actually penetrated through the fly ash and was terminated within residual soils.

Within boring A-1, we collected a bulk sample of the fly ash between 8.5 and 13.5 feet and a Shelby tube sample from between approximately 13.5 and 15.5 feet. Within borings A-2 and A-3, we collected bulk samples between 8.5 and 13.5 and 23.5 and 28.5 feet and Shelby tube samples from between 13.5 and 15.5 and 28.5 and 30.5 feet. The samples were identified in the field and delivered to our soil laboratories in Spartanburg, South Carolina or Charlotte, North Carolina for selected laboratory testing.

In addition to the above sample collections, Duke Power conducted field conductivity tests in borings A-1, A-2, and A-3. These tests consisted of installing NW casing to near 15.5 feet in all three borings and to near 30.5 feet in borings A-2 and A-3 as the borings were advanced, filling the NW casing with potable water, and measuring the water level decline over time.

Finally, Duke Power provided two bulk samples of the bottom ash, sample BA-1 (termed "Bottom of Basin" sample) and BA-2 (termed "Behind Basin" sample).

Boring Logs for the completed borings are attached in Appendix A. Duke Power noted and recorded the boring locations, which are not identified in this report. Furthermore, Duke Power collected and retained the field conductivity test data, which is not included in this report.

Laboratory Testing

The desired fly ash characteristics to be tested included grain size distribution, void ratio, and permeability. (The primary choice for permeability of the fly ash was undisturbed from the Shelby tubes; the bulk samples were collected as a contingency in case the Shelby tube samples were not successful. As it turned out, the Shelby tube fly ash samples were successfully recovered and tested. Shelby tube sample A-2 from between 28.5 and 30.5 feet was found to be all residual soil when extracted in the laboratory.) The desired bottom ash characteristics to be tested included grain size distribution, standard Proctor compaction, and void ratio and permeability under re-compacted conditions at near 90 percent of the standard Proctor maximum dry density.

The *Summary of Laboratory Test Data* sheet included in Appendix B summarizes the laboratory testing results. Supporting laboratory data sheets are also included in Appendix B.

Two items are noteworthy from the laboratory test data. First, the void ratio values were computed indirectly from laboratory measurements of specific gravity and dry unit weight (reference calculations included as *Void Ratio Computation Sheet* in Appendix C). Secondly, permeability values are provided for both minimal confining pressures (2.5± pounds per square inch) and confining pressures approximating in-situ conditions based on the sample depth (reference calculations included as *Confining Pressure Computation Sheet* in Appendix C).

Closure

S&ME appreciates this and every opportunity to be of service to Duke Power. We trust this information is responsive to your needs. Certainly, if you have questions, comments, or desire our assistance further, please contact us.

Sincerely,

S&ME, Inc.

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

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

Cc: Mr. Malcolm F. Schaeffer, Duke Power

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Appendix A

LEGEND TO SOIL CLASSIFICATION AND SYMBOLS

SOIL TYPES

(Shown in Graphic Log)

- Fill
- Asphalt
- Concrete
- Topsoil
- Gravel
- Sand
- Silt
- Clay
- Organic
- Silty Sand
- Clayey Sand
- Sandy Silt
- Clayey Silt
- Sandy Clay
- Silty Clay
- Partially Weathered Rock
- Cored Rock

WATER LEVELS

(Shown in Water Level Column)

▽ = Water Level At Termination of Boring
▼ = Water Level Taken After 24 Hours
◄ = Loss of Drilling Water
HC = Hole Cave

CONSISTENCY OF COHESIVE SOILS

CONSISTENCY	STD. PENETRATION RESISTANCE BLOWS/FOOT
Very Soft	0 to 2
Soft	3 to 4
Firm	5 to 8
Stiff	9 to 15
Very Stiff	16 to 30
Hard	31 to 50
Very Hard	Over 50

RELATIVE DENSITY OF COHESIONLESS SOILS

RELATIVE DENSITY	STD. PENETRATION RESISTANCE BLOWS/FOOT
Very Loose	0 to 4
Loose	5 to 10
Medium Dense	11 to 30
Dense	31 to 50
Very Dense	Over 50

SAMPLER TYPES

(Shown in Samples Column)

- ■ Shelby Tube
- ☒ Split Spoon
- I Rock Core
- ☐ No Recovery

TERMS

Standard Penetration Resistance - The Number of Blows of 140 lb. Hammer Falling 30 in. Required to Drive 1.4 in. I.D. Split Spoon Sampler 1 Foot. As Specified in ASTM D-1586.

REC - Total Length of Rock Recovered in the Core Barrel Divided by the Total Length of the Core Run Times 100%.

RQD - Total Length of Sound Rock Segments Recovered that are Longer Than or Equal to 4" (mechanical breaks excluded) Divided by the Total Length of the Core Run Times 100%.

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PROJECT: Belew's Creek Landfill Ash Testing S&ME Project No. 1264-00-157C	BORING LOG A-1

DATE DRILLED: 3/12/01	ELEVATION:	NOTES: NW casing installed to 18.5 feet for field conductivity test.
DRILLING METHOD: 3¼" H.S.A.	BORING DEPTH: 18.5	
LOGGED BY: Malcolm Schaeffer	WATER LEVEL:	
DRILLER: Costello & Millwood	DRILL RIG: Diedrich D-120	

DEPTH (feet)	GRAPHIC LOG	MATERIAL DESCRIPTION	WATER LEVEL	ELEVATION (feet)	SAMPLE NO. SAMPLE TYPE	STANDARD PENETRATION TEST DATA (blows/ft) 10 20 30 60 80	N VALUE
		Auger boring through fly ash					
5							
10					Bulk Sample		
15							
		Field conductivity test at 18.5 feet					
		BORING TERMINATED AT 18.5 FEET					

BORING LOG 6400157C.GPJ S&ME.GDT 4/25/01

1. BORING AND SAMPLING IS IN ACCORDANCE WITH ASTM D-1586.
2. PENETRATION (N-VALUE) IS THE NUMBER OF BLOWS OF 140 LB. HAMMER FALLING 30 IN. REQUIRED TO DRIVE 1.4 IN. I.D. SAMPLER 1 FT.

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PROJECT: Belew's Creek Landfill Ash Testing S&ME Project No. 1264-00-157C	BORING LOG A-2

DATE DRILLED: 3/12/01	ELEVATION:	NOTES: NW casing installed to 18.5 feet and 32 feet for field conductivity tests.
DRILLING METHOD: 3¼" H.S.A.	BORING DEPTH: 32.0	
LOGGED BY: Malcolm Schaeffer	WATER LEVEL:	
DRILLER: Costello & Millwood	DRILL RIG: Diedrich D-120	

DEPTH (feet)	GRAPHIC LOG	MATERIAL DESCRIPTION	WATER LEVEL	ELEVATION (feet)	SAMPLE NO. SAMPLE TYPE	STANDARD PENETRATION TEST DATA (blows/ft) 10 20 30 60 80	N VALUE
		Auger boring through fly ash					
5							
10					Bulk Sample		
15		Field conductivity test at 18.5 feet					
20							
25					Bulk Sample		
30		Field conductivity test at 32 feet					
		BORING TERMINATED AT 32 FEET					

BORING LOG 6400157C.GPJ S&ME.GDT 4/25/01

1. *BORING AND SAMPLING IS IN ACCORDANCE WITH ASTM D-1586.*
2. *PENETRATION (N-VALUE) IS THE NUMBER OF BLOWS OF 140 LB. HAMMER FALLING 30 IN. REQUIRED TO DRIVE 1.4 IN. I.D. SAMPLER 1 FT.*

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PROJECT: Belew's Creek Landfill Ash Testing S&ME Project No. 1264-00-157C	BORING LOG A-3

DATE DRILLED: 3/13/01	ELEVATION:
DRILLING METHOD: 3¼" H.S.A.	BORING DEPTH: 32.0
LOGGED BY: Kevin Snyder	WATER LEVEL:
DRILLER: Costello & Millwood	DRILL RIG: Diedrich D-120

NOTES:
NW casing installed to 18.5 feet and 32 feet for field conductivity tests.

DEPTH (feet)	GRAPHIC LOG	MATERIAL DESCRIPTION	WATER LEVEL	ELEVATION (feet)	SAMPLE NO. SAMPLE TYPE	STANDARD PENETRATION TEST DATA (blows/ft) 10 20 30 60 80	N VALUE
		Auger boring through fly ash					
5							
10					Bulk Sample		
15							
		Field conductivity test at 18.5 feet					
20							
25					Bulk Sample		
30		Field conductivity test at 32 feet					
		BORING TERMINATED AT 32 FEET					

BORING LOG 6400157C.GPJ S&ME.GDT 4/25/01

1. BORING AND SAMPLING IS IN ACCORDANCE WITH ASTM D-1586.
2. PENETRATION (N-VALUE) IS THE NUMBER OF BLOWS OF 140 LB. HAMMER FALLING 30 IN. REQUIRED TO DRIVE 1.4 IN. I.D. SAMPLER 1 FT.

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PROJECT: Belew's Creek Landfill Ash Testing S&ME Project No. 1264-00-157C	BORING LOG **B-1**

DATE DRILLED: **3/12/01**	ELEVATION:	NOTES: **Boring abandoned due to absence of fly ash.**
DRILLING METHOD: **3¼" H.S.A.**	BORING DEPTH: **10.0**	
LOGGED BY: **Malcolm Schaeffer**	WATER LEVEL:	
DRILLER: **Costello & Millwood**	DRILL RIG: **Diedrich D-120**	

DEPTH (feet)	GRAPHIC LOG	MATERIAL DESCRIPTION	WATER LEVEL	ELEVATION (feet)	SAMPLE NO. SAMPLE TYPE	STANDARD PENETRATION TEST DATA (blows/ft) 10 20 30 60 80	N VALUE
5		Auger boring through residual soils					
10		**BORING TERMINATED AT 10 FEET**					

BORING LOG 6400157C.GPJ S&ME.GDT 4/11/01

1. BORING AND SAMPLING IS IN ACCORDANCE WITH ASTM D-1586.
2. PENETRATION (N-VALUE) IS THE NUMBER OF BLOWS OF 140 LB. HAMMER FALLING 30 IN. REQUIRED TO DRIVE 1.4 IN. I.D. SAMPLER 1 FT.

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Appendix B

SUMMARY OF LABORATORY TEST DATA
FLY ASH SAMPLES FROM ASH LANDFILL
DUKE POWER BELEWS CREEK STEAM STATION
S&ME Project 1284-00-187C

Sample Number	Sample Depth (Feet)	Sample Type	% Finer than 200 Sieve	In-Situ Conditions: Moisture Content	Void Ratio	Porosity	Specific Gravity	Unit Weight (pcf)	Hydraulic Conductivity (cm/sec) @ Confining Pressure (psi)	Standard Proctor Data: Maximum Dry Density (pcf)	Optimum Moisture Content	Void Ratio	Porosity	Specific Gravity	Remolded Conditions: Hydraulic Conductivity (cm/sec) @ Confining Pressure (psi)	Percent Compaction	Percent from Optimum MC
A-1	13.5-15.5	UD	88	13.1	0.64	0.39	2.33	88.9	3.10E-05 @ 2.5								
									2.32E-05 @ 4.0								
A-2	8.5-13.5	Bulk		19.6						82	23						
A-2	13.5-15.2	UD	87.8	18.1	0.88	0.47	2.22	73.7	8.30E-05 @ 2.5								
									9.03E-05 @ 4.0								
A-2	28.5-30.5	UD	No fly ash in UD tube - all residual soils														
A-3	13.5-15.5	UD	89.1	12.1	0.92	0.48	2.26	73.4	1.09E-04 @ 2.5								
									1.64E-04 @ 4.0								
A-3	28.5-30.5	UD	87.9	22.3	0.82	0.45	2.23	76.4	2.36E-04 @ 2.5								
									1.02E-04 @ 8.0								
BA-1	Bottom of Basin	Bulk	1.25							62	32	0.92	0.48	1.72	9.75E-04 @ 2.5 psi	86	-0.5
															2.09E-04 @ 10 psi		
BA-2	Behind Basin	Bulk	11.5							67	36.5	1.25	0.56	2.17	1.57E-03 @ 2.5 psi	87	-0.8
															2.00E-04 @ 10 psi		

NOTES:

1. Void Ratio for bulk samples BA-1 and BA-2 computed at 90% standard Proctor compaction.
2. Gray shaded areas indicate associated testing not applicable to corresponding sample numbers.

GRAIN SIZE DISTRIBUTION TEST DATA

Client: DUKE POWER
Project: BELEWS CREEK ASH LANDFILL-FLY ASH
Project Number: 00-157C

Sample Data

Source:
Sample No.: A-1 (U.D.)
Elev. or Depth: 13.5-15.5'
Sample Length (in./cm.):
Location:
Description: FLY ASH
Liquid Limit:
Plastic Limit:
USCS Classification:
AASHTO Classification:
Testing Remarks: TESTED BY KMW

Mechanical Analysis Data

	Initial
Dry sample and tare=	227.80
Tare =	0.00
Dry sample weight =	227.80

Sample split on number 10 sieve
Split sample data:
Sample and tare = 50.00 Tare = .00 Sample weight = 50.00
Cumulative weight retained tare= .00
Tare for cumulative weight retained= .00

Sieve	Cumul. Wt. retained	Percent finer
# 10	0.00	100.0
# 20	0.15	99.7
# 40	0.31	99.4
# 60	0.56	98.9
# 100	1.15	97.7
# 200	5.98	88.0

Hydrometer Analysis Data

Separation sieve is #10
Percent -#10 based upon complete sample= 100.0
Weight of hydrometer sample: 50.00
Hygroscopic moisture correction:
Moist weight & tare = 28.62
Dry weight & tare = 28.61
Tare = 17.02
Hygroscopic moisture= 0.1 %
Calculated biased weight= 49.96
Table of composite correction values:

Temp, deg C:	21.0	21.5	22.0
Comp. corr:	-6.0	-6.0	-6.0

Meniscus correction only= 1
Specific gravity of solids= 2.33
Specific gravity correction factor= 1.091
Hydrometer type: 152H
Effective depth L= 16.294964 - 0.164 x Rm

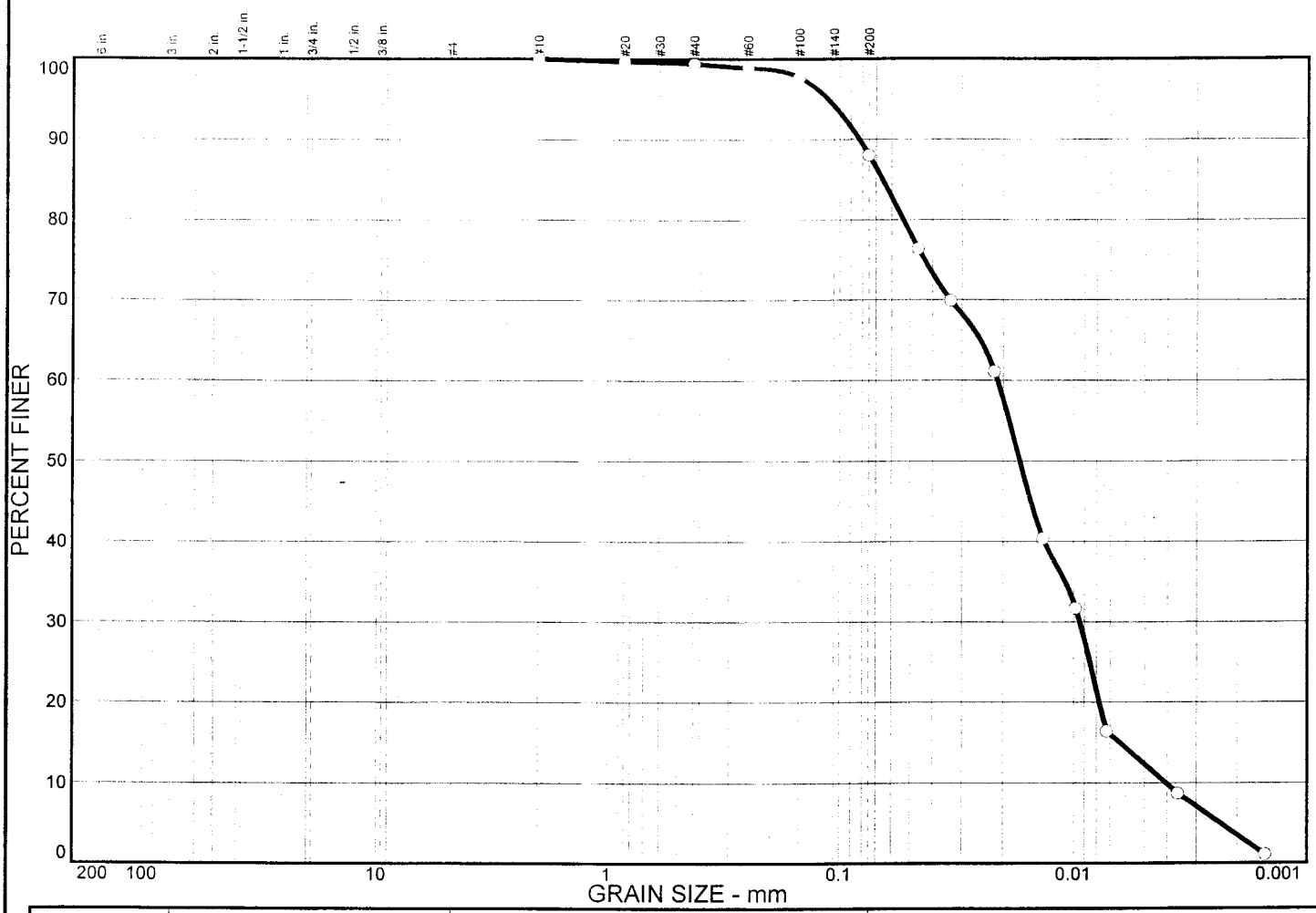
Elapsed time, min	Temp, deg C	Actual reading	Corrected reading	K	Rm	Eff. depth	Diameter mm	Percent finer
1.00	21.0	41.0	35.0	0.0150	42.0	9.4	0.0460	76.4
2.00	21.0	38.0	32.0	0.0150	39.0	9.9	0.0334	69.9
5.00	21.0	34.0	28.0	0.0150	35.0	10.6	0.0218	61.1
15.00	21.0	24.5	18.5	0.0150	25.5	12.1	0.0135	40.4
30.00	21.0	20.5	14.5	0.0150	21.5	12.8	0.0098	31.7
60.00	21.0	13.5	7.5	0.0150	14.5	13.9	0.0072	16.4
250.00	21.5	10.0	4.0	0.0149	11.0	14.5	0.0036	8.7
1440.00	22.0	6.5	0.5	0.0148	7.5	15.1	0.0015	1.1

Fractional Components

Gravel/Sand based on #4
Sand/Fines based on #200
% COBBLES = % GRAVEL =
% SAND = 12.0 (% coarse = % medium = 0.6 % fine = 11.4)
% SILT = 75.7 % CLAY = 12.3

D_{85}= 0.07 D_{60}= 0.02 D_{50}= 0.02
D_{30}= 0.01 D_{15}= 0.01 D_{10}= 0.00
C_c= 1.0359 C_u= 5.2364

Particle Size Distribution Report



% COBBLES	% GRAVEL		% SAND			% FINES	
	CRS.	FINE	CRS.	MEDIUM	FINE	SILT	CLAY
0.0	0.0	0.0	0.0	0.6	11.4	75.7	12.3

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
		0.0657	0.0212	0.0170	0.0094	0.0064	0.0040	1.04	5.24

MATERIAL DESCRIPTION	USCS	AASHTO
FLY ASH		

Project No. 00-157C **Client:** DUKE POWER

Project: BELEWS CREEK ASH LANDFILL-FLY ASH

Source: **Sample No.:** A-1 (U.D.) **Elev./Depth:** 13.5-15.5'

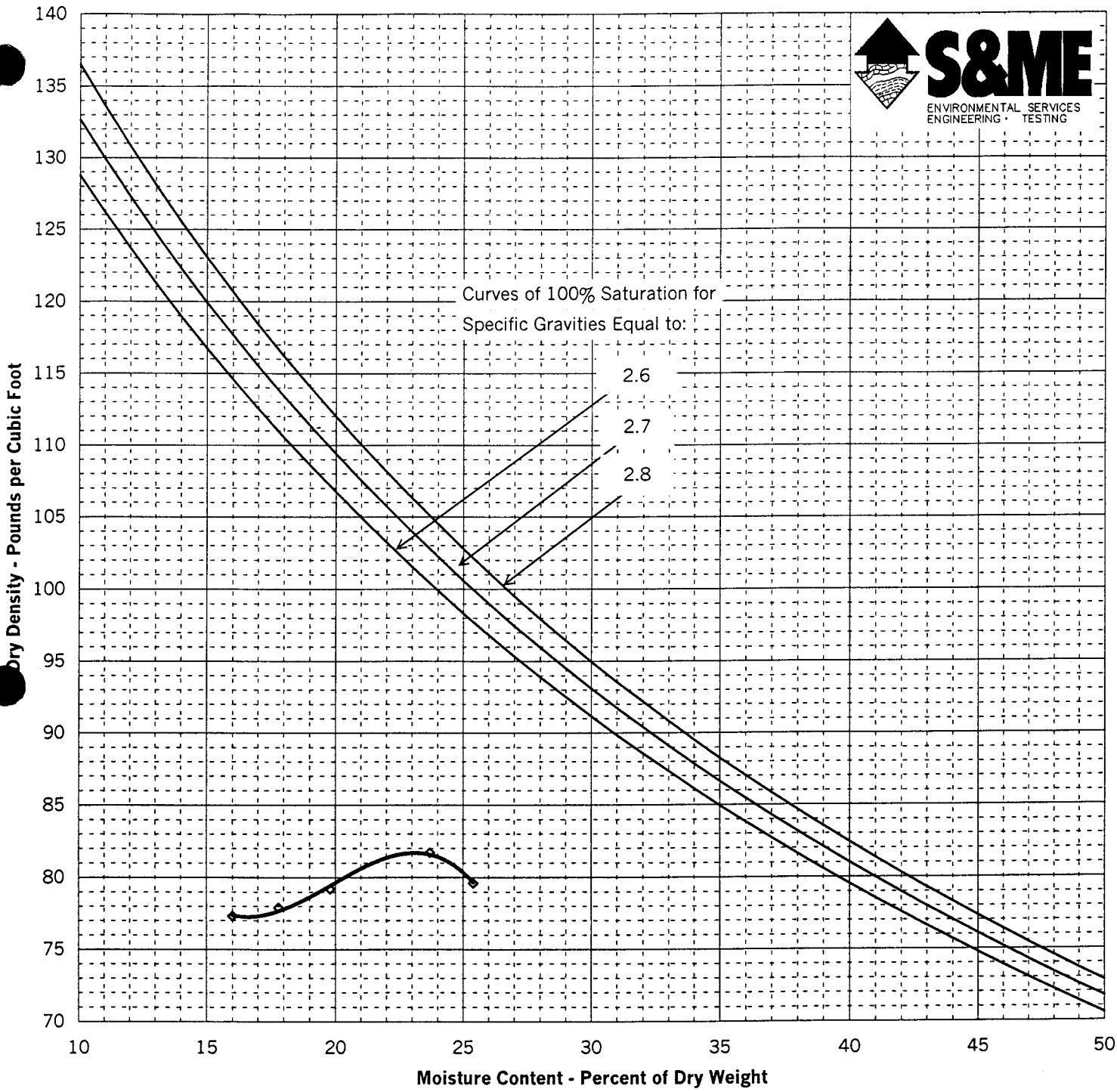
Remarks:

○ TESTED BY KMW

Particle Size Distribution Report

S & ME, INC.

SAMPLE A-1



Job Name	Duke Power Belews Creek Ash Landfill Ash Testing	**Date Performed**	3/23/01	
		S&ME Lab No.	79	
Sample Location	A-2 8.5-13.5'	**LL**	n/a	
		PI	n/a	
S&ME, Inc. Job Number	1264-00-157C	**% finer #200**	n/a	%
		Max. Dry Density	82.0	pcf
Soil Description	Gray Fly Ash	**Opt. Moist. Content**	23.0	%
		Nat. Moist. Content	19.6	%

Filename: Ash Landfill A-2 8.5-13.5' Proctor

GRAIN SIZE DISTRIBUTION TEST DATA

Client: DUKE POWER
Project: BELEWS CREEK ASH LANDFILL-FLY ASH
Project Number: 00-157C

Sample Data

Source:
Sample No.: A-2 (U.D.)
Elev. or Depth: 13.5-15.2'
Sample Length (in./cm.):
Location:
Description: FLY ASH
Liquid Limit:
Plastic Limit:
USCS Classification:
AASHTO Classification:
Testing Remarks: TESTED BY KMW

Mechanical Analysis Data

	Initial
Dry sample and tare=	178.20
Tare =	0.00
Dry sample weight =	178.20

Sample split on number 10 sieve
Split sample data:
Sample and tare = 50.00 Tare = .00 Sample weight = 50.00
Cumulative weight retained tare= .00
Tare for cumulative weight retained= .00

Sieve	Cumul. Wt. retained	Percent finer
# 10	0.00	100.0
# 20	0.12	99.8
# 40	0.32	99.4
# 60	0.62	98.8
# 100	1.17	97.7
# 200	6.08	87.8

Hydrometer Analysis Data

Separation sieve is #10
Percent -#10 based upon complete sample= 100.0
Weight of hydrometer sample: 50.00
Hygroscopic moisture correction:
Moist weight & tare = 29.47
Dry weight & tare = 29.44
Tare = 16.56
Hygroscopic moisture= 0.2 %
Calculated biased weight= 49.88
Table of composite correction values:

Temp, deg C:	21.0	21.5	22.0
Comp. corr:	-6.0	-6.0	-6.0

Meniscus correction only= 1
Specific gravity of solids= 2.22
Specific gravity correction factor= 1.133
Hydrometer type: 152H
Effective depth L= 16.294964 - 0.164 x Rm

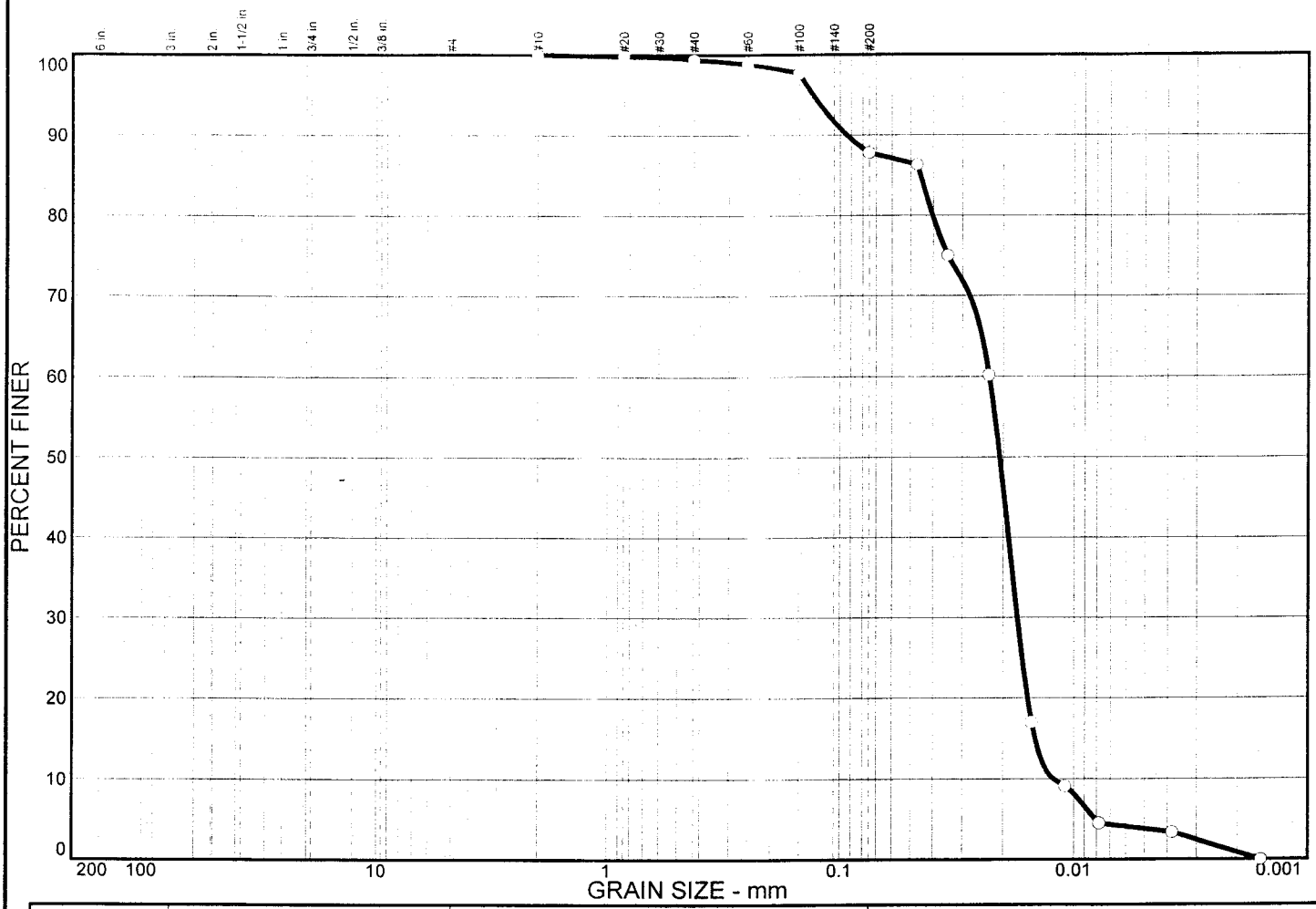
Elapsed time, min	Temp, deg C	Actual reading	Corrected reading	K	Rm	Eff. depth	Diameter mm	Percent finer
1.00	21.0	44.0	38.0	0.0157	45.0	8.9	0.0468	86.3
2.00	21.0	39.0	33.0	0.0157	40.0	9.7	0.0346	75.0
5.00	21.0	32.5	26.5	0.0157	33.5	10.8	0.0230	60.2
15.00	21.0	13.5	7.5	0.0157	14.5	13.9	0.0151	17.0
30.00	21.0	10.0	4.0	0.0157	11.0	14.5	0.0109	9.1
60.00	21.0	8.0	2.0	0.0157	9.0	14.8	0.0078	4.5
250.00	21.5	7.5	1.5	0.0156	8.5	14.9	0.0038	3.4
1440.00	22.0	6.0	0.0	0.0155	7.0	15.1	0.0016	0.0

Fractional Components

Gravel/Sand based on #4
Sand/Fines based on #200
% COBBLES = % GRAVEL =
% SAND = 12.2 (% coarse = % medium = 0.6 % fine = 11.6)
% SILT = 84.0 % CLAY = 3.8 (% CLAY COLLOIDS = 0.0)

D_{85}= 0.05 D_{60}= 0.02 D_{50}= 0.02
D_{30}= 0.02 D_{15}= 0.01 D_{10}= 0.01
C_c= 1.0759 C_u= 1.8782

Particle Size Distribution Report



% COBBLES	% GRAVEL		% SAND			% FINES	
	CRS.	FINE	CRS.	MEDIUM	FINE	SILT	CLAY
0.0	0.0	0.0	0.0	0.6	11.6	84.0	3.8

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
		0.0454	0.0230	0.0207	0.0174	0.0146	0.0122	1.08	1.88

MATERIAL DESCRIPTION	USCS	AASHTO
FLY ASH		

Project No. 00-157C **Client:** DUKE POWER

Project: BELEWS CREEK ASH LANDFILL-FLY ASH

Source: **Sample No.:** A-2 (U.D.) **Elev./Depth:** 13.5-15.2'

Remarks:

○ TESTED BY KMW

Particle Size Distribution Report

S & ME, INC.

SAMPLE A-2

GRAIN SIZE DISTRIBUTION TEST DATA

Client: DUKE POWER
Project: BELEWS CREEK ASH LANDFILL-FLY ASH
Project Number: 00-157C

Sample Data

Source:
Sample No.: A-3* (U.D.)
Elev. or Depth: 13.5-15.5'
Sample Length (in./cm.):
Location:
Description: FLY ASH
Liquid Limit:
Plastic Limit:
USCS Classification:
AASHTO Classification:
Testing Remarks: TESTED BY KMW

Mechanical Analysis Data

	Initial
Dry sample and tare=	212.10
Tare =	0.00
Dry sample weight =	212.10

Sample split on number 10 sieve
Split sample data:
Sample and tare = 50.00 Tare = .00 Sample weight = 50.00
Cumulative weight retained tare= .00
Tare for cumulative weight retained= .00

Sieve	Cumul. Wt. retained	Percent finer
# 10	0.00	100.0
# 20	0.01	100.0
# 40	0.05	99.9
# 60	0.10	99.8
# 100	0.68	98.6
# 200	5.47	89.1

Hydrometer Analysis Data

Separation sieve is #10
Percent -#10 based upon complete sample= 100.0
Weight of hydrometer sample: 50.00
Hygroscopic moisture correction:
Moist weight & tare = 28.37
Dry weight & tare = 28.34
Tare = 15.65
Hygroscopic moisture= 0.2 %
Calculated biased weight= 49.88
Table of composite correction values:

Temp, deg C:	21.0	21.5	22.0
Comp. corr:	-6.0	-6.0	-6.0

Meniscus correction only= 1
Specific gravity of solids= 2.26
Specific gravity correction factor= 1.117
Hydrometer type: 152H
Effective depth L= 16.294964 - 0.164 x Rm

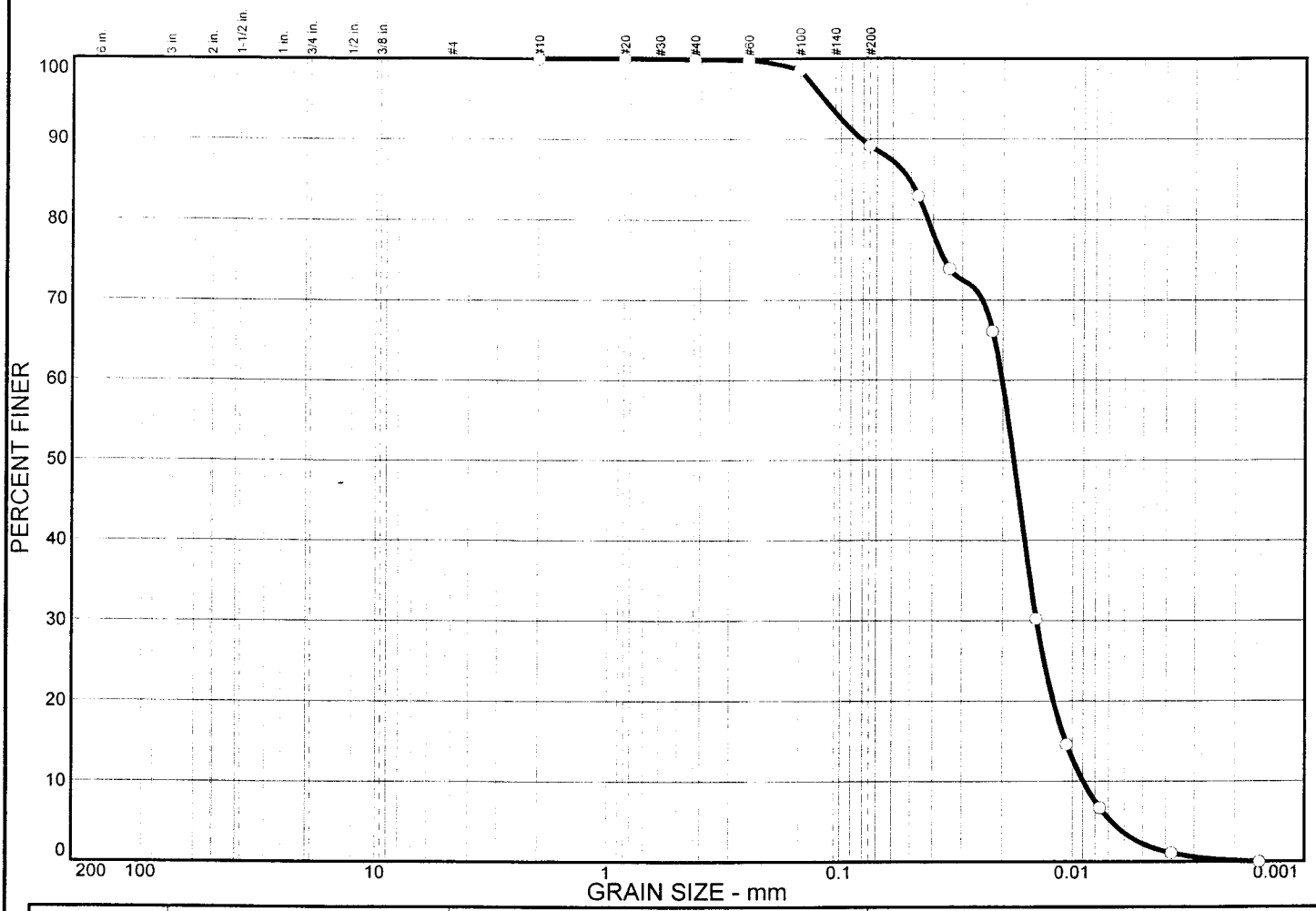
Elapsed time, min	Temp, deg C	Actual reading	Corrected reading	K	Rm	Eff. depth	Diameter mm	Percent finer
1.00	21.0	43.0	37.0	0.0154	44.0	9.1	0.0465	82.9
2.00	21.0	39.0	33.0	0.0154	40.0	9.7	0.0340	73.9
5.00	21.0	35.5	29.5	0.0154	36.5	10.3	0.0221	66.1
15.00	21.0	19.5	13.5	0.0154	20.5	12.9	0.0143	30.2
30.00	21.0	12.5	6.5	0.0154	13.5	14.1	0.0106	14.6
60.00	21.0	9.0	3.0	0.0154	10.0	14.7	0.0076	6.7
250.00	21.5	6.5	0.5	0.0153	7.5	15.1	0.0038	1.1
1440.00	22.0	6.0	0.0	0.0152	7.0	15.1	0.0016	0.0

Fractional Components

Gravel/Sand based on #4
Sand/Fines based on #200
% COBBLES = % GRAVEL =
% SAND = 10.9 (% coarse = % medium = 0.1 % fine = 10.8)
% SILT = 86.9 % CLAY = 2.2 (% CLAY COLLOIDS = 0.0)

D_{85}= 0.05 D_{60}= 0.02 D_{50}= 0.02
D_{30}= 0.01 D_{15}= 0.01 D_{10}= 0.01
C_c= 1.1254 C_u= 2.2408

Particle Size Distribution Report



% COBBLES	% GRAVEL		% SAND			% FINES	
	CRS.	FINE	CRS.	MEDIUM	FINE	SILT	CLAY
0.0	0.0	0.0	0.0	0.1	10.8	86.9	2.2

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
		0.0510	0.0202	0.0179	0.0143	0.0107	0.0090	1.13	2.24

MATERIAL DESCRIPTION	USCS	AASHTO
FLY ASH		

Project No. 00-157C **Client:** DUKE POWER

Project: BELEWS CREEK ASH LANDFILL-FLY ASH

Source: **Sample No.:** A-3* (U.D.) **Elev./Depth:** 13.5-15.5'

Remarks:

○ TESTED BY KMW

Particle Size Distribution Report

S & ME, INC.

SAMPLE A-3*

GRAIN SIZE DISTRIBUTION TEST DATA

Client: DUKE POWER
Project: BELEWS CREEK ASH LANDFILL-FLY ASH
Project Number: 00-157C

Sample Data

Source:
Sample No.: A-3 (U.D.)
Elev. or Depth: 28.5-30.5'
Location:
Description: FLY ASH
Liquid Limit:
USCS Classification:
Testing Remarks: TESTED BY KMW

Sample Length (in./cm.):
Plastic Limit:
AASHTO Classification:

Mechanical Analysis Data

	Initial
Dry sample and tare=	211.90
Tare =	0.00
Dry sample weight =	211.90

Sample split on number 10 sieve
Split sample data:
Sample and tare = 50.00 Tare = .00 Sample weight = 50.00
Cumulative weight retained tare= .00
Tare for cumulative weight retained= .00

Sieve	Cumul. Wt. retained	Percent finer
# 10	0.00	100.0
# 20	0.04	99.9
# 40	0.15	99.7
# 60	0.33	99.3
# 100	0.98	98.0
# 200	6.04	87.9

Hydrometer Analysis Data

Separation sieve is #10
Percent -#10 based upon complete sample= 100.0
Weight of hydrometer sample: 50.00
Hygroscopic moisture correction:
Moist weight & tare = 29.39
Dry weight & tare = 29.36
Tare = 15.93
Hygroscopic moisture= 0.2 %
Calculated biased weight= 49.89
Table of composite correction values:

Temp, deg C:	21.0	21.5	22.0
Comp. corr:	-6.0	-6.0	-6.0

Meniscus correction only= 1
Specific gravity of solids= 2.23
Specific gravity correction factor= 1.129
Hydrometer type: 152H
Effective depth L= 16.294964 - 0.164 x Rm

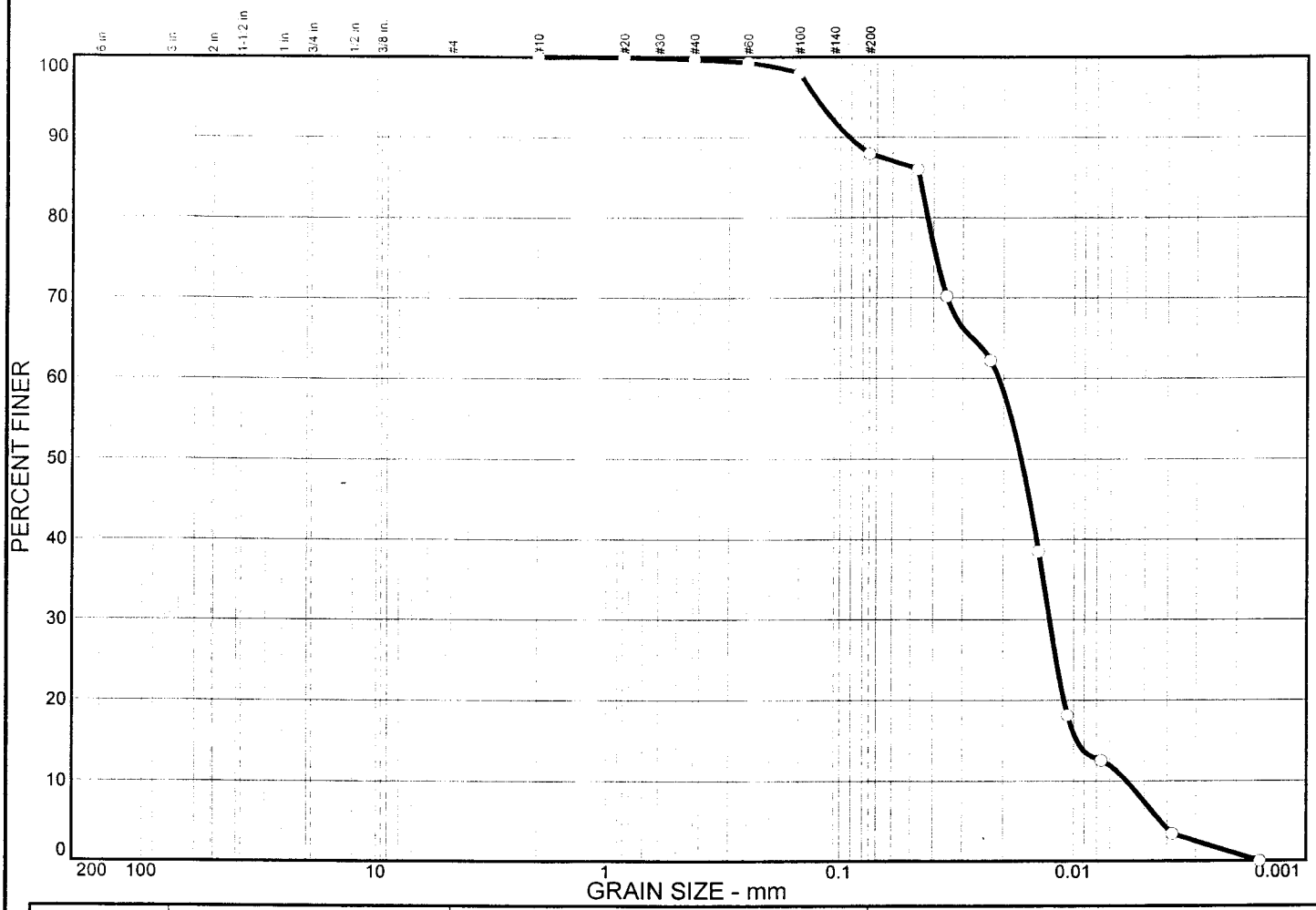
Elapsed time, min	Temp, deg C	Actual reading	Corrected reading	K	Rm	Eff. depth	Diameter mm	Percent finer
1.00	21.0	44.0	38.0	0.0156	45.0	8.9	0.0466	86.0
2.00	21.0	37.0	31.0	0.0156	38.0	10.1	0.0350	70.2
5.00	21.0	33.5	27.5	0.0156	34.5	10.6	0.0228	62.2
15.00	21.0	23.0	17.0	0.0156	24.0	12.4	0.0142	38.5
30.00	21.0	14.0	8.0	0.0156	15.0	13.8	0.0106	18.1
60.00	21.0	11.5	5.5	0.0156	12.5	14.2	0.0076	12.5
250.00	21.5	7.5	1.5	0.0155	8.5	14.9	0.0038	3.4
1440.00	22.0	6.0	0.0	0.0154	7.0	15.1	0.0016	0.0

Fractional Components

Gravel/Sand based on #4
Sand/Fines based on #200
% COBBLES = % GRAVEL =
% SAND = 12.1 (% coarse = % medium = 0.3 % fine = 11.8)
% SILT = 80.5 % CLAY = 7.4 (% CLAY COLLOIDS = 0.0)

D_{85}= 0.05 D_{60}= 0.02 D_{50}= 0.02
D_{30}= 0.01 D_{15}= 0.01 D_{10}= 0.01
C_c= 1.2885 C_u= 3.5301

Particle Size Distribution Report



% COBBLES	% GRAVEL		% SAND			% FINES	
	CRS.	FINE	CRS.	MEDIUM	FINE	SILT	CLAY
0.0	0.0	0.0	0.0	0.3	11.8	80.5	7.4

LL	PL	D_{85}	D_{60}	D_{50}	D_{30}	D_{15}	D_{10}	C_c	C_u
		0.0459	0.0210	0.0168	0.0127	0.0097	0.0060	1.29	3.53

MATERIAL DESCRIPTION	USCS	AASHTO
FLY ASH		

Project No. 00-157C **Client:** DUKE POWER

Project: BELEWS CREEK ASH LANDFILL-FLY ASH

Source: **Sample No.:** A-3 (U.D.) **Elev./Depth:** 28.5-30.5'

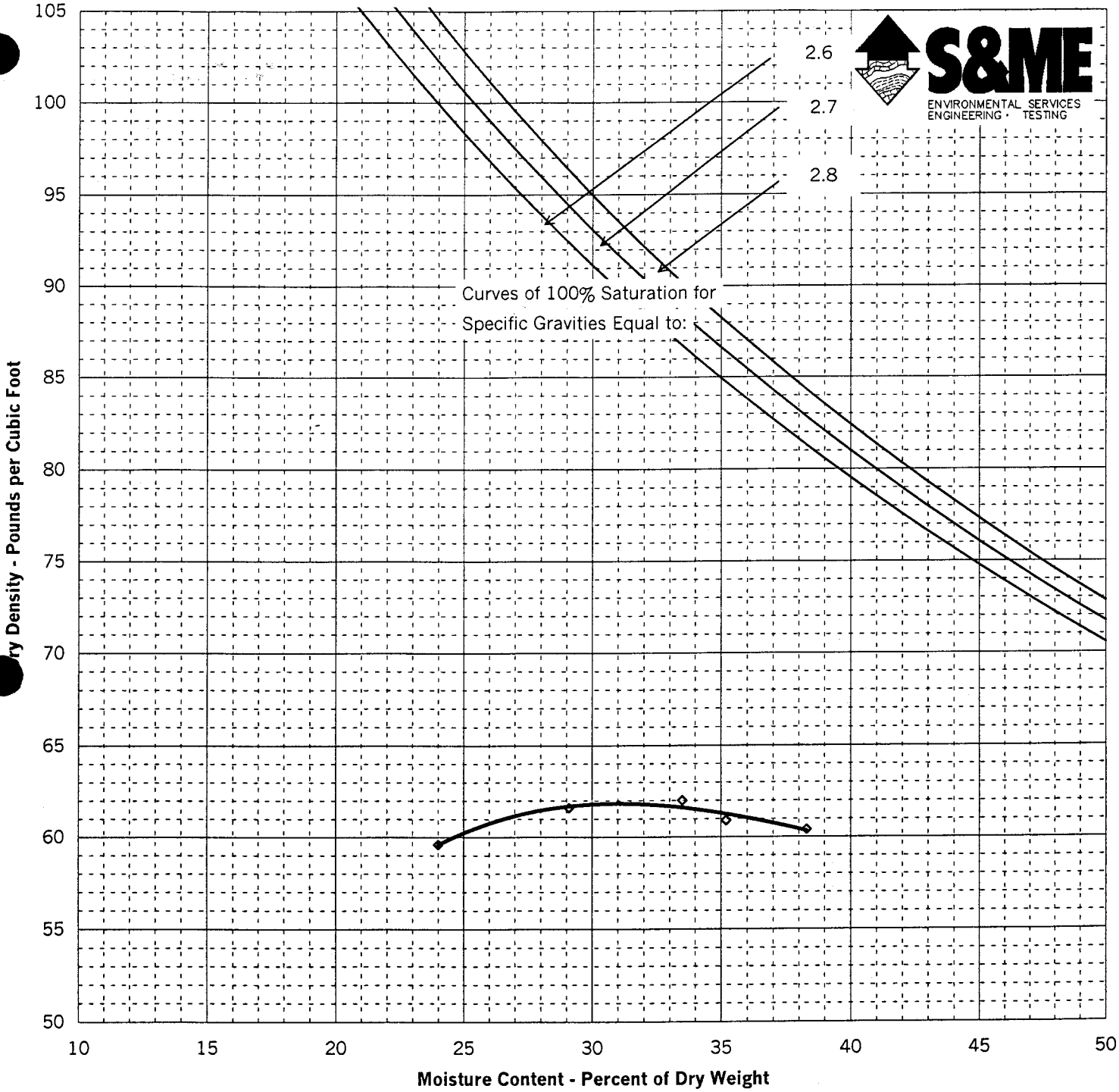
Remarks:

○ TESTED BY KMW

Particle Size Distribution Report

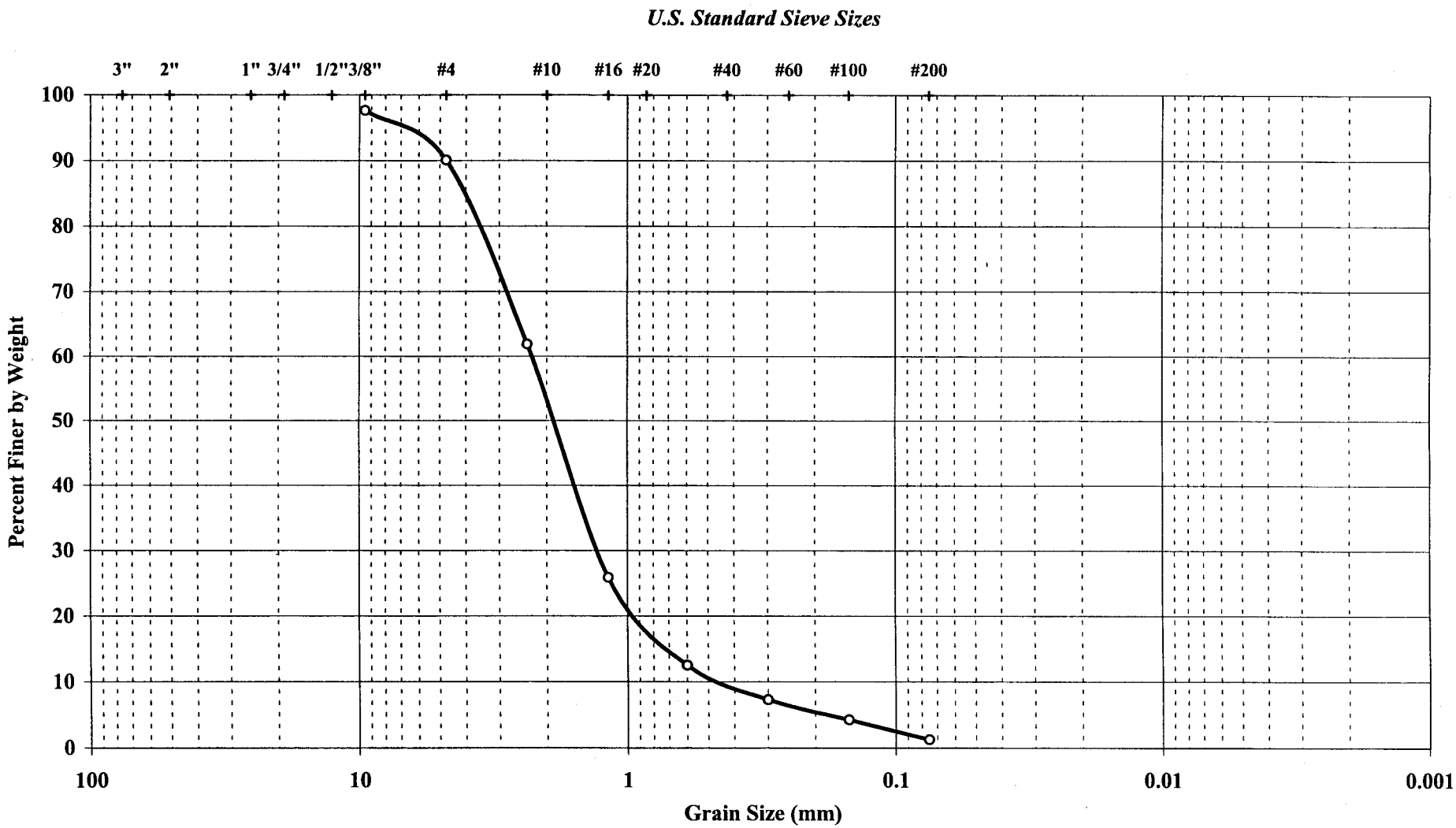
S & ME, INC.

SAMPLE A-3



Job Name	Duke Power Belews Creek Ash Landfill Ash Testing	**Date Performed**	3/14/01	
		S&ME Lab No.	70	
Sample Location	BA-1 Bottom of Basin	**LL**	n/a	
		PI	n/a	
S&ME, Inc. Job Number	1264-00-157C	**% finer #200**	1.3	%
		Max. Dry Density	62.0	pcf
		Opt. Moist. Content	32.0	%
Soil Description	Gray Bottom Ash	**Nat. Moist. Content**	n/a	%

Filename: BA-1 Bottom of Basin Proctor



Job Name	Duke Power Belews Creek Ash Landfill Ash Testing	**Sample No.**	BA-1	**GRAIN SIZE DISTRIBUTION**
		Depth	Surface *feet*	*ASTM D-421 and 422*
Job Location	Belews Creek, North Carolina	**Nat. Moist.**	NA %	
		Gs	1.72	S&ME ENVIRONMENTAL SERVICES ENGINEERING · TESTING
Job Number	1264-00-157C	**% Finer #200**	1.25	
		LL	NA	
Laboratory Test Method		**PI**	NA	
ASTM D-421 and ASTM D-422		**USCS Symbol**	NA	

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING

SIEVE ANALYSIS

JOB #: 1264-00-157C

JOB NAME: Duke Power Belews Creek Ash Landfill

TESTED BY: P. Birchall

MATERIAL DESCRIPTION: Gray Bottom Ash

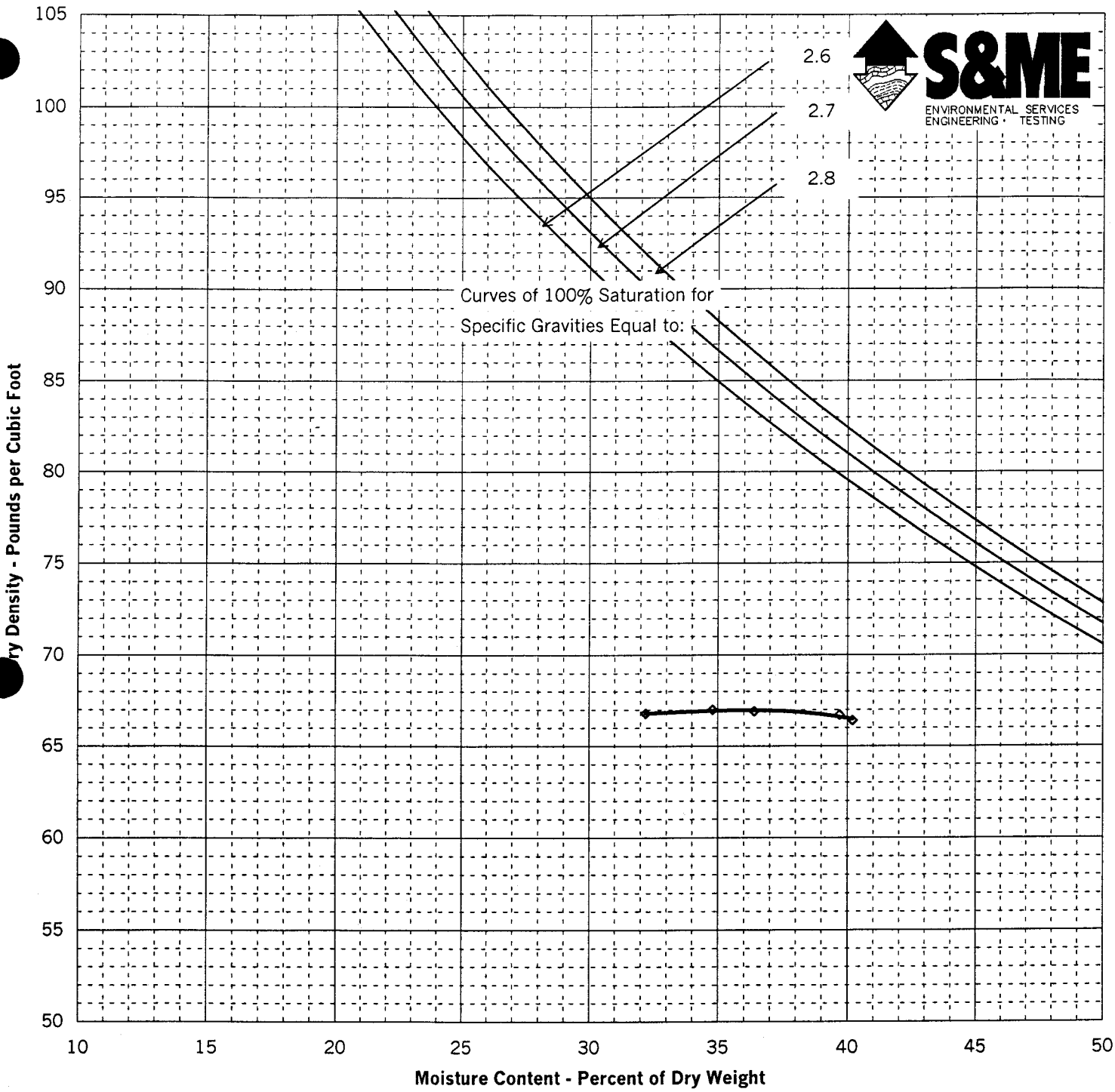
SAMPLE #: BA-1

LOCATION: Behind Basin

DRY WT. (-TARE) BEFORE WASH 155.87

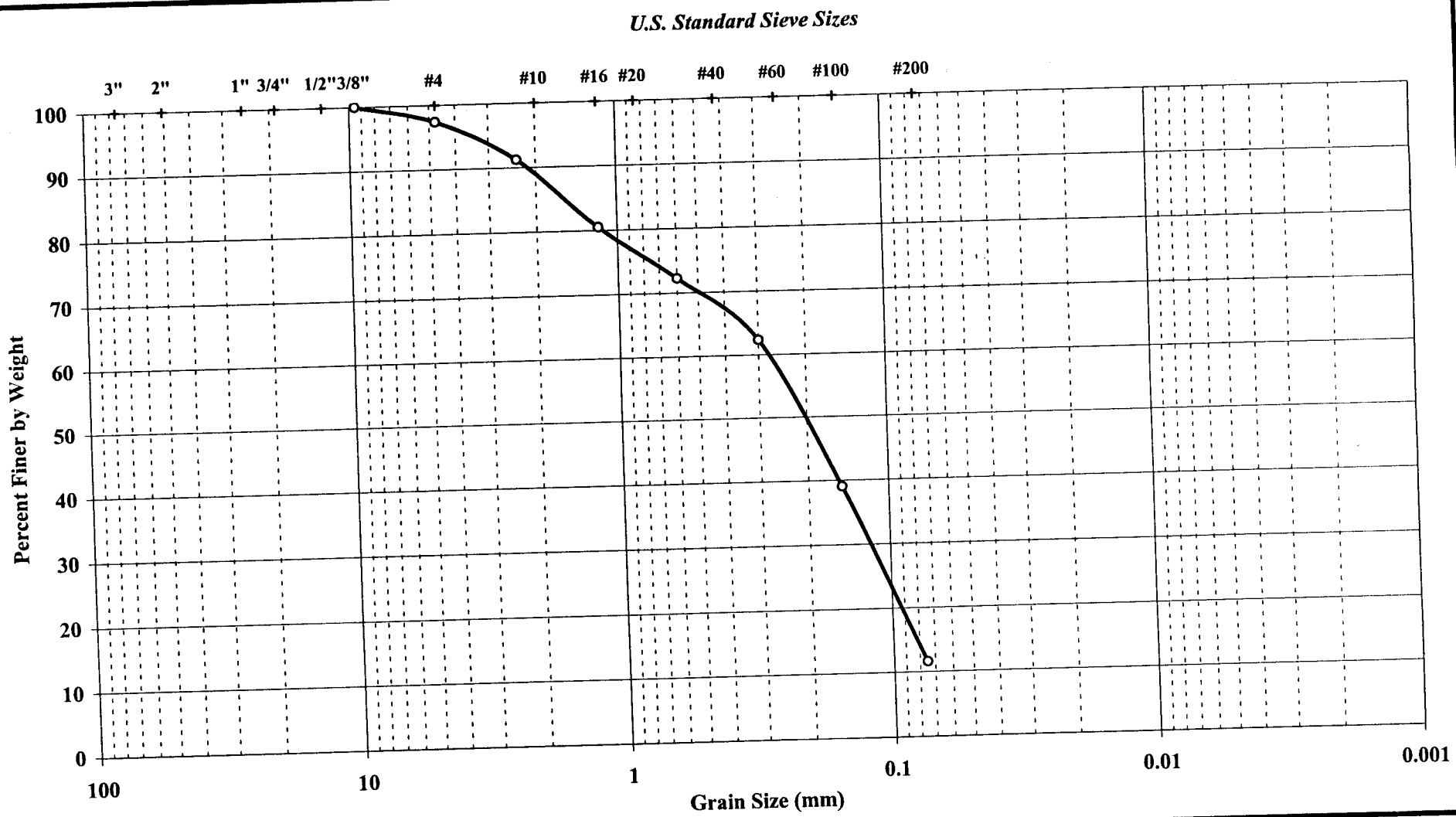
DRY WT. (-TARE) AFTER WASH 153.92

SIEVE#	M.M. DIA.	WT RETAINED	WT PASSED	% PASSING	SPECIFIED RANGE
1/2	12.5	0	155.87	100.0	NA
3/8	9.5	3.70	152.17	97.6	NA
#4	4.75	15.49	140.38	90.1	NA
#8	2.36	59.42	96.45	61.9	NA
#16	1.18	115.57	40.30	25.9	NA
#30	0.600	136.39	19.48	12.5	NA
#50	0.300	144.53	11.34	7.3	NA
#100	0.150	149.24	6.63	4.3	NA
#200	0.075	153.92	1.95	1.25	NA



Job Name	Duke Power Belews Creek Ash Landfill Ash Testing	**Date Performed**	3/14/01	
		S&ME Lab No.	71	
Sample Location	BA-2 Behind Basin	**LL**	n/a	
		PI	n/a	
S&ME, Inc. Job Number	1264-00-157C	**% finer #200**	11.5	%
		Max. Dry Density	67.0	pcf
Soil Description	Gray Bottom Ash	**Opt. Moist. Content**	36.5	%
		Nat. Moist. Content	n/a	%

Filename: BA-2 Behind Basin Proctor



Job Name	Duke Power Belews Creek Ash Landfill Ash Testing	**Sample No.**	BA-2	**GRAIN SIZE DISTRIBUTION**
		Depth	Surface *feet*	*ASTM D-421 and 422*
		Nat. Moist.	NA %	
Job Location	Belews Creek, North Carolina	**Gs**	2.17	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		% Finer #200	11.58	
Job Number	1264-00-157C	**LL**	NA	
		PI	NA	
Laboratory Test Method		**USCS Symbol**	NA	
ASTM D-421 and ASTM D-422				

Appendix C

S&ME

JOB NO. 126400157C
SHEET NO. 104Q
DATE 3/27/2001

JOB NAME BELEWS CREEK ASH LANDFILL
COMPUTED BY L. ARMSTRONG
SUBJECT CONFINING PRESSURE COMPUTATION SHEET
CHECKED BY

PROCTOR RESULTS FROM A-2, 13.5-15.5 : 82 PCF
@ 3% MOISTURE

IN-PLACE MOISTURE : 19.6%

MAX. DRY DENSITY @ IN-PLACE MOISTURE = 79.5 PCF

90% COMPACTION WEIGHT = 71.5 PCF

K_0 = AT-REST COEFFICIENT = 0.50

FOR 15' TUBES:

$$CP_0 = \frac{71.5\ \#/FT^3 * 15\ FT * 0.50}{144\ IN^2/FT^2} = \boxed{4\ PSI}$$

FOR 30' TUBES:

$$CP_0 = \frac{71.5\ \#/FT^3 * 30\ FT * 0.50}{144\ IN^2/FT^2} = \boxed{7.5\ PSI}$$

S&ME

JOB NO. 126400157C
SHEET NO. 7 of 2
DATE 3/27/2001

JOB NAME BELEWS CREEK ASH LANDFILL
SUBJECT CONFINING PRESSURE COMPUTATION SHEET

COMPUTED BY C. ARMSTRONG
CHECKED BY

FOR BOTTOM ASH (1)

$$CP_0 = \frac{71.5\ \#/FT^3 * 40\ FT * 0.50}{144\ IN^2/FT^2} = \boxed{10\ PSI}$$

(1) BOTTOM ASH, IF USED, WOULD BE USED FOR DRAINAGE AT LANDFILL BASE, UNDER AN ESTIMATED AVERAGE OF 40-FEET OF FLY ASH.

S&ME

JOB NO. 126400157C
SHEET NO. 1 OF 1
DATE 4/4/2001

JOB NAME Keelers Creek Ash Landfill
COMPUTED BY Armstrong
SUBJECT Void Ratio Computation Sheet
CHECKED BY

$$\text{Void Ratio, } e = \frac{G_s \gamma_w}{\gamma_d} - 1$$

$$\text{Porosity, } n = 1 - \frac{\gamma_d}{\gamma_w G_s}$$

Modified from Table 9.5 of Civil Engineering Reference Manual 4th Ed., Lindeburg.

Where G_s = Specific Gravity of Material
γ_w = Unit weight of water = 62.4 #/ft³
γ_d = Unit weight (dry) of material

Sample	Depth	G_s	γ_d	e	n
A-1	13.5-15.5	2.33	88.9	0.64	0.39
A-2	13.5-15.5	2.22	73.7	0.88	0.47
A-2	28.5-30	Shelby tube sample not recoverable in lab			
A-3	13.5-15.5	2.26	73.4	0.92	0.48
A-3	28.5-30	2.23	76.4	0.82	0.45
BA-1	Basin Bottom	1.72	90%(62) = 55.8	0.92	0.48
BA-2	Behind Basin	2.17	90%(67) = 60.3	1.25	0.56

Appendix 2

Appendix 2

Site-Specific Chemical Attenuation Parameters of Selected Constituents for Proposed Belews Creek Ash Landfill

Ish Inc. February 2001

Site-Specific Chemical Attenuation Parameters of Selected Constituents for Proposed Belews Creek Ash Landfill

Prepared for
Duke Power Company
Charlotte, NC

Prepared by
Ish Inc.
Sunnyvale, CA
and
Purdue University
W. Lafayette, IN

February 2001

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Site-Specific Chemical Attenuation Parameters of Selected Constituents for Proposed Belews Creek Ash Landfill

Introduction

Duke Power Company owns and operates the Belews Creek Steam Station located in Stokes County, North Carolina. The Belews Creek Station burns coal in the boilers to generate electricity. The coal ash is managed in an on-site landfill by the utility. The Utility and the State regulators are interested in accurately assessing the potential for groundwater contamination from the coal ash management facility at Belews Creek Site.

Duke Power Company retained Ish Inc. to develop site-specific chemical attenuation data for arsenic, cadmium, chromium, selenium, manganese and iron. Eleven soil samples from the Belews Creek site were collected by Duke Power company staff and shipped to the Soils and Environmental Chemistry Laboratory at Purdue University. Ten of these soils were utilized in completing the development of chemical attenuation data. All soil samples were characterized for texture, pH, organic matter, Cation Exchange Capacity (CEC), and Anion Exchange Capacity (AEC). Clay types were identified qualitatively. Extractable iron and manganese amounts were also determined for the soil samples and the one coal ash sample.

Chemical Attenuation Processes

The interactions of leachate constituents with soils/geologic materials that influence the migration and pore water concentrations are known as chemical attenuation processes. There are two major types of chemical reactions that define the extent of attenuation for a given constituent. These are precipitation-dissolution reactions, and adsorption-desorption reactions. The precipitation-dissolution reactions are defined by the thermodynamic properties of the constituents whereas both the properties of the constituent and the properties of the geological material define the extent of adsorption-

desorption reactions. Most groundwater transport-fate models do not differentiate between precipitation-dissolution reactions and reversible adsorption-desorption reactions but represent them in lumped K_d values obtained from adsorption experiments. Accordingly, the scope of this project was restricted to developing laboratory-based results to quantitatively determine the range in values of the site-specific distribution coefficients (i.e., K_d) for each of the six selected chemicals for the Belews Creek site soils.

Precipitation-Dissolution Reactions

Precipitation of dissolved constituents to form solid phase compounds is an important chemical attenuation mechanism. When the rates of precipitation-dissolution reactions are rapid, then the groundwater concentration in equilibrium with the solid phase compounds are controlled by the solubility of the least soluble solid phase although some adsorption-desorption reactions may also occur concurrently. Examples of solubility controlling solid/mineral phases are: $BaSO_4$, $PbCO_3$, and $Cr(OH)_3$ that determine the aqueous phase concentrations of Ba, Pb, and Cr (III), respectively.

Adsorption-Desorption Reactions

Adsorption is a widely recognized attenuation mechanism arising from the chemical reactions between ionic species of dissolved constituents with the surfaces of mineral constituents or soil organic matter in soil/geologic material. Adsorption reactions result in the removal of the dissolved constituents from the aqueous phase, thereby reducing (attenuating) their concentrations in the flowing groundwater. A large body of literature exists reporting results on adsorption of a number of inorganic and organic constituents by soils obtained through numerous laboratory scale studies. Many methods have been utilized by the researchers to analyze adsorption data and derive constants for evaluating attenuation potentials of the constituents. The most common adsorption models reported in the literature are:

1) Linear distribution coefficients (K_d)
2) Freundlich Isotherms (K_f, N)
3) Langmuir Isotherms (K_L, A_m)

Linear Distribution Coefficient (K_d): A distribution coefficient is defined as a parameter that describes the linear partitioning between leachate constituents and the soil material at equilibrium. It is mathematically defined as:

$$K_d = C_s/C_w$$

where Cs is the amount of sorbed mass of constituents per mass of adsorbent (soil) at equilibrium and C_w is equilibrium concentration of the constituent in solution.

The linear distribution or partition coefficient (K_d) is converted to a unitless retardation factor for use in groundwater transport and fate models. The retardation factor or R_d is calculated by the following equation:

$$R_d = 1 + (\rho_b K_d)/\theta_w$$

where ρ_b is the dry bulk density, and θ_w is the volumetric water content or total porosity (volumetric) of the soil at saturation.

Freundlich Isotherm: Another commonly used adsorption equation is the Freundlich adsorption equation as shown below:

$$C_s = K_f C_w^N$$

where K_f is the Freundlich adsorption coefficient and N is a measure of sorption nonlinearity. Both coefficients have positive values. When the Freundlich coefficient N is one, K_f is equal to the linear distribution coefficient K_d.

Langmuir Isotherm: Another adsorption model is defined by the Langmuir isotherm shown in the equation below:

$$C_s = (K_L A_M C_w)/(1+K_L C_w)$$

where, C_s is the constituent adsorbed at equilibrium (moles per gram of adsorbent); A_M is the maximum adsorption capacity of the absorbent (moles per gram of adsorbent); and K_L is the Langmuir adsorption constant.

All three adsorption models are available to analyze adsorption data commonly produced by conducting batch equilibration studies under laboratory conditions. Often times if constituent concentrations are much lower than the maximum adsorption capacity of the soil, a linear distribution coefficient (K_d) and thus a unitless retardation factor can be used to reasonably estimate chemical behavior within the designated concentration range, simplifying incorporation of laboratory batch data to groundwater transport and fate models. In the next portions of this report, methods and results of batch equilibration studies are presented.

Materials and Methods

SPLP Analysis of Ash Samples

Duke Power Company collected 7 daily composite samples of fly ash from the Belews Creek Steam Station during February 2000. All seven samples were subjected to SPLP leaching test. Results of the SPLP leaching test for arsenic, cadmium, chromium, iron, selenium and manganese were used to choose the concentrations range for conducting the adsorption tests and to develop the adsorption isotherms. Based on the literature and the soil pH values of the Belews Creek soils, arsenic adsorption was estimated to be very high. Therefore, the upper end of the initial arsenic concentrations applied to the soils in the adsorption test was above those observed in the SPLP leaching test to enhance the likelihood of having detectable arsenic concentrations in the aqueous phase at equilibrium with the soils.

CEC and AEC

Cation and anion exchange capacities for the soils were evaluated using a method specific for acid soils (Soil Science Society of America (SSSA) Book Series No. 3 Methods of Soil Analysis Part 3 Chemical Methods pp 154-157). This method enables the simultaneous estimation of both CEC and AEC of the soil under natural field conditions of pH as measured in a 1:5 soil/water extract. Soils were saturated with Ba using a $BaCl_2$ reagent solution and subsequently substituted with Mg from $MgSO_4$ solution. The loss of Mg from reactant solution measured using flame AA is used to

calculate the CEC (cmol/kg). The displacement of chloride by sulfate measured colorimetrically is used to estimate AEC (cmol/kg).

CBD extraction for Mn and Fe oxides from Whole Soils

Extractable Fe and Mn amounts were determined using the citrate-bicarbonate-dithionite (CBD) extraction procedure as outlined in SSSA Book Series No. 3, Methods of Soil Analysis, Part 3- Chemical Methods, 1996. pp. 645-648. The CBD method targets free Fe and Mn oxides, which are considered to be the active fraction in soil for chemical attenuation. The CBD extraction method, however, will include the water-soluble fraction as well as Fe and Mn that may be sorbed to cation exchange sites. In soils, Fe and Mn mostly are present as oxides with very small amount present as sorbed. Approximately 1 to 3 g of soil samples are extracted with 40-mL of 0.3-M sodium citrate and 5mL of 1.0-M sodium bicarbonate by heating in a water bath at 75-80°C for several minutes. Then sodium dithionite (1 g) is added to each tube and stirred for 1 minute constantly and then intermittently for 5 additional minutes. A second one-gram of sodium dithionite is added and the mixture stirred again for an additional 10 minutes followed by centrifuging. If any brown or red color persists, the procedure is repeated. Fe and Mn were determined by atomic absorption instrument (AA) at wavelengths of 386 and 403.1 nm, respectively.

Soil pH

Soil pH was determined in both water and in 0.01 N $CaCl_2$ solutions. A 5g subsample of soil was vigorously slurried in 10-mL of designated solution for 1.5 hours followed by pH measurements of the slurry using a combination electrode as described in SSSA Book Series No. 3, Methods of Soil Analysis, Part 2, pp. 208-209.

Particle Size Analysis

Particle size analysis was carried out using the pipette method as detailed in the SSSA Book Series No. 3, Methods of Soil Analysis, Part I. Choice of this method allowed collection of the clay fraction for use in the subsequent XRD analysis.

X-Ray Diffraction (XRD)

A mineralogical characterization of a fraction of the soil below 0.2 μm was undertaken using X-ray diffraction (XRD) techniques. For each soil, two slides with clay films were prepared for XRD analysis using the clay fractions obtained from the texture analysis. X-Ray diffraction patterns were obtained using CuKα radiation and a type F Siemens Diffractometer with omega drive. The Diffractometer was equipped with a 1°-divergence slit, 0.25^{o} receiving slit, 0.4^{o} scatter slit, and a graphite monochromator. Samples were scanned from 2 to 30° 2(θ) using a 0.02-degree increment and a 1 second count time. Slide preparation consisted of treating clay fractions by saturating with K or Mg, or solvated with glycerol. During the analysis the K saturated samples were analyzed after being exposed to four separate temperature regimes (room temperature, 100°C, 300°C, and 550°C).

Carbon Analysis

Total carbon for each of the soils was determined in duplicate. Approximately 0.5 g of soil was accurately weighed, placed in a Fisions C/N Analyzer, where carbon is determined by combustion. An acid carbonate test was negative on all soils; therefore, reported values for carbon represent total organic carbon.

Adsorption Tests

Adsorption tests were conducted using a batch equilibration approach in which a solution containing the constituents (also referred to as solutes) of interest at a range of known concentrations is equilibrated with the soil for some designated time followed by analysis of the constituents remaining in solution. Additional details on the batch-type procedures for estimating soil adsorption of chemicals can be found in the Technical Resource Document (EPA/530-SW87-006-F) issued by the Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency. Using this approach, adsorption isotherms were constructed by measuring solution concentrations of the constituents (C_w, μg/L) of interest at equilibrium and estimating the amount of loss to the soil (C_s, μg/kg) at equilibrium by the difference between the initial solute concentrations applied to the

soil (C_i, μg/L) and C_w. Adsorption tests were performed separately for three constituent groups as follows:

1. As (V), Se (VI) and Mn (II)
2. Cr (VI) and Cd (II)
3. Fe (III)

Iron was done alone to eliminate the potential for precipitation reactions with the other solutes.

For each soil and multi-solute system, isotherms were measured by adding 50 mL of multi-solute solutions to approximately 3 g of air-dried soil in plastic centrifuge tubes. For each isotherm, 7 solute concentrations, including zero, in duplicate were used except for Fe in which only 4 concentrations, including zero, was used. Multi-solute solutions containing target concentration ranges were achieved by diluting with 0.01 N $CaCl_2$ stock solutions prepared in 0.01 N $CaCl_2$ using the individual solutes as summarized in Table 1.

Table 1. Concentrations (ug/L) of initial multi-solute solutions equilibrated with soils in the laboratory studies.

Constituent Name	Symbol and Oxidation State	Solid Form Used in Stock Preparation	Stock (μg/L)	Increments (%) of stock	Range (μg/L)
Arsenic	**As (V)**	Na_2HAsO_4	1050	5, 20, 40, 60, 80, 100	60 –1050
Cadmium	**Cd (II)**	$CdCl_2$	100	10, 20, 40, 60, 80, 100	10 – 100
Chromium	**Cr (VI)**	$K_2Cr_2O_7$	200	10, 20, 40, 60, 80, 100	20 – 200
Manganese	**Mn (II)**	$MnCl_2 \cdot 4H_2O$	225	10, 20, 40, 60, 80, 100	25 – 225
Selenium	**Se (VI)**	$Na_2SeO_4 \cdot 10H_2O$	650	5, 20, 40, 60, 80, 100	35 – 650
Iron	**Fe (III)**	$FeCl_3$	300	15, 33, 66, 100	40 - 300

Soil-solution samples were equilibrated for approximately 24 hours on an end-over-end rotary mixer at 22°C ± 2°C. Samples were then centrifuged at 3000 rpm for 20 minutes, and the clear supernatant sub-sampled, filtered through a 0.45 μm filter which were pre-rinsed with dilute acid solution, and acidified to approximately a pH of 2 with 1 or 2

drops of a dilute nitric acid solution. Supernatants of soil blanks were analyzed directly and with a spike of known solute concentration to determine the matrix effect. As, Se, and Fe were analyzed using GFAA, Cd and Cr were analyzed using ICP, and Mn was analyzed using standard flame AA. Solute concentrations were measured in the initial solutions and after equilibration with the soil. Due to the number of soil-solution combinations, not all isotherms were started at the same time, and solutions applied to soils were prepared fresh daily but the range in initial solute concentrations were approximately the same. Background concentrations (i.e., concentrations measured in aqueous phase in the soil-water equilibration tests where zero amount of target constituent was added to the initial solutions) of targeted solutes measured at the same soil to solution ratio (3g:50mL) are summarized in Table 2. Sorbed concentrations (C_s, μg/kg) were calculated by difference as follows:

$$C_s = [C_i + C_{background} - C_e](V/m)$$

where C_i, C_e, and $C_{background}$ are solution concentrations (μg/L) added to the soil, at equilibrium with the soil, and in soil-solution blanks at equilibrium as defined by a 24-h contact time; m is soil mass (kg) and V is solution volume (L) of the constituent or blank solution added to the soil.

Table 2. Background concentrations* after equilibration of 3 g in 50 mL 0.01 N $CaCl_2$.

Soil ID	As μg/L	Cd μg/L	Cr μg/L	Se μg/L	Mn μg/L	Fe μg/L
BC3 40-50'	<1	<1	<5	<10	1147	<20
BC3 50-60'	<1	<1	<4	<10	609	<20
BC3 0-10'	<1	<1	<7	<10	550	<20
BC6 0-10'	<1	<1	<2	<10	694	<20
BC6 10-20'	<1	<1	<1	<10	1164	<20
BC6 20-24'	<1	<1	<1	<10	1498	<20
MW2-1 35-45'	<1	<1	<12	<10	1587	<20
MW2-2 30-40'	<1	<1	<9	<10	2145	<20
MW6 28-38'	<1	<1	<6	<10	2041	<20
MW6 38-48'	<1	<1	<8	<10	2852	<20

*Background concentrations are defined as concentrations that were obtained in the aqueous phase for equilibration tests with zero addition of the target constituent. In other words, background concentration represents the aqueous phase concentration associated with soil-water equilibrium partitioning as a natural condition.

Results

Soils

Eleven soil samples and one fly ash sample from the Belews Creek site were received and various physical-chemical properties were measured as described in the materials and methods section of this report. Upon receipt, soils were spread into a lined cardboard box and color photographs with a digital camera were taken and imported into a PowerPoint presentation. Appendix A contains a hard copy of these photographs. Table 3 presents visual data on the soil color using the Munsell Color Charts assessed on moist soil and visual observation of the relative amounts of particles greater than 2 mm. Following visual observations, soils were air-dried and sieved through a 2-mm sieve. Textural and organic carbon data for the less than 2 mm fraction are presented in Table 3 along with the visual data. From the textural analysis, all eleven soils were classified as fine sandy loams using the soil texture triangle. Table 4 is a summary of the XRD analysis of the identified clay minerals and their relative abundance in the soil samples. Soils were primarily kaolinitic with substantial amounts of vermiculite or hydroxy-interlayered vermiculite in a few samples. Table 5 summarizes results for pH, CEC, AEC, and CBD-extractable amounts of manganese and iron in the soil samples.

These results indicate that the soils from Belews Creek site are predominantly fine sandy loam textured with very little organic matter. These soils are acidic with a pH range of about 5 to 6.3. Significant amount of extractable iron is also present in these soils although the amount varies significantly from sample to sample. The most abundant clay mineral present is kaolinite followed by hydroxy-interlayered Vermiculite. Small amounts of mica are also found in most of the samples. These soils possess an order-of-magnitude higher CEC as compared to the AEC. Figures 1 through 3 show the expected positive correlation between clay content in the soil samples and the CEC, CBD-extractable Fe, and CBD-extractable Mn, respectively. These graphs show that the amount of clay in the soils controls the key geochemical properties that affect adsorption of metals and thus determine the attenuation capacity of the soils. Figures 4 and 5 show

the positive correlation between CEC and the extractable amounts of Fe and Mn in the soils from Belews Creek site, which is expected given that CEC, Fe, and Mn were all positively correlated to clay content. Figure 6 shows the positive correlation between extractable Fe and extractable Mn in the soils from Belews Creek site. These correlations are indicative of surface coatings of Fe and Mn in these fine sandy soils.

Table 3: Physical Characteristics of the Soil Samples from Belews Creek Site

Sample Location and Depth	Munsell Color Primary; Secondary	> 2 mm rocks	Particle Size Distribution			Organic Carbon (%) [a]	
			% Sand	%Clay	%Silt	Average[b]	SD[b]
BC3 0-10'	10YR 6/6; 7.5R 5/6	None	58.2	12.1	29.7	0.163	0.000
BC3 40-50'	2.5YR 5/4	None	63.4	4.8	31.9	0.099	0.001
BC3 50-60'	2.5YR 5/3	moderate amount	62.1	4.8	33.1	0.127	0.001
BC6 0-10'	10YR 5/6; 7.5R 5/8	very few	54.7	14.8	30.5	0.093	0.003
BC6 8.8-10.3'	10YR 5/6; 7.5R 5/8	very few	69.4	2.9	27.7	0.062	0.003
BC6 10-20'	10YR 5/4	very few	58.6	7.5	33.9	0.048	0.002
BC6 20-24'	10YR 5/3	moderate amount	70	6.4	23.7	0.031	0.002
MW-2-2 30-40'	10YR 5/4; 10YR 6/8; 7.5R 5/8	None	49.4	13.3	37.3	0.037	0.001
MW-2-1 35-45'	10YR 5/6	Many	71.9	8.4	19.6	0.025	0.001
MW6 28-38'	10YR 6/8; 7.5R 5/8	None	59	10	30.9	0.03	0.002
MW6 38-48'	10YR 6/8; 7.5R 5/8	None	59.8	11.9	28.3	0.039	0.003
BC Fly Ash	Grey 4/N	None	NA	NA	NA	NA	NA

[a] Free carbonate test results for all samples were negative, indicating that all carbon present is organic carbon

[b] Average and standard deviation (SD) were obtained from triplicate analysis.

Table 4. Results of XRD analysis for Clay Minerals in the Soil Samples from Belews Creek Site. Relative abundance is indicated by the progressions from much to little as follows: XX, X, and x with t for trace.

Sample Location and Depth	Kaolinite	Vermiculite	Hydroxy-interlayered Vermiculite	Mica
BC3 0-10'	XX		x	t
BC3 40-50'	x		X	t
BC3 50-60'	x		X	t
BC6 0-10'	XX		x	
BC6 8.8-10.3'	XX		x	
BC6 10-20'	XX		x	
BC6 20-24'	x		X	t
MW-2-2 30-40'	XX		x	t
MW-2-1 35-45'	X	X		t
MW6 28-38'	XX	x		x
MW6 38-48'	X		x	t
BC Fly Ash	ND[a]	ND	ND	ND

[a] Not determined

Table 5. Chemical characterization results of the soil samples from the Belews Creek Site

Soil Location and Depth	Measured Soil pH 1:2 g:mL with 1.5 h vigorous shake in		CEC (cmol/kg)[a]		AEC (cmol/kg)		CBD Extractable Fe (g/kg)		CBD Extractable Mn (g/kg)	
	Water	0.01 N $CaCl_2$	Average	SD	Average	SD	Average	SD	Average	SD
BC3 0-10'	6.28	5.55	3.14	0.05	0.481	0.022	8.84	0.13	0.125	0.006
BC3 40-50'	6.05	5.6	2.87	0.08	0.267	0.007	0.48	0.09	0.066	0.003
BC3 50-60'	5.83	4.2	3.17	0.10	0.240	0.001	0.54	0.07	0.111	0.010
BC6 0-10'	5.11	4.24	3.14	0.15	0.446	0.054	15.94	0.19	0.295	0.002
BC6 8.8-10.3'	5.27	4.17	3.20	0.10	0.439	0.011	9.50	0.30	0.388	0.049
BC6 10-20'	5.44	4.32	2.97	0.09	0.484	0.038	9.50	0.17	0.403	0.000
BC6 20-24'	5.95	4.86	2.83	0.32	0.355	0.034	6.30	0.37	0.285	0.005
MW-2-2 30-40'	6.23	5.45	7.10	1.17	0.505	0.108	22.25	0.15	0.831	0.013
MW-2-1 35-45'	6.72	5.81	5.17	0.42	0.273	0.037	8.02	0.06	0.326	0.051
MW6 28-38'	6.09	4.95	3.91	0.07	0.392	0.062	13.37	0.16	0.367	0.010
MW6 38-48'	5.99	4.9	6.31	1.20	0.494	0.069	13.26	0.31	0.367	0.029
BC Fly Ash	4.19	ND	ND	ND	ND	ND	0.78	0.24	0.066	0.017

[a] Same as meq/100g

Figure 1. Clay (%) vs. CEC (cmol/kg) for the 11 soil samples from Belews Creek site.

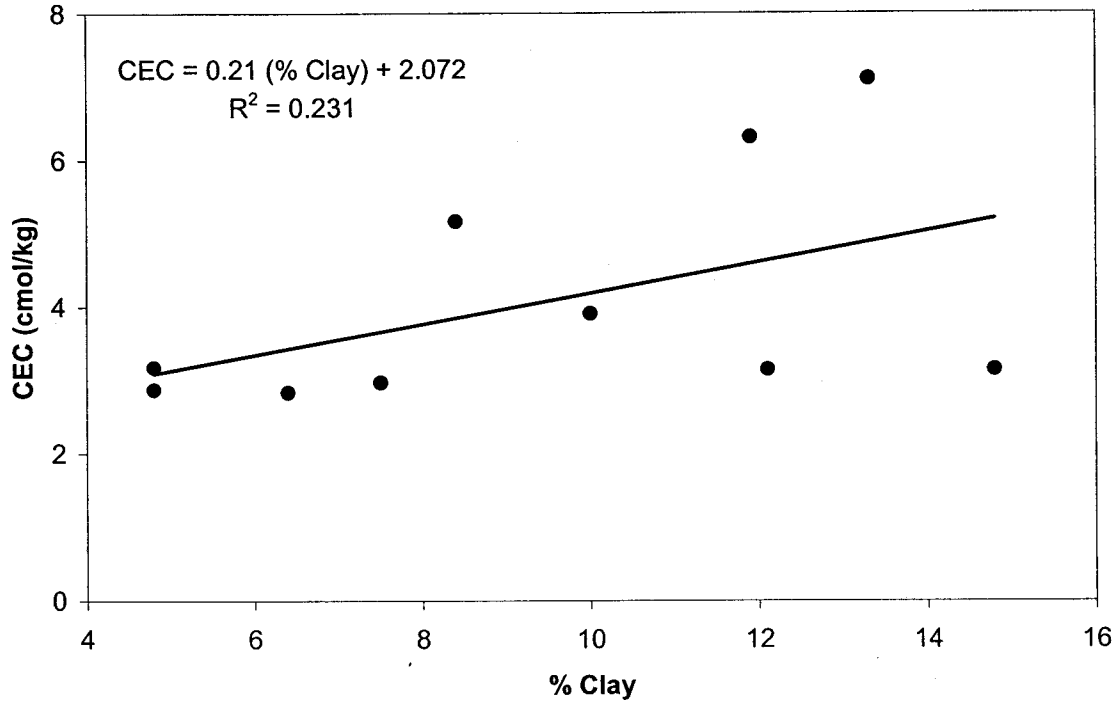


Figure 2. CBD-extractable Fe (g/kg) vs Clay(%) for the 11 soil samples from Belews Creek site.

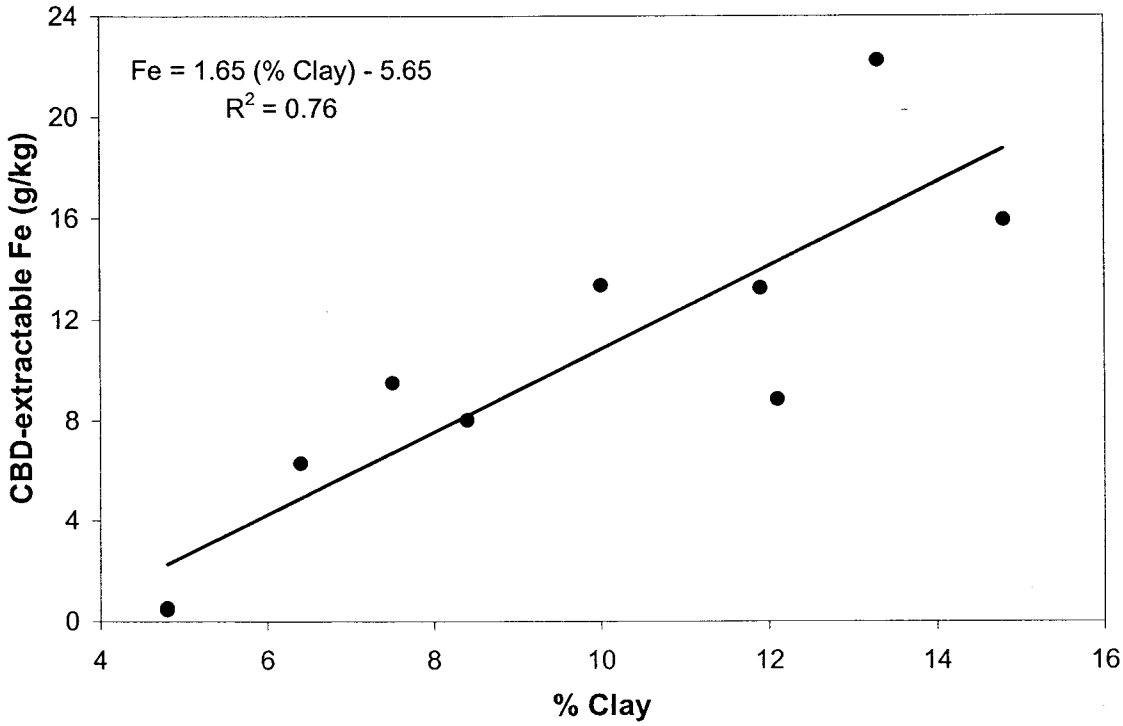


Figure 3. Clay (%) vs. CBD-extractable Mn (g/kg) for the 11 soil samples from Belews Creek site.

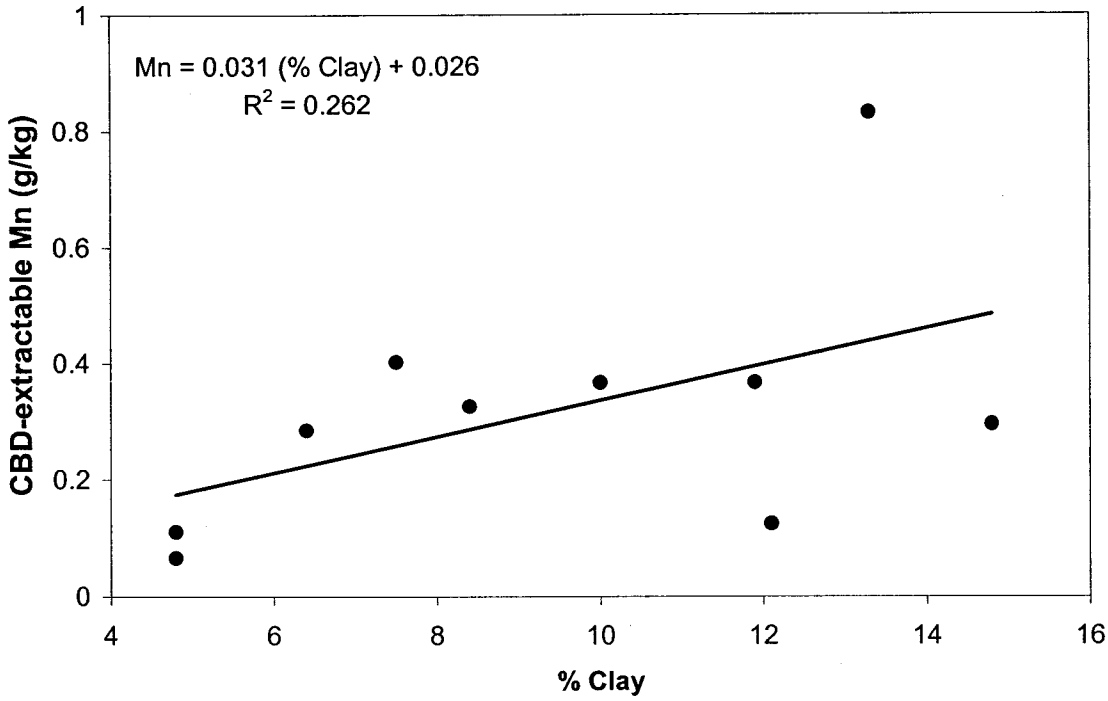


Figure 4. CBD-extractable Fe (g/kg) vs. CEC (cmol/kg) for the 11 soil samples from Belews Creek site.

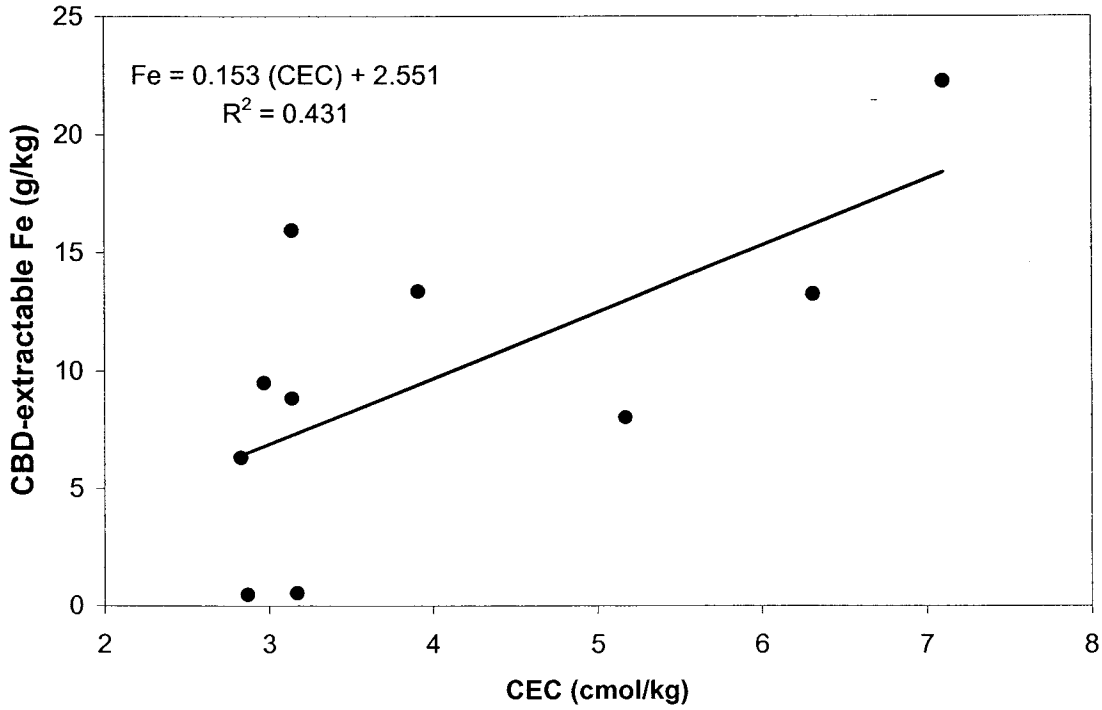


Figure 5. CBD-extractable Mn (g/kg) vs. CEC (cmol/kg) for the 11 soil samples from Belews Creek site.

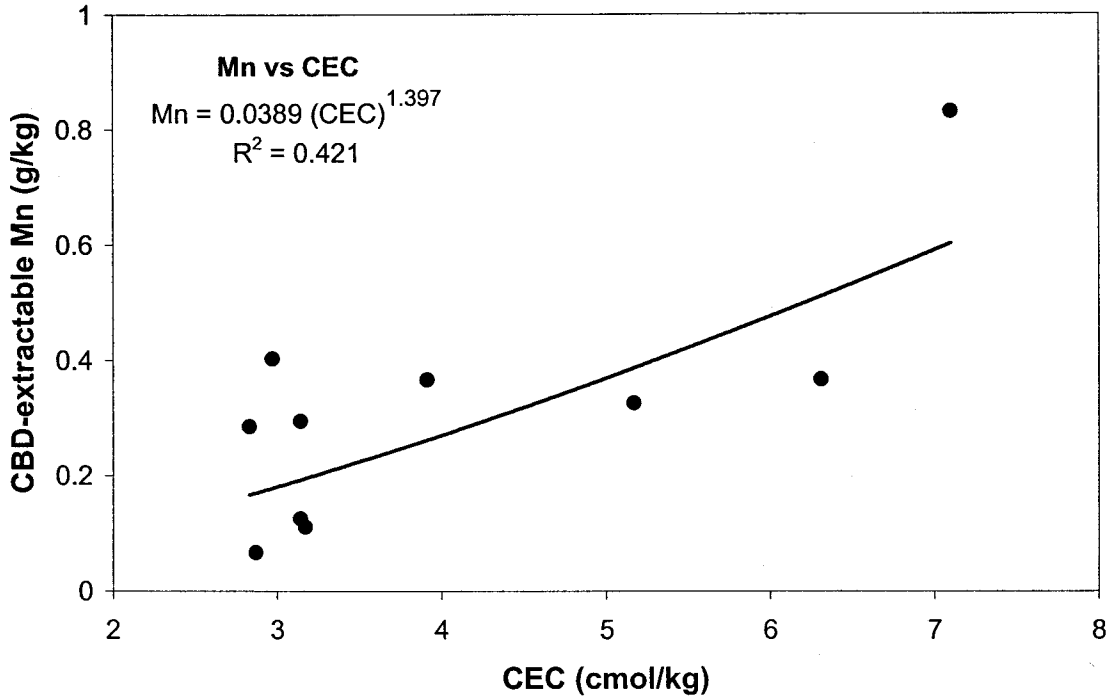
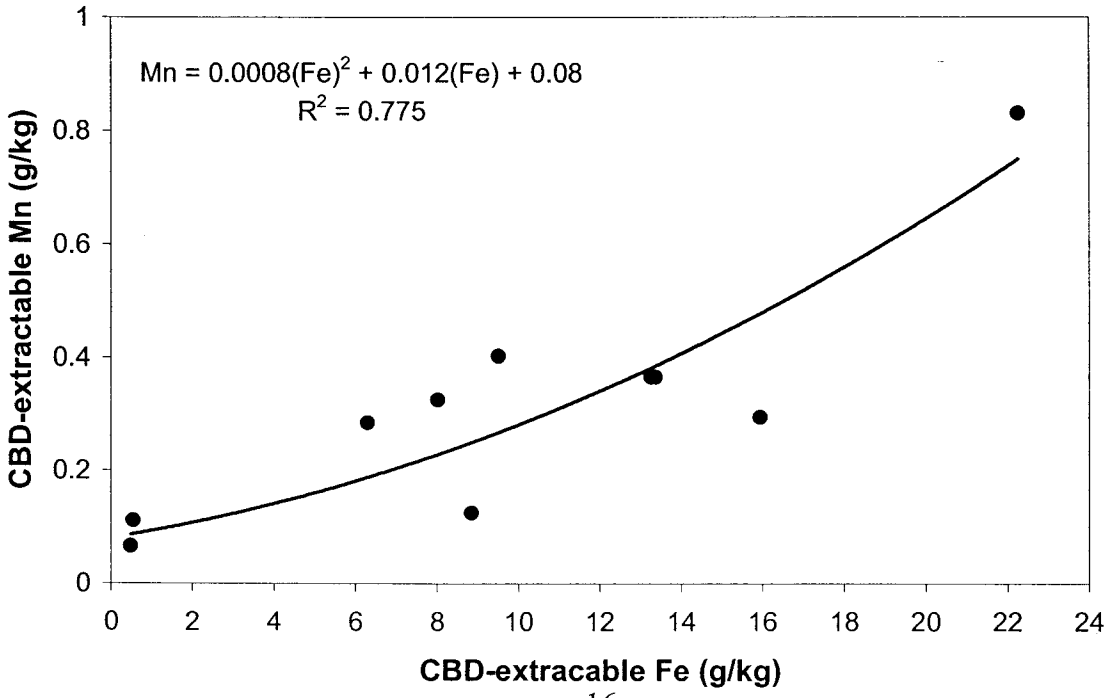


Figure 6. CBD-extractable Mn (g/kg) vs. CBD-extractable Fe (g/kg) for the 11 soil samples from Belews Creek site.



SPLP Test Results

Table 6 provides the measured concentrations of the six constituents in SPLP extracts for the seven coal ash samples.

Table 6. Coal Ash SPLP Extract Concentrations (μg/L) for the Six Constituents

Sample Date	As	Cd	Cr	Fe	Mn	Se
2/14/00	15.1	8.03	66.44	1110	88	33.9
2/15/00	22.5	5.46	34.18	253	48	136
2/16/00	3.9	7.24	6.59	133	77	32.3
2/17/00	23.6	7.83	57.44	300	40	102.4
2/21/00	27.3	6.70	47.02	230	35	126.5
2/22/00	20.6	8.11	58.46	310	44	102.8
2/24/00	<2.0	3.19	<1.0	14	45	26.0

These SPLP results indicate that leachate from the Belews Creek Steam Station ash is likely to contain arsenic at concentrations of less than 30 μg/L, cadmium concentrations of less than 10 μg/L, chromium concentrations of less than 70 μg/L, iron concentrations of less than 1,200 μg/L, manganese concentrations of less than 100 μg/L, and selenium concentrations of less than 130 μg/L. Therefore, the adsorption isotherms were developed with initial solution concentrations that included the range of these leachate concentrations.

Adsorption Test Results

All data, plots, and regression results on the adsorption tests for the six constituents and the 10 soils are given in Appendix B. Of the 6 targeted constituents, arsenic (As), chromium (Cr), and selenium (Se) typically exist as anionic species formed by complexing with oxygen under most environmentally relevant scenarios, whereas Cd, Mn, and Fe exists as cationic species.

Arsenic (As), Chromium (Cr), and Selenium (Se)

Table 7 contains the linear distribution coefficients (K_d, L/kg) estimated from the adsorption isotherms and subsequent linear regression statistics for As, Cr, and Se. Also

noted in Table 7 are the analytical limits of detection (LOD) and reasonable limits of quantitation (LOQ). The maximum number of data points (n) per soil-solute combination was 14; however, in many cases such as with As, solution concentrations were below analytical LOD or LOQ reducing the number of data points (n) that could be used in the regression analysis.

Table 7. Linear distribution coefficients (K_d, L/kg) of As (V), Cr (VI), and Se (VI) for 10 soil samples from the Belews Creek Site.

	As (V)			Cr (VI)			Se (VI)		
	[a]LOD = 0.2 ug/L [b]LOQ = 3 ug/L			LOD = 0.5 ug/L LOQ = 2 ug/L			LOD = 1 ug/L LOQ = 3 ug/L		
Soil ID	K_d	r^2	n[c]	K_d (L/kg)	r^2	n	K_d (L/kg)	r^2	n
BC3 0-10'	7600	0.629	4 [d]	13.5	0.938	14	43.6	0.967	14
BC3 40-50'	1630	0.808	11	12.8	0.970	14	9.5	0.971	10
BC3 50-60'	4000	0.528	7 [d]	501.4	0.947	14	27.2	0.907	14
BC6 0-10'	9900	0.997	5 [d]	325.6	0.946	14	145.9	0.969	11
BC6 10-20'	> 11000		0 [e]	131.5	0.945	14	59.6	0.861	13
BC6 20-24'	> 11000		0[e]	400 [f]		2	21.6	0.912	12
MW-2-2 30-40'	2440 [f]		2	11.5	0.980	14	8.3	0.96	12
MW-2-1 35-45'	3300	0.795	5 [d]	41.0	0.985	14	18.7	0.989	12
MW6 28-38'	2460	0.225	10 [d]	54.4	0.966	14	20.8	0.907	11
MW6 38-48'	4200	0.291	12 [d]	128.9	0.969	14	43.8	0.869	11

[a] LOD = Limit of Detection

[b] LOQ = Limit of Quantification

[c] number of data points used in the linear fits to the isotherms

[d] Most solute concentrations (C_w) were below LOD or reasonable LOQ even if used in the linear regression to estimate K_d values

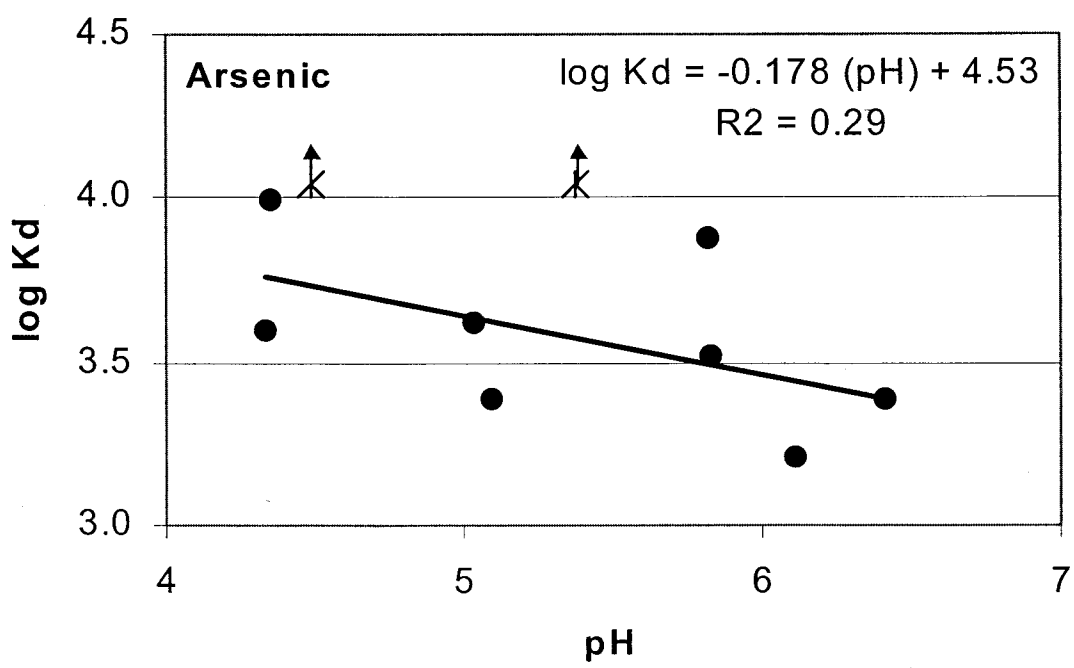
[e] All solute concentrations were below LOD and K_d values estimated to be larger than any observed, thus > 11,000 L/kg

[f] All solute concentrations were below LOD except for the highest initial concentration, which was used to estimate a very conservative single point K_d value ($K_d = C_s/C_w$)

Arsenic:

Results summarized in Table 7 indicate that adsorption of arsenate (i.e., As(V)) on the Belews Creek soils is very high yielding K_d values ranging from a low of about 1,600 (L/kg) to a high of over 9,900 (L/kg). Initial As concentrations applied to the soils ranged from approximately 50 μg/L to over 1000 μg/L (Table 1); however, after 24-h contact with soil, solution concentrations of As were attenuated to less than 10 μg/L for all soils, and less than 5 μg/L for 9 of the 11 soils. For all combinations of soils and initial As concentrations used, over 96% of the applied As was attenuated by the soil. These results are consistent with the published literature (EPRI 2000) that indicates that Arsenic (V) has a strong affinity to adsorb onto iron oxides/hydroxides in soils as well as clay minerals (e.g., kaolinite, vermiculite, montmorillonite). Correlation between measured K_d values for As(V) and pH of the soil solutions after equilibration is shown in Figure 7. As(V) adsorption is observed to decrease with increasing pH, which is consistent with the published literature. Arsenic(V) is highly sorbed below pH values of about 8.

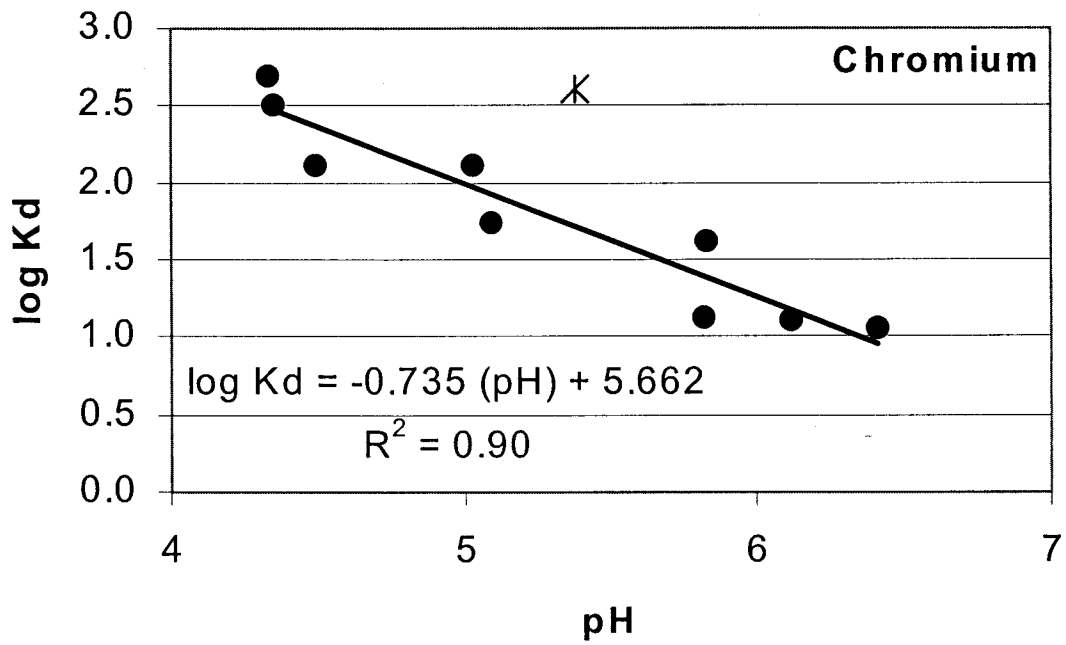
Figure 7. Log K_d versus pH for Arsenic (V) adsorption for the 10 soil samples from the Belews Creek Site. Not included in the regression, but shown as asterisks with an arrow are the K_d estimates of > 11000 L/kg for the 2 soils where As was attenuated to below LOD.



Chromium:

Data in Table 7 for adsorption of Cr (VI) (i.e., chromate) shows K_d values ranging from a low of about 11 L/kg to a high value of about 500 (L/Kg). Available literature indicates that adsorption of chromate is highly dependent on the pH of the soil solution. Figure 8 shows the strong positive correlation between the measured K_d for chromate and pH of the soil solution for the Belews Creek soils pH after equilibration. This plot indicates that chromate adsorption decreases with the increase in pH, which is consistent with the published literature.

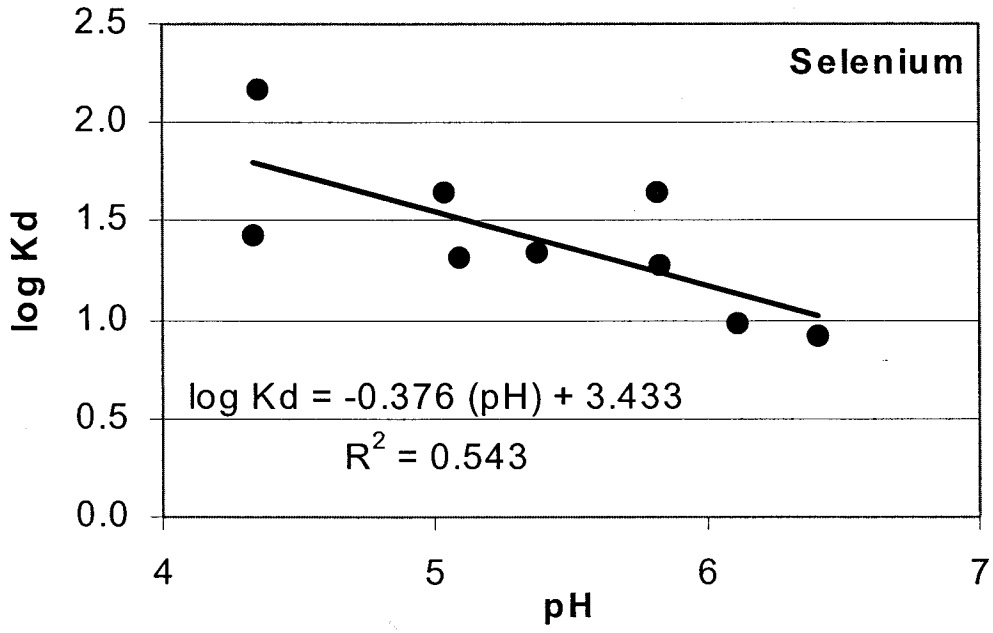
Figure 8. Log K_d versus pH for Chromium (VI) adsorption for the 10 soil samples from the Belews Creek Site. Not included in the regression, but shown as an asterisk is the single point K_d estimate for BC6 20-24' soil where Cr was



Selenium:

Data in Table 7 for adsorption of Se(VI) (i.e., selenate) shows K_d values ranging from a low of about 8 L/kg to a high of about 150 (L/Kg). Table 8 presents the measured adsorption coefficients of selenate. Available literature indicates that hydrous oxides of Fe and Al and amorphous aluminosilicates have a high affinity for adsorption of selenium species. Literature also indicates that adsorption of selenium species on soil minerals is highly pH dependent. Figure 9 shows correlation of the measured K_d values with pH of the soil solutions after equilibration. This plot indicates that selenate adsorption decreases with increase in pH.

Figure 9. Log K_d versus pH for Selenium (VI) adsorption for the 10 soil samples from the Belews Creek Site.



In general, anions such as arsenate, selenate, and chromate adsorb strongly under acidic conditions and as pH increases the adsorption decreases. Sorption of arsenic was the greatest followed by chromium, then selenium consistent with the published papers in the literature.

Cadmium

Table 8 presents the summary of adsorption results for cadmium. These data show that distribution coefficient for adsorption of Cd on the Belews Creek Station soils varies from a low of 5.5 L/kg to a high of about 47 L/kg. Available literature indicates that ion exchange processes between metallic cations such as Cd and the major base cations such as K, Na, Mg, and Ca sorbed on the exchange sites of soil minerals may control the aqueous concentrations of metals ions. These cation exchange reactions, therefore, play a significant role in attenuating the transport of metal cations in the subsurface. Literature also indicates that adsorption of Cd on soil minerals is highly dependent on pH. Figure 10 shows correlation of the measured K_d values for cadmium versus pH of the soil solutions after equilibration. This plot indicates that Cd adsorption increases with increase in pH, which is consistent with the published literature.

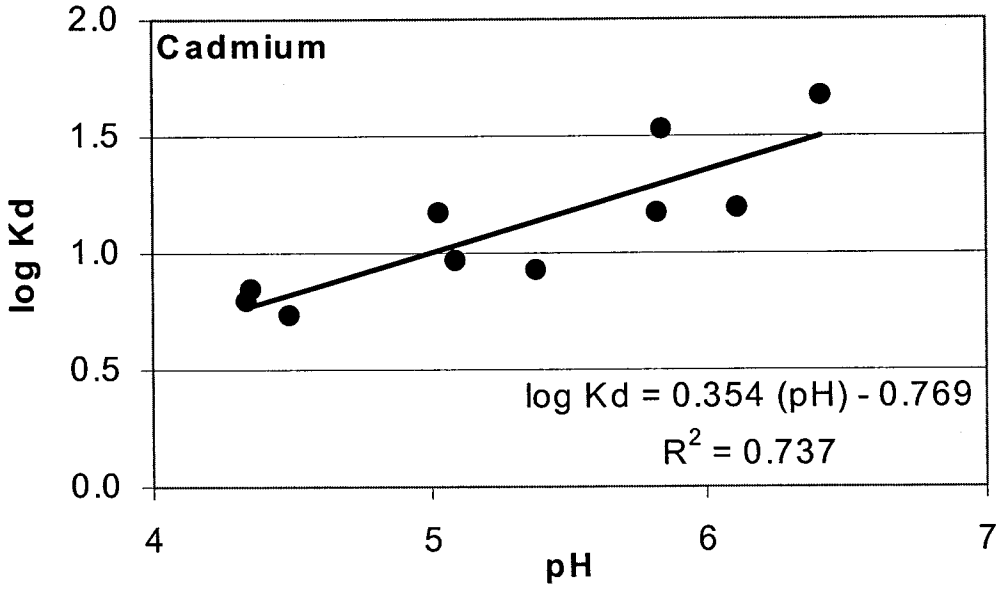
Table 8. Linear distribution coefficients (K_d, L/kg) of Cd (II) for 10 soil samples from the Belews Creek Site.

	Cadmium (II)		
	[a]LOQ = 2 μg/L; LOD =0.5 μg/L		
Soil ID	**K_d(L/kg)**	**R^2**	**n[b]**
BC3 0-10'	14.9	0.894	14
BC3 40-50'	15.5	0.994	14
BC3 50-60'	6.3	0.934	14
BC6 0-10'	7.1	0.871	14
BC6 10-20'	5.5	0.826	14
BC6 20-24'	8.5	0.929	14
MW-2-2 30-40'	46.7	0.985	14
MW-2-1 35-45'	34.2	0.986	14
MW6 28-38'	9.4	0.994	14
MW6 38-48'	14.9	0.996	14

[a] LOQ = Limit of Quantification; LOD = Limit of Detection

[b] n = number of data points used in the linear fits to the isotherms

Figure 10. Log K_d versus pH for Cadmium (II) adsorption for the 10 soil samples from the Belews Creek Site.



Manganese and Iron

A summary of the Manganese (Mn) and Iron (Fe) adsorption tests are shown in Table 9. For all soils, Mn (II) and Fe (III) concentrations were attenuated to background levels obtained as water soluble (WS) Mn and WS-Fe, respectively, for the entire range of initial solution concentrations employed. Background levels of water-soluble Mn and Fe refers to the solution concentrations measured after equilibration with 0.01 N CaCL2 solutions where no Mn or Fe was added. These data show that the manganese and iron oxides contained in the Belews Creek soils control the precipitation-dissolution and adsorption-dissolution reactions. WS-Mn concentrations for these soils range between 350 μg/L to 3400 μg/L, which is much higher than the initial concentrations in the aqueous solutions applied to the soils for the adsorption studies. Substantial amounts of WS-Mn are expected in acidic soils containing Mn oxides. The initial solution concentrations for Fe were higher than those used for manganese ranging from 240 to 1200 μg/L; however, Fe concentrations after 24-h contact with these soils were generally much smaller than those observed for Mn. Iron rapidly precipitates as iron oxyhydroxides at the pH values for these soils, which would imply that in oxygen containing environment iron will rapidly precipitate out of solution rendering it immobile.

Complete attenuation of Mn (II) and Fe (III) by the soil occurred; therefore, K_d values could not be calculated and are meaningless for these soil conditions. Due to the significant amounts of Mn and Fe oxides, Mn and Fe behavior in these soils is controlled by the precipitation-dissolution reactions of the these naturally occurring solid phases, thus added amounts of Mn (II) and Fe (III) are quickly attenuated to those levels that would be present in the soil naturally.

Table 9. Manganese (Mn, II) and Iron (Fe, III) adsorption summary for the 10 soil samples from the Belews Creek Site.

Soil ID	Mn (II) *Initial Concentration Range: 5 - 250 μg/L*		Fe (III) *Initial Concentration Range: 240 -1 200 μg/L*	
	Average	SD	Average	SD
BC3 0-10'	662	112	223	69
BC3 40-50'	1275	91	404	184
BC3 50-60'	632	96	207	64
BC6 0-10'	820	94	270	94
BC6 10-20'	1300	99	344	280
BC6 20-24'	1624	122	368	144
MW-2-2 30-40'	2207	81	249	91
MW-2-1 35-45'	1685	88	204	51
MW6 28-38'	2196	91	114	77
MW6 38-48'	3162	129	207	188

CONCLUSIONS

Laboratory equilibration studies were conducted to generate site-specific distribution coefficients (K_d) for Chromium (VI), Cadmium (II), Arsenic (V), Selenium (VI), Manganese (II), and Iron (III). Adsorption of these 6 selected constituents by 9 of the 10 soil samples from the Belews Creek Plant were measured to construct adsorption isotherms over a range of initial solution concentrations selected based on the SPLP results for fly ash leaching. The derived K_d values exhibited a range of numbers reflecting the variability in soil properties and in particular the pH. The largest K_d values were observed for As (V) followed by Cr (VI), Se (VI), and Cd. Meaningful K_d values could not be obtained for Mn (II) and Fe (III) because of the ubiquitous nature of Fe and Mn oxides in the Belews Creek site soils.

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Murarka, I.P. 2000. Environmental Chemistry of Arsenic: A Literature Review. EPRI Report No. 1000585, Palo Alto, CA.

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U.S. EPA. 1991. Technical Resource Document, Batch-type Procedures for Estimating Soil Adsorption of Chemicals. Office of Solid Waste and Emergency Response, Washington, D.C. Report No. EPA/530/SW-87/006-F.

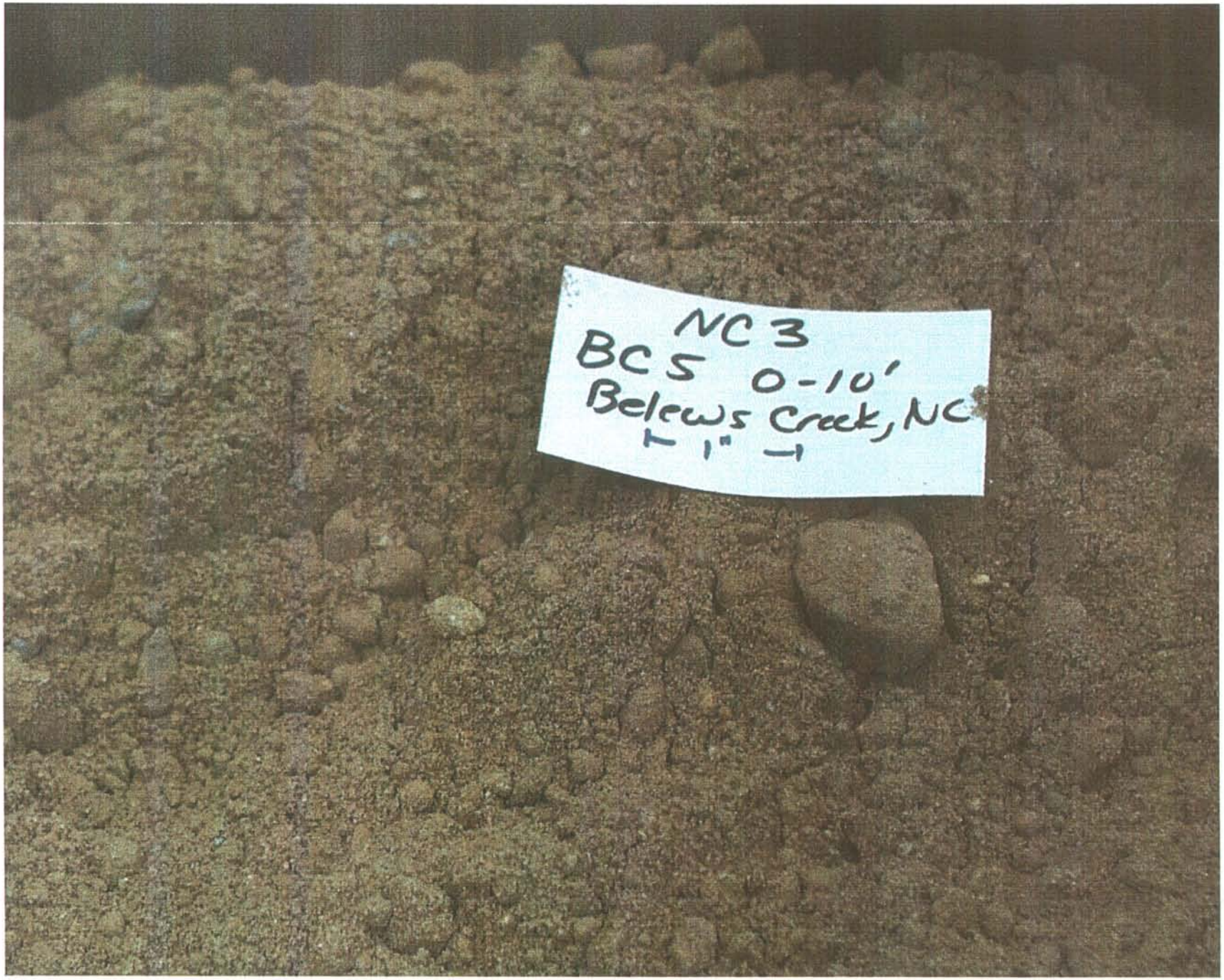
Appendix A

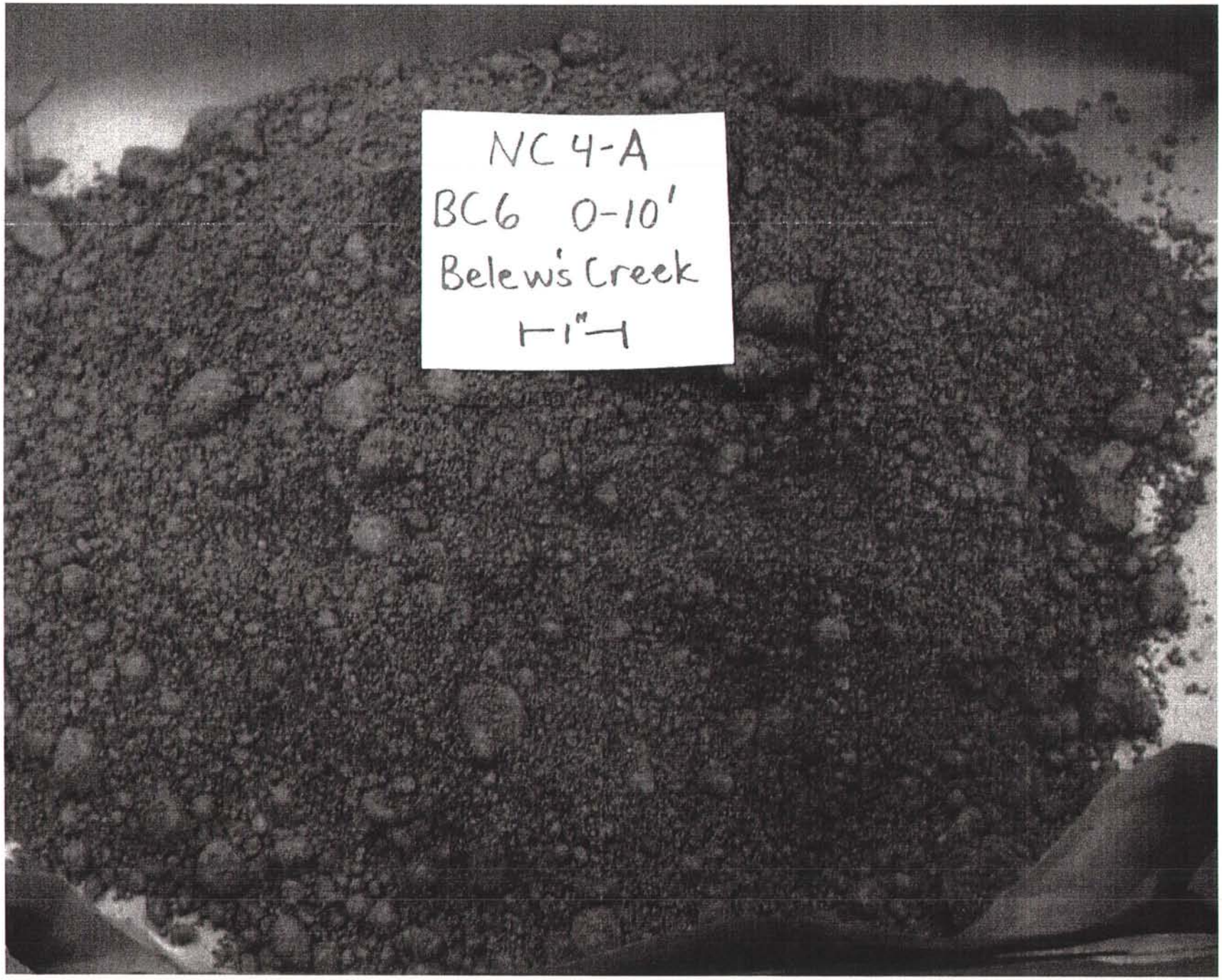
Belews Creek Site Soils

Photographs of the Soil Samples

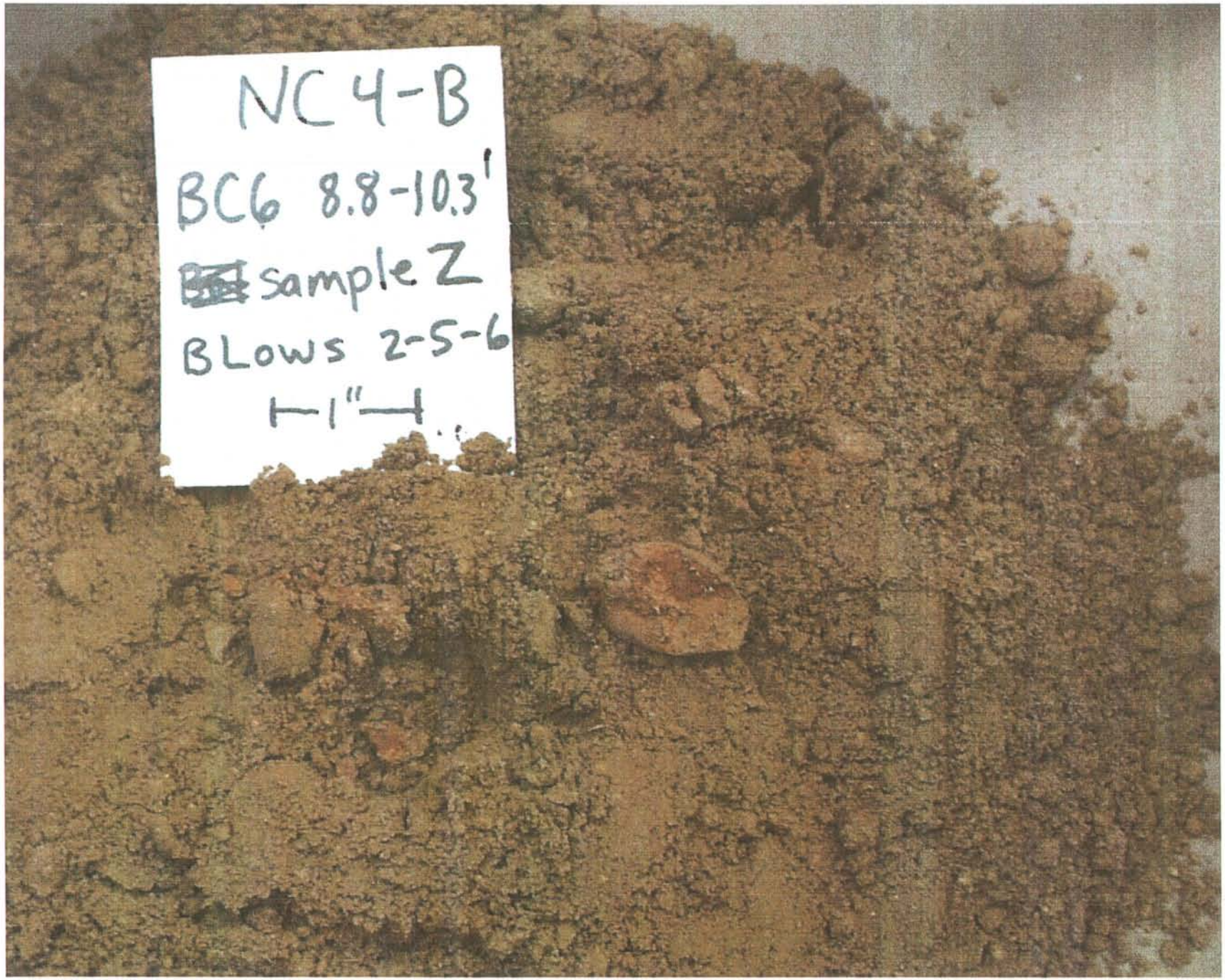
NC1
BC 3 40'-50'
Below Creek, NC

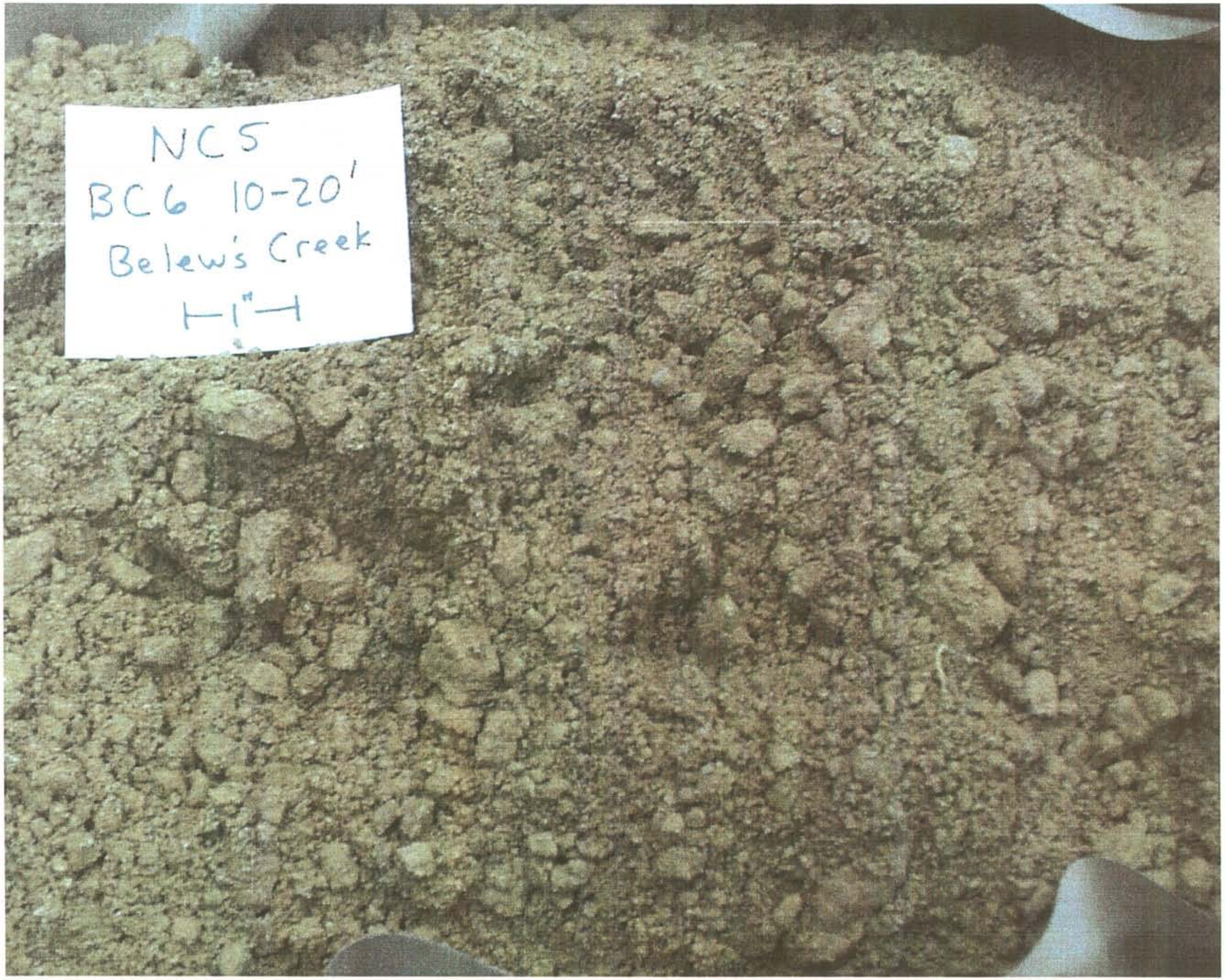
NC2
BC-3 50'-60'
Belew's Creek
1"


NC 3
BC 5 0-10'
Belews Creek, NC
1"


NC 4-A
BC6 0-10'
Belew's Creek
1"

NC 4-A
BC6 0-10'
Belew's Creek
1"

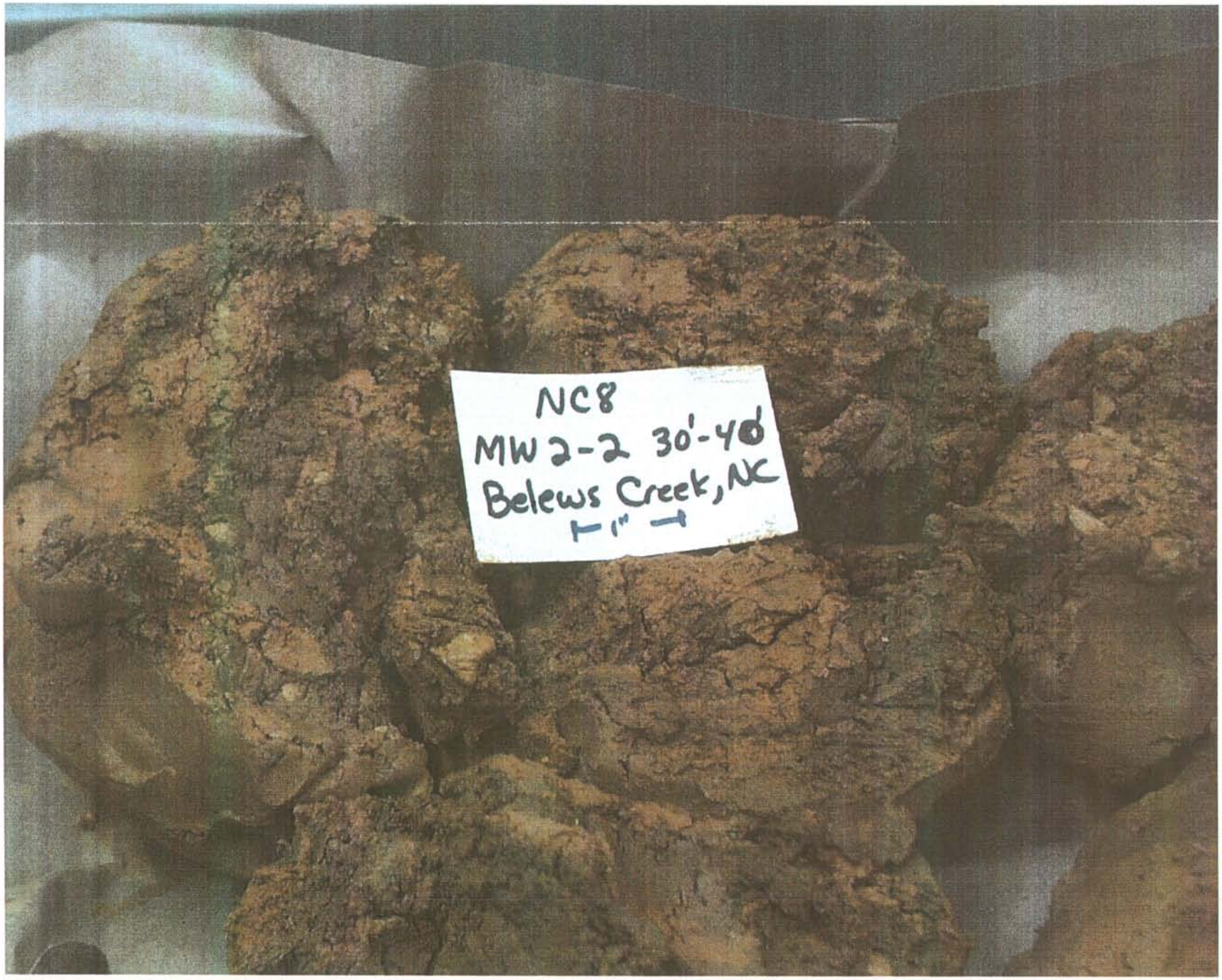

NC 4-B
BC6 8.8-10.3'
sample Z
BLows 2-5-6
1"

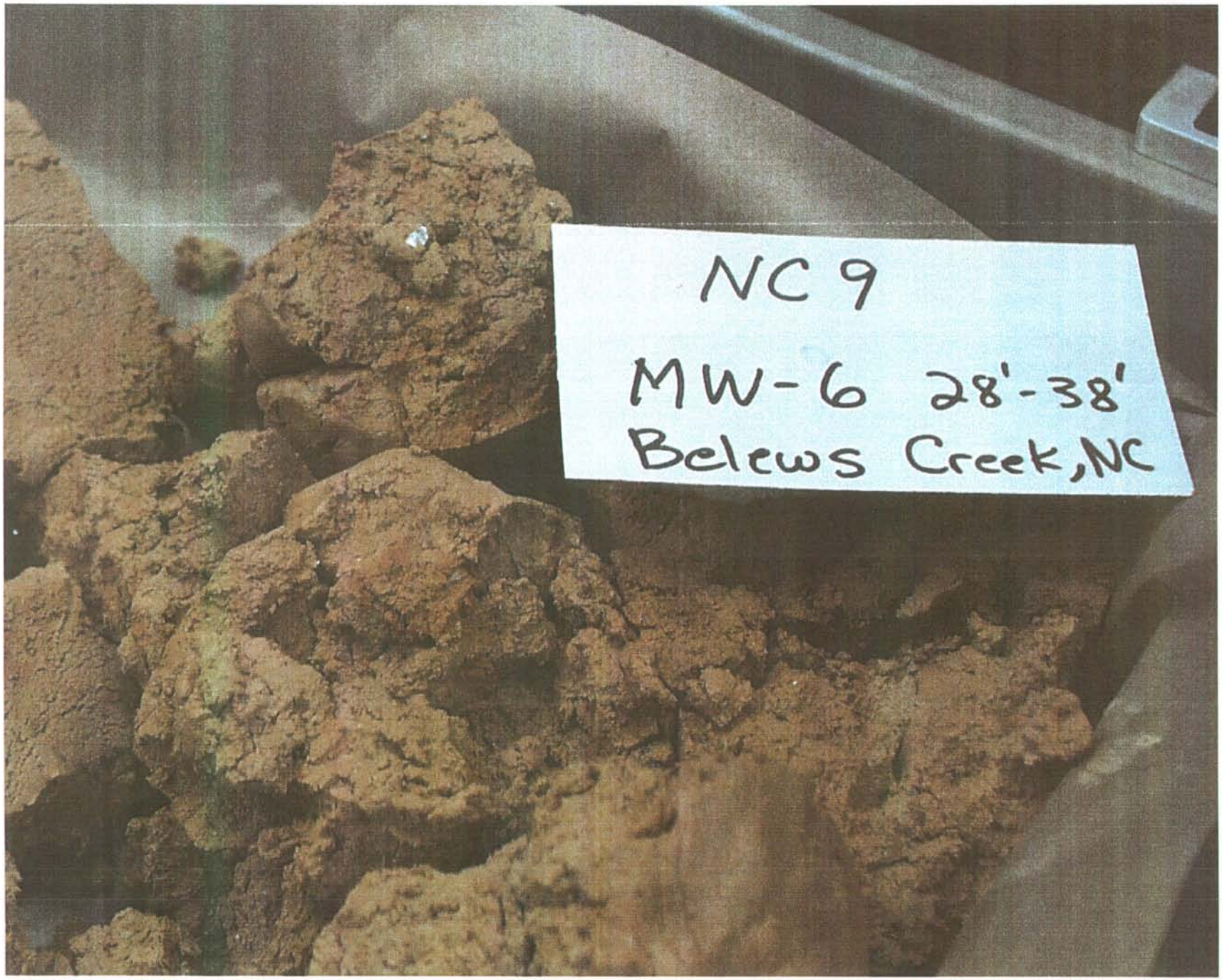

NC5
BC6 10-20'
Belew's Creek
1"

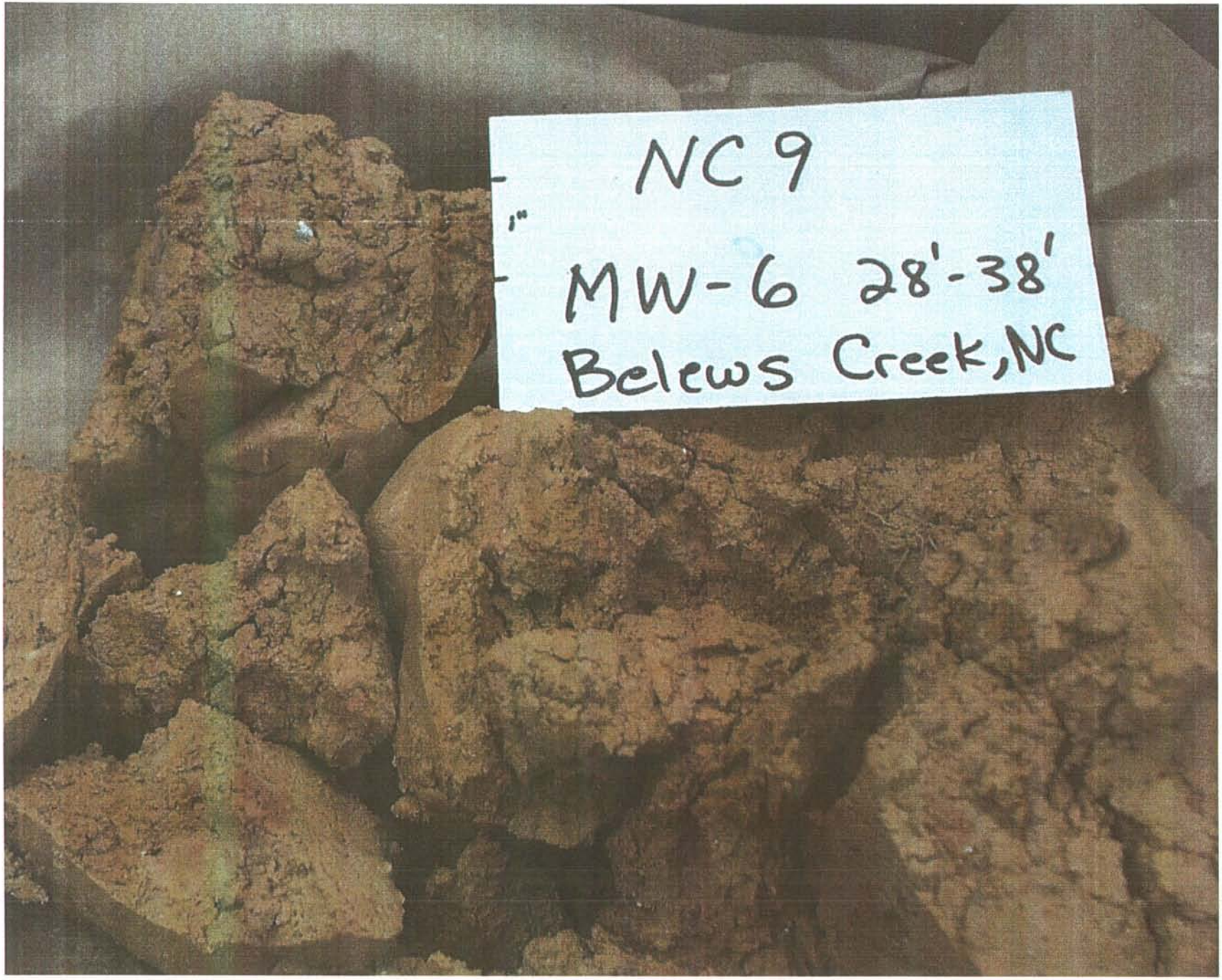
NC5
BC6 10-20'
Belew's Creek
1"

NC6
BC6 20-24'
Belew's Creek
1"

NC 7
MW-2-1 35-45'
Belew's Creek
⊢1"⊣


NC8
MW 2-2 30'-40'
Belews Creek, NC
1"


NC 9
MW-6 28'-38'
Belews Creek, NC


NC 9
MW-6 28'-38'
Belews Creek, NC

NC 10
MW6 38'-48'
Belews Creek, NC

NC11
BC Fly Ash
1"

APPENDIX B
Belews Creek Site Soils
Isotherm Data

As (V)
Cd (II)
Cr (VI)
Fe (III)
Mn (II)
Se (VI)

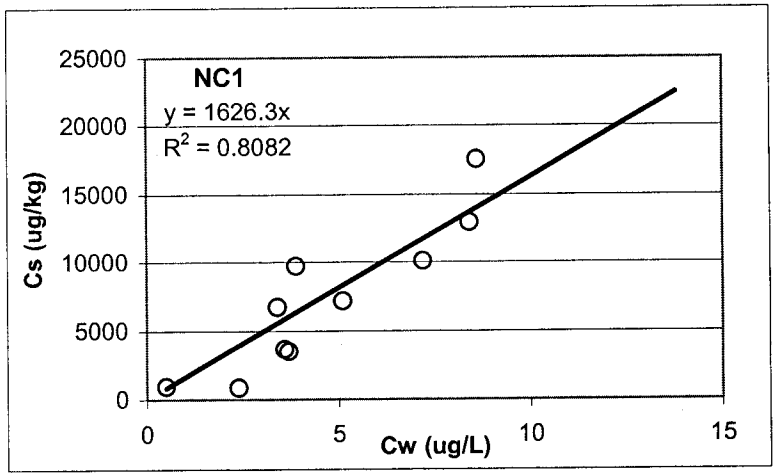
Dec. 21-22, 2001 GFAA Analysis
Bellows Creek Soils

Arsenic (V)

Ci (ug/L) = Initial solution concentrations
Cw* (ug/L) = Equilibrium solution concentrations corrected for background
Cs (ug/kg) = Loss to soil calculated by difference: (Ci-Cw*)(V/m)
m = soil mass (kg)
V = solution volume (0.050 L)
n.d. = not determined

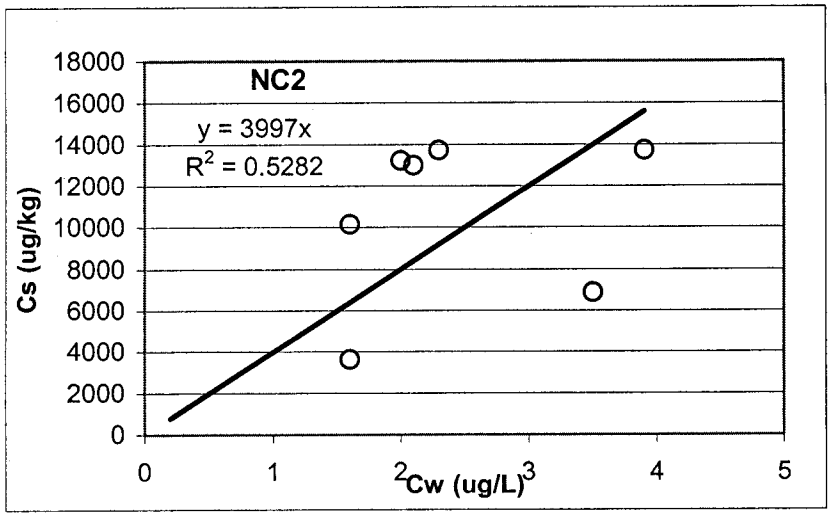
Purdue ID	Duke ID
NC1	BC3 40-50'
NC2	BC3 50-60'
NC3	BC3 0-10'
NC4A	BC6 0-10'
NC4B	BC6 8.8-10.3'
NC5	BC6 10-20'
NC6	BC6 20-24'
NC7	MW-2-1 35-45'
NC8	MW-2-2 30-40'
NC9	MW6 28-38'
NC10	MW6 38-48'

Sample	pH	Soil mass g	Ci	Cw*	Cs
NC1-20	6.62	3.017	0	1	
NC1-21	6.19	2.99	58	1	958
NC1-22	6.14	3.062	228	4	3669
NC1-23	6.13	3.087	417	3	6694
NC1-24	6.04	3.024	591	4	9702
NC1-25	5.98	2.969	850	4	
NC1-26	5.95	2.963	1048	9	17535
NC1-27	6.23	2.996	0	4	
NC1-28	6.17	3.077	57	2	882
NC1-29	6.1	3.057	218	4	3505
NC1-30	6.04	2.932	426	5	7178
NC1-31	5.99	2.983	610	7	10104
NC1-32	5.98	3.026	792	8	12948
NC1-33	5.96	2.984	843	14	
Average pH =	6.11				
Std. Dev. =	0.174				

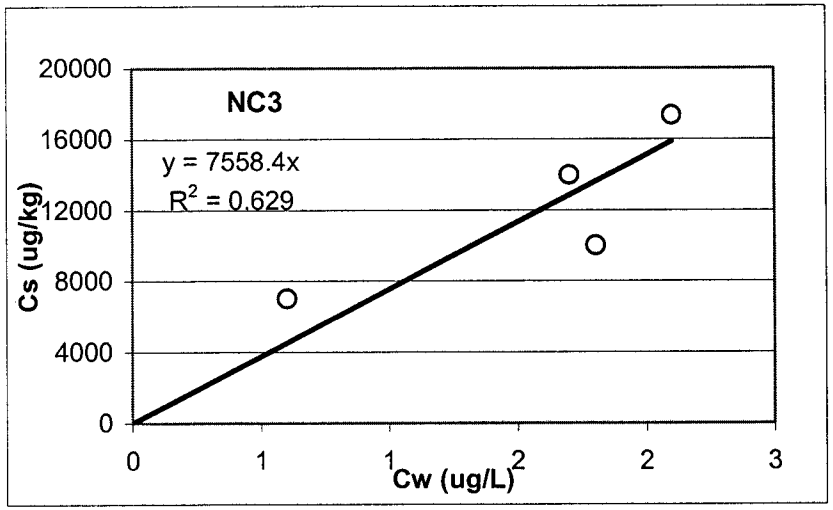


Arsenic (continued)

Sample	pH	g	Ci	Cw*	Cs
NC2-20	4.34	3.076	0	2	
NC2-21	4.31	2.934	57	1	
NC2-22	4.31	2.947	218	2	
NC2-23	4.3	3.071	426	4	6879
NC2-24	4.3	2.999	610	2	10143
NC2-25	4.31	3.039	792	2	12996
NC2-26	4.34	3.057	843	4	13724
NC2-27	4.31	2.912	0	1	
NC2-28	4.29	2.923	57	2	
NC2-29	4.3	2.977	218	2	3635
NC2-30	4.29	3.051	426	0	
NC2-31	4.28	3.037	610	0	
NC2-32	4.29	2.988	792	2	13220
NC2-33	4.28	3.059	843	2	13741
Average pH =	4.30				
Std. Dev. =	0.019				

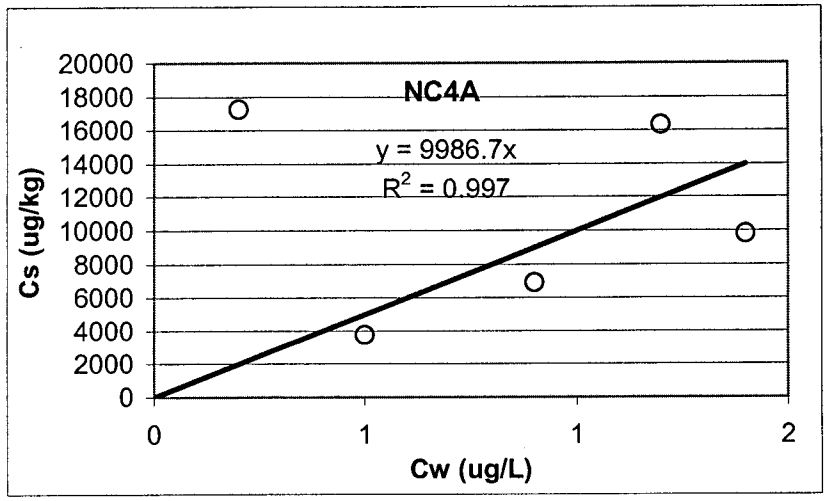


Sample	pH	g	Ci	Cw*	Cs
NC3-20	4.31	3.01	0	0	
NC3-21	4.32	3.003	58	0	
NC3-22	4.29	2.992	228	0	
NC3-23	4.3	2.959	417	1	7031
NC3-24	4.31	2.9457	591	2	9996
NC3-25	4.33	3.037	850	2	13971
NC3-26	4.31	3.0141	1048	2	17345
NC3-27	4.32	2.756	0	0	
NC3-28	4.28	3.044	58	0	
NC3-29	4.3	2.715	228	0	
NC3-30	4.42	2.903	417	0	
NC3-31	4.32	2.966	591	0	
NC3-32	4.35	2.73	850	0	
NC3-33	4.3	2.917	1048	0	
Average pH =	4.32				
Std. Dev. =	0.034				



Arsenic (continued)

Sample	pH	g	Ci	Cw*	Cs
NC4a-20	4.36	3.025	0	0	
NC4a-21	4.36	3.015	58	0	
NC4a-22	4.37	2.9885	228	0	
NC4a-23	4.37	3.2434	417	0	
NC4a-24	4.38	2.8647	591	0	
NC4a-25	4.36	3.228	850	0	
NC4a-26	4.38	3.2029	1048	1	16337
NC4a-27	4.35	3.034	0	0	
NC4a-28	4.34	3.028	58	0	
NC4a-29	4.34	3.007	228	1	3788
NC4a-30	4.33	3.01	417	1	6907
NC4a-31	4.33	2.995	591	1	9838
NC4a-32	4.34	3.037	850	0	
NC4a-33	4.34	3.034	1048	0	17263
Average pH =	4.35				
Std. Dev. =	0.017				



Sample	pH	g	Ci	Cw*	Cs
NC5-20	4.47	3.071	0	0	23
NC5-21	4.47	2.978	57	0	964
NC5-22	4.47	2.995	218	0	3686
NC5-23	4.48	2.989	426	0	7153
NC5-24	4.48	2.9211	610	0	10506
NC5-25	4.48	3.0876	792	0	12877
NC5-26	4.45	3.0088	843	0	14060
NC5-27	4.43	3.018	0	0	20
NC5-28	4.43	2.938	57	0	1028
NC5-29	4.45	3.002	218	0	3686
NC5-30	4.44	3.054	426	0	7032
NC5-31	4.44	2.948	610	0	10419
NC5-32	4.44	3.025	792	0	13164
NC5-33	4.45	2.951	843	0	14366
Average pH =	4.46				
Std. Dev. =	0.019				

NC5

All solution concentrations < LOD

Arsenic (continued)

Sample	pH	g	Ci	Cw*	Cs
NC6-20	5.14	3.043	0	0	12
NC6-21	5.03	3.2441	57	0	936
NC6-22	5.19	2.9761	218	0	3708
NC6-23	5.18	3.2351	426	0	6657
NC6-24	5.22	3.0626	610	0	10016
NC6-25	5.27	3.0105	792	0	13204
NC6-26	5.24	3.1158	843	0	13542
NC6-27	5.2	3.006	0	0	48
NC6-28	5.77	3.064	57	0	1031
NC6-29	5.28	3.026	218	0	3713
NC6-30	5.24	3.016	426	0	7134
NC6-31	5.26	3.057	610	0	10070
NC6-32	5.24	3.023	792	0	13172
NC6-33	5.17	3.051	843	0	13823
Average pH =	5.25				
Std. Dev. =	0.164				

NC6

All solution concentrations < LOD

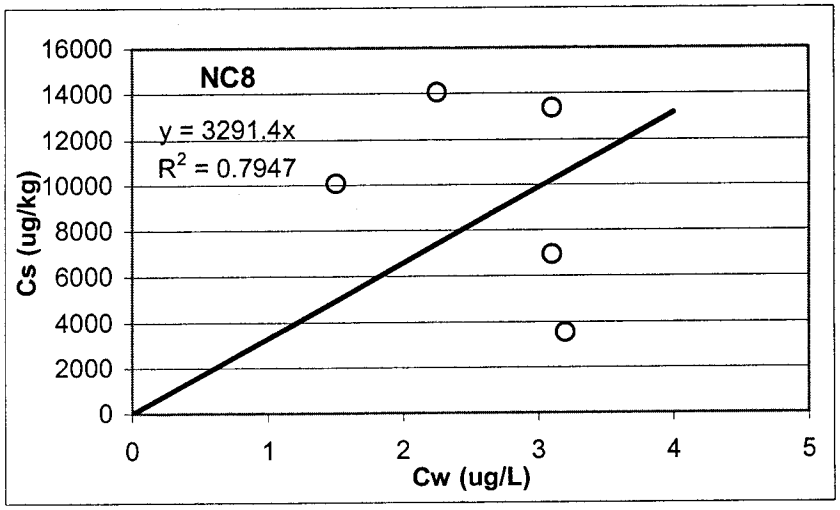
Sample	pH	g	Ci	Cw*	Cs
NC7-20	5.96	2.98	0	0	
NC7-21	5.88	3.427	57	0	
NC7-22	5.97	3.1551	218	0	
NC7-23	6.02	2.8303	426	0	
NC7-24	6.05	3.0191	610	0	
NC7-25	6.06	2.9803	792	0	
NC7-26	6	3.0963	843	5	13526
NC7-27	6.05	3.02	0	0	
NC7-28	6.07	2.967	57	0	
NC7-29	6.06	2.93	218	0	
NC7-30	6.07	2.982	426	0	
NC7-31	6.14	2.966	610	0	
NC7-32	6.16	3.046	792	0	
NC7-33	6.05	2.946	843	6	14206
Average pH =	6.04				
Std. Dev. =	0.071				

NC7

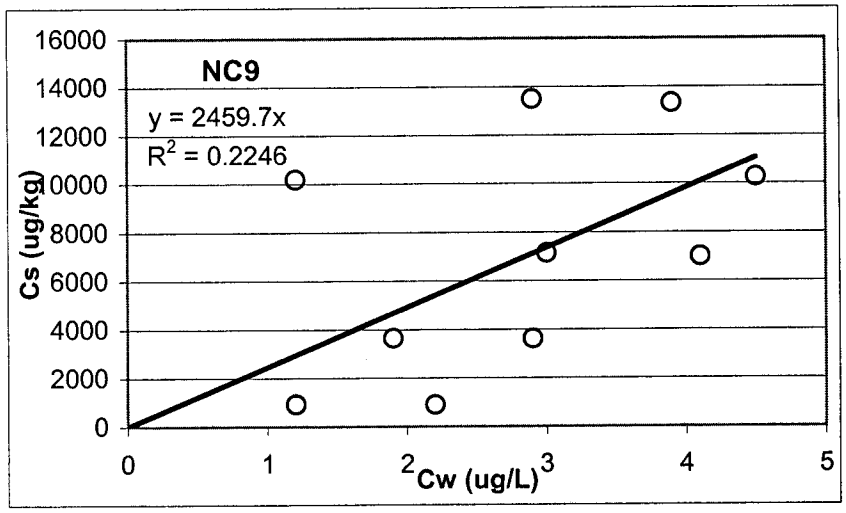
Single Point Kd estimate:
2505
2368
2436 Ave.

Arsenic (continued)

Sample	pH	g	Ci	Cw*	Cs
NC8-20	5.68	3.057	0	0	
NC8-21	5.48	2.997	57	0	
NC8-22	5.51	3.033	218	0	
NC8-23	5.55	3.128	426	0	
NC8-24	5.58	3.014	610	0	
NC8-25	5.6	2.986	792	0	
NC8-26	n.d.	3.127	843		
NC8-27	5.6	2.953	0	0	
NC8-28	5.6	2.983	57	4	
NC8-29	5.59	3.032	218	3	3542
NC8-30	5.58	3.043	426	3	6949
NC8-31	5.58	3.024	610	2	10061
NC8-32	5.6	2.952	792	3	13362
NC8-33	5.66	2.989	843	2	14064
Average pH =	5.59				
Std. Dev. =	0.053				

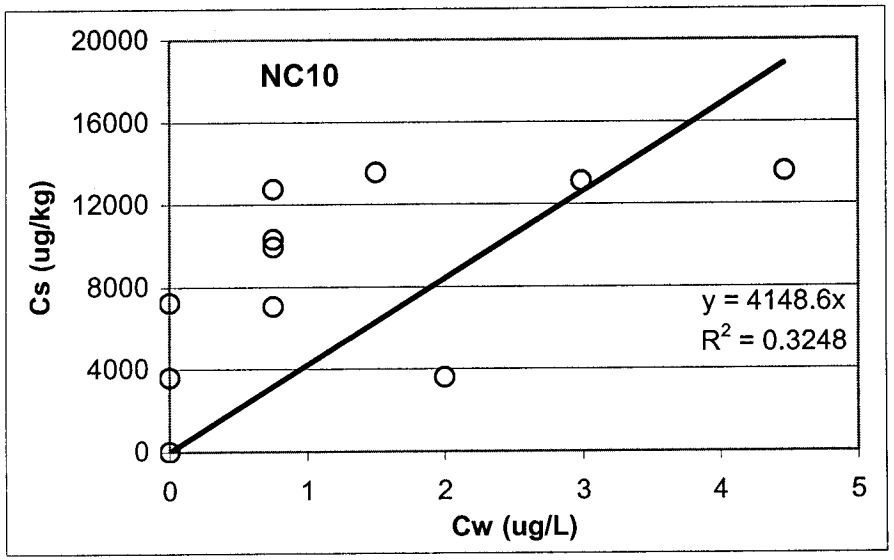


Sample	pH	g	Ci	Cw*	Cs
NC9-20	5.05	3.073	0	0	
NC9-21	5.36	2.98	57	1	931
NC9-22	5.06	2.984	218	3	3604
NC9-23	5.04	2.962	426	3	7140
NC9-24	5.05	2.9541	610	5	10248
NC9-25	5.14	2.9594	792	4	13315
NC9-26	5.11	3.0172	843	0	
NC9-27	5.02	3.032	0	3	
NC9-28	5.17	2.997	57	2	909
NC9-29	5.03	2.975	218	2	3632
NC9-30	5.02	3.014	426	4	6999
NC9-31	5.04	2.989	610	1	10184
NC9-32	5.04	2.927	792	3	13480
NC9-33	5.14	3.001	843	0	
Average pH =	5.09				
Std. Dev. =	0.092				



Arsenic (continued)

Sample	pH	g	**Ci**	**Cw***	**Cs**
NC10-20	4.94	2.971	0	0	0
NC10-21	5.13	2.997	57	1	
NC10-22	5.02	3.018	218	2	3579
NC10-23	5.1	3.016	426	1	7050
NC10-24	5.05	3.0654	610	1	9937
NC10-25	5.02	3.102	792	1	12754
NC10-26	5.01	3.1042	843	2	13554
NC10-27	4.94	3.087	0	0	0
NC10-28	4.95	3.124	57	1	
NC10-29	4.95	3.04	218	0	3586
NC10-30	4.95	2.942	426	0	7240
NC10-31	4.94	2.956	610	1	10305
NC10-32	4.96	3.003	792	3	13137
NC10-33	4.95	3.085	843	4	13590
Average pH =	4.99				
Std. Dev. =	0.063				



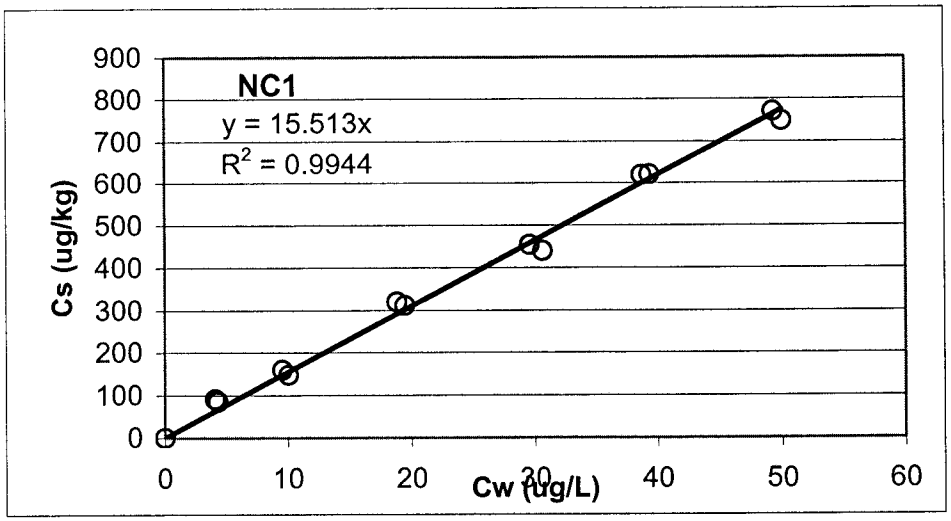
Jan. 24-26, 2001 ICP Analysis
Bellows Creek Soils

Cadmium

Ci (ug/L) = Initial solution concentrations
Cw* (ug/L) = Equilibrium solution concentrations corrected for background
Cs (ug/kg) = Loss to soil calculated by difference: (Ci-Cw*)(V/m)
m = soil mass (kg)
V = solution volume (0.050 L)
n.d. = not determined

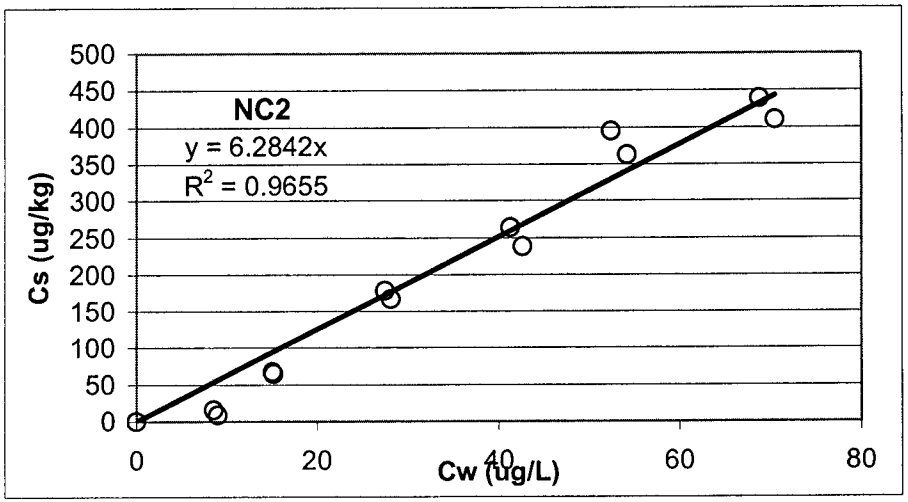
Purdue ID	Duke ID
NC1	BC3 40-50'
NC2	BC3 50-60'
NC3	BC3 0-10'
NC4A	BC6 0-10'
NC4B	BC6 8.8-10.3'
NC5	BC6 10-20'
NC6	BC6 20-24'
NC7	MW-2-1 35-45'
NC8	MW-2-2 30-40'
NC9	MW6 28-38'
NC10	MW6 38-48'

Sample	pH	Soil mass g	Ci	Cw*	Cs
NC1-20	6.81	3	0		n.d.
NC1-21	6.53	2.98	0	0.0	0
NC1-22	6.40	2.988	10	4.1	91
NC1-23	6.27	3.061	10	4.3	85
NC1-24	6.12	2.973	19	9.5	160
NC1-25	6.06	3.04	19	10.0	148
NC1-26	5.99	2.995	38	19.5	311
NC1-27	5.97	3.006	38	18.8	320
NC1-28	5.95	3.018	57	30.6	439
NC1-29	5.92	3.032	57	29.5	455
NC1-30	5.87	3.02	76	38.7	620
NC1-31	5.88	2.96	76	39.3	622
NC1-32	5.88	3.012	95	50.0	750
NC1-33	5.86	2.974	95	49.3	771
Average pH =	6.11				
Std. Dev. =	0.291				

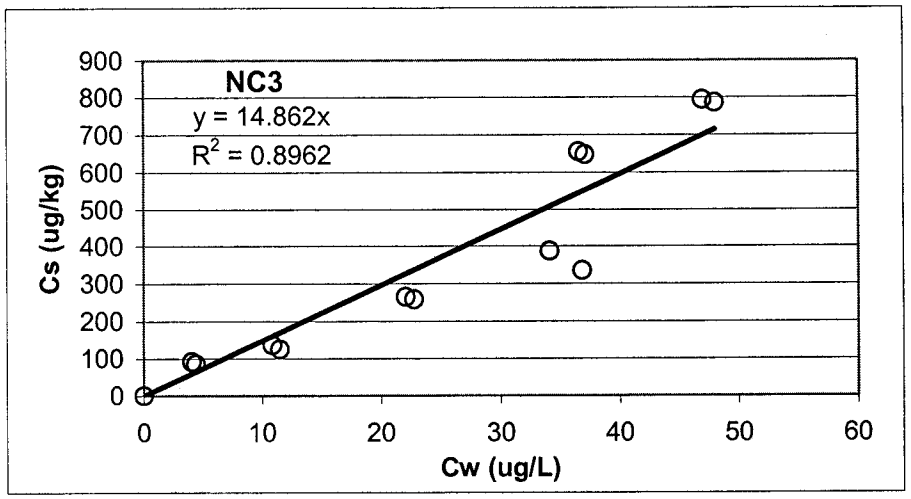


Cadmium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC2-20	4.35	2.997	0	0.0	0
NC2-21	4.35	3.012	0	0.0	0
NC2-22	4.33	3.001	10	9.0	9
NC2-23	4.32	3.011	10	8.6	16
NC2-24	4.30	2.968	19	15.2	65
NC2-25	4.33	2.974	19	15.0	67
NC2-26	4.33	2.991	38	27.4	178
NC2-27	4.33	2.981	38	28.1	167
NC2-28	4.33	3.031	57	42.6	239
NC2-29	4.32	3.002	57	41.3	264
NC2-30	4.33	3.022	76	54.2	363
NC2-31	4.34	3.009	76	52.4	395
NC2-32	4.33	3	95	68.8	439
NC2-33	4.33	3.01	95	70.5	410
Average pH =	4.33				
Std. Dev. =	0.012				

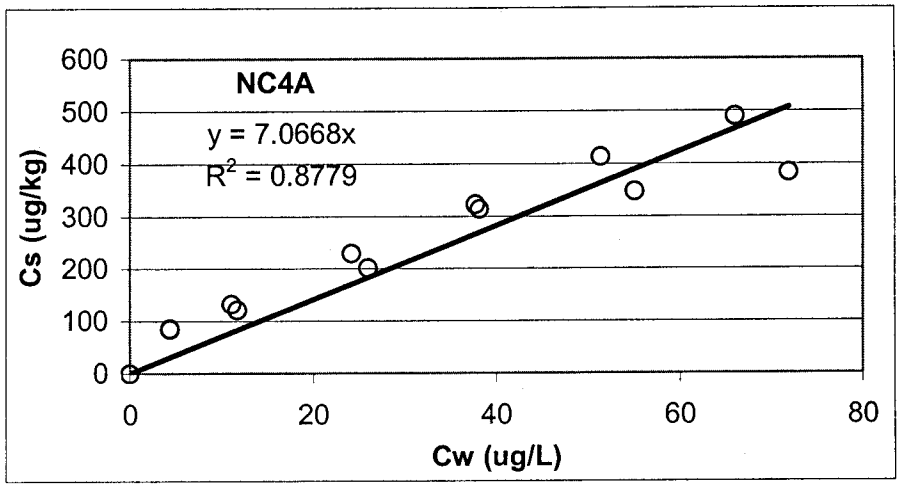


Sample	pH	g	Ci	Cw*	Cs
NC3-20	5.61	2.999	0	0.0	0
NC3-21	5.75	3.015	0	0.0	0
NC3-22	5.79	2.993	10	4.0	91
NC3-23	5.82	3.018	10	4.4	85
NC3-24	5.84	2.992	19	10.8	137
NC3-25	5.80	3.015	19	11.5	125
NC3-26	5.84	2.97	38	22.7	259
NC3-27	5.86	3.02	38	22.0	266
NC3-28	5.87	3.023	57	36.8	335
NC3-29	5.87	2.972	57	34.1	387
NC3-30	5.82	3.021	76	36.6	655
NC3-31	5.85	3.017	76	37.1	647
NC3-32	5.87	3.004	95	48.0	785
NC3-33	5.89	3.037	95	47.0	794
Average pH =	5.82				
Std. Dev. =	0.071				

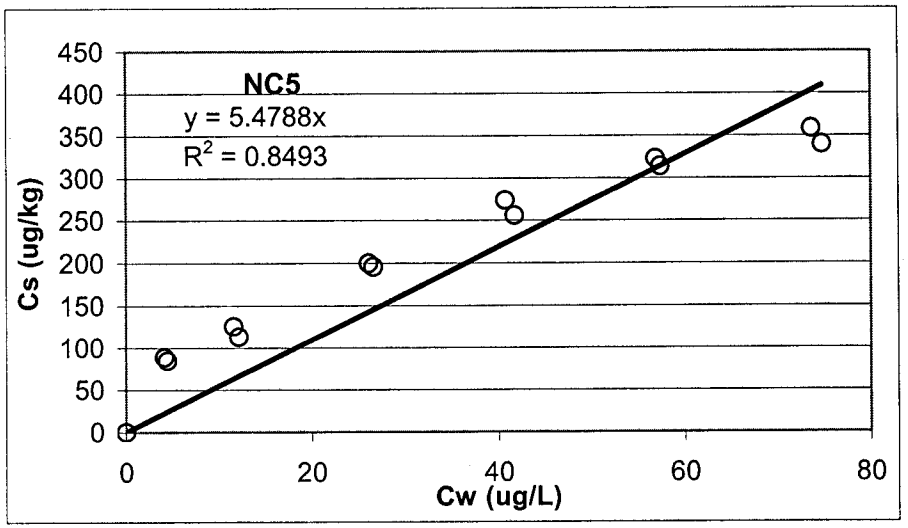


Cadmium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC4a-20	4.38	2.992	0	0.0	0
NC4a-21	4.33	2.99	0	0.0	0
NC4a-22	4.34	3.033	10	4.4	85
NC4a-23	4.35	2.983	10	4.4	85
NC4a-24	4.33	3.008	19	11.7	121
NC4a-25	4.35	2.997	19	11.1	132
NC4a-26	4.36	2.992	38	26.0	202
NC4a-27	4.35	3.019	38	24.2	230
NC4a-28	4.36	2.998	57	37.7	323
NC4a-29	4.37	3.017	57	38.1	314
NC4a-30	4.37	2.99	76	51.4	413
NC4a-31	4.35	3.024	76	55.1	347
NC4a-32	4.35	2.975	95	66.0	490
NC4a-33	4.35	3.038	95	71.9	383
Average pH =	4.35				
Std. Dev. =	0.014				

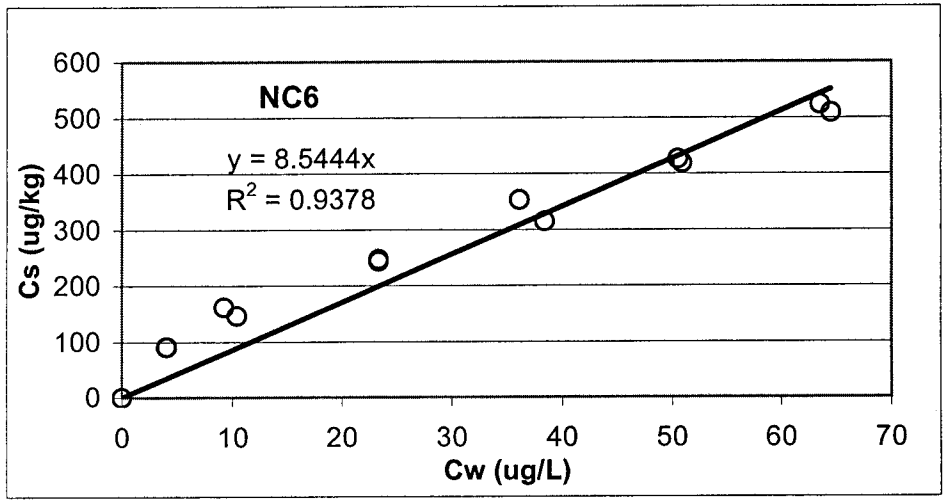


Sample	pH	g	Ci	Cw*	Cs
NC5-20	4.65	3.019	0	0.0	0
NC5-21	4.52	2.991	0	0.0	0
NC5-22	4.50	3.014	10	4.2	89
NC5-23	4.46	2.988	10	4.4	85
NC5-24	4.45	2.985	19	11.6	125
NC5-25	4.43	3.05	19	12.2	113
NC5-26	4.47	3.011	38	26.0	200
NC5-27	4.46	2.961	38	26.5	195
NC5-28	4.46	3.005	57	41.7	256
NC5-29	4.47	2.994	57	40.7	274
NC5-30	4.49	2.987	76	56.8	323
NC5-31	4.47	2.985	76	57.4	314
NC5-32	4.46	3.007	95	73.6	359
NC5-33	4.50	3.009	95	74.7	340
Average pH =	4.49				
Std. Dev. =	0.053				

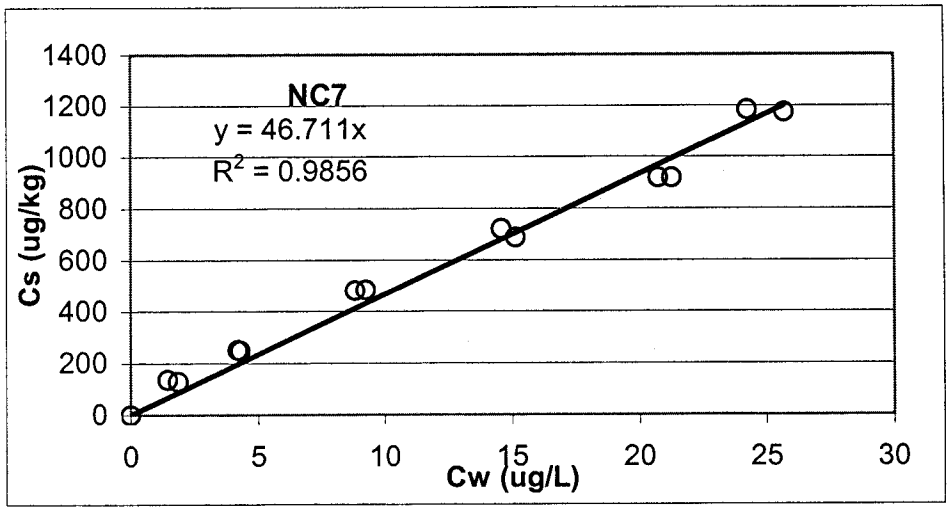


Cadmium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC6-20	5.57	2.994	0	0.0	0
NC6-21	5.60	3.012	0	0.0	0
NC6-22	5.52	3.029	10	4.1	90
NC6-23	5.46	3.034	10	4.0	91
NC6-24	5.41	2.942	19	10.4	147
NC6-25	5.38	3.025	19	9.2	162
NC6-26	5.40	3.035	38	23.3	244
NC6-27	5.33	2.98	38	23.3	247
NC6-28	5.31	2.973	57	38.4	315
NC6-29	5.28	2.972	57	36.1	353
NC6-30	5.27	3.015	76	50.9	418
NC6-31	5.27	3.004	76	50.5	426
NC6-32	5.25	3.023	95	64.5	508
NC6-33	5.25	3.023	95	63.5	524
Average pH =	5.38				
Std. Dev. =	0.12				

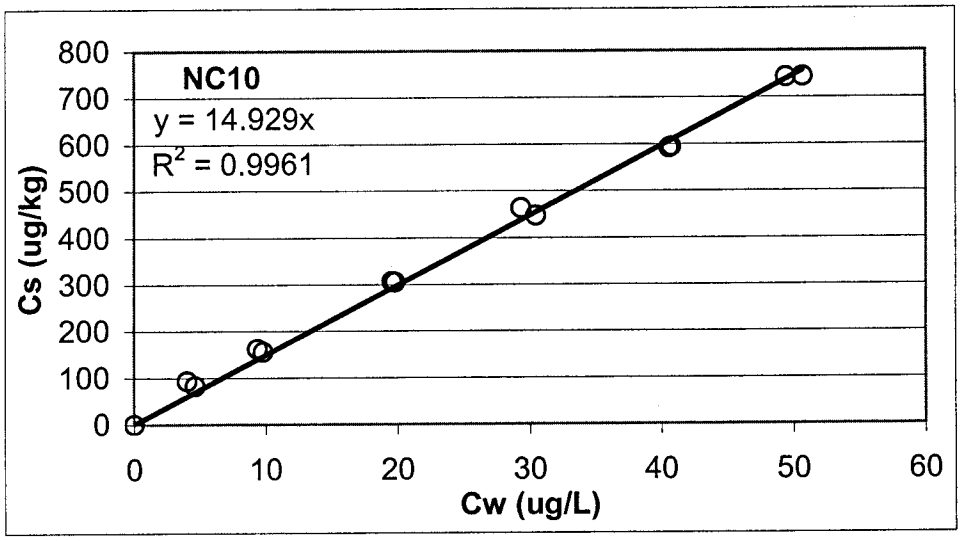


Sample	pH	g	Ci	Cw*	Cs
NC7-20	6.62	3.007	0	0.0	0
NC7-21	6.61	2.953	0	0.0	0
NC7-22	6.56	2.978	10	1.4	136
NC7-23	6.50	3.001	10	1.9	128
NC7-24	6.44	2.974	19	4.2	249
NC7-25	6.40	2.985	19	4.3	247
NC7-26	6.37	3.039	38	8.8	481
NC7-27	6.32	2.977	38	9.2	484
NC7-28	6.30	2.953	57	14.6	720
NC7-29	6.39	3.049	57	15.1	689
NC7-30	6.34	3.014	76	20.7	919
NC7-31	6.30	2.985	76	21.3	919
NC7-32	6.27	2.962	95	25.7	1173
NC7-33	6.25	2.994	95	24.3	1184
Average pH =	6.41				
Std. Dev. =	0.124				



Cadmium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC10-20	5.44	3.017	0	0.0	0
NC10-21	5.29	2.998	0	0.0	0
NC10-22	5.19	2.987	10	4.0	93
NC10-23	5.10	3.013	10	4.6	82
NC10-24	5.06	3	19	9.7	155
NC10-25	4.99	2.995	19	9.3	162
NC10-26	5.00	3	38	19.8	305
NC10-27	5.13	3.012	38	19.6	307
NC10-28	5.03	3.005	57	29.3	463
NC10-29	4.99	2.988	57	30.4	447
NC10-30	4.97	2.976	76	40.7	595
NC10-31	4.97	3.011	76	40.5	591
NC10-32	4.97	3.079	95	49.4	743
NC10-33	4.97	2.984	95	50.7	745
Average pH =	5.08				
Std. Dev. =	0.142				



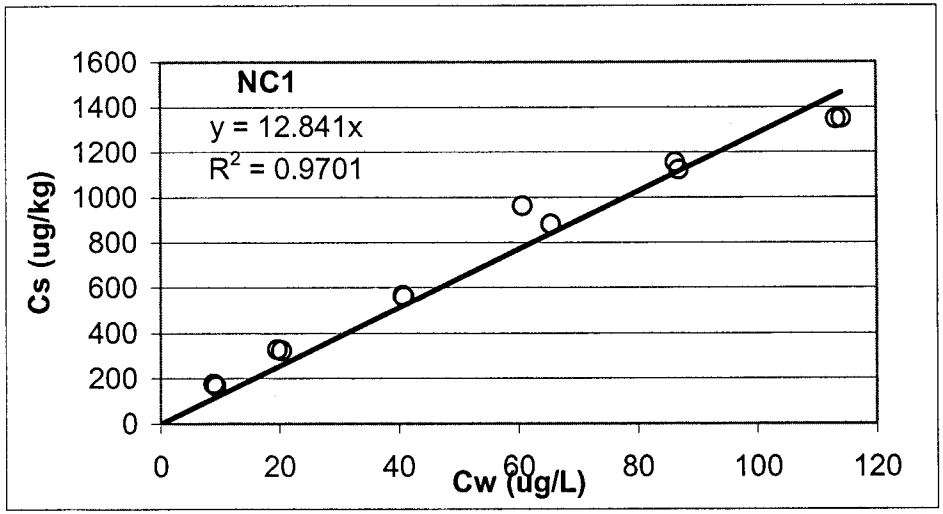
Jan. 24-26, 2001 ICP Analysis
Bellows Creek Soils

Chromium (VI)

Ci (ug/L) = Initial solution concentrations
Cw* (ug/L) = Equilibrium solution concentrations corrected for background
Cs (ug/kg) = Loss to soil calculated by difference: (Ci-Cw*)(V/m)
m = soil mass (kg)
V = solution volume (0.050 L)
n.d. = not determined

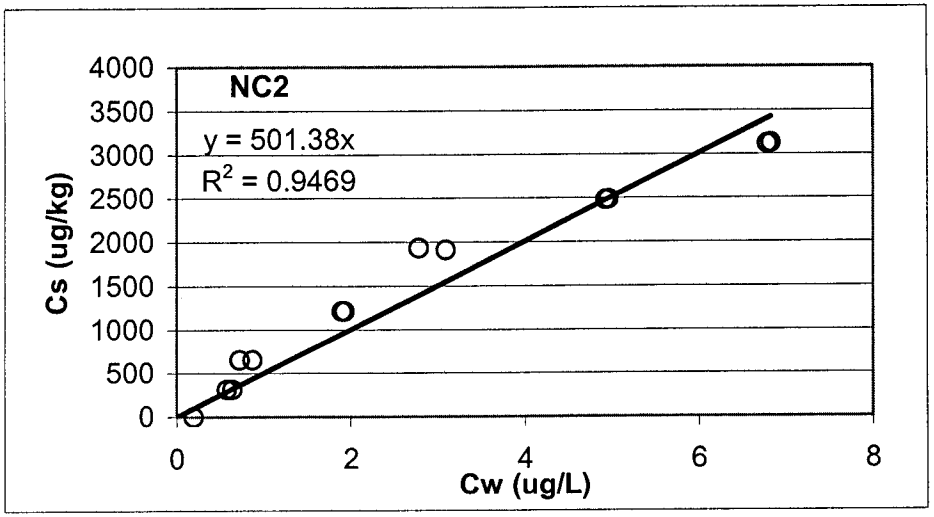
Purdue ID	Duke ID
NC1	BC3 40-50'
NC2	BC3 50-60'
NC3	BC3 0-10'
NC4A	BC6 0-10'
NC4B	BC6 8.8-10.3'
NC5	BC6 10-20'
NC6	BC6 20-24'
NC7	MW-2-1 35-45'
NC8	MW-2-2 30-40'
NC9	MW6 28-38'
NC10	MW6 38-48'

Sample	pH	Soil mass g	Ci	Cw*	Cs
NC1-20	6.81	3	0		n.d.
NC1-21	6.53	2.98	0	0	0
NC1-22	6.40	2.988	19	9	177
NC1-23	6.27	3.061	19	9	166
NC1-24	6.12	2.973	39	20	323
NC1-25	6.06	3.04	39	20	328
NC1-26	5.99	2.995	74	41	564
NC1-27	5.97	3.006	74	41	559
NC1-28	5.95	3.018	119	61	962
NC1-29	5.92	3.032	119	65	881
NC1-30	5.87	3.02	155	87	1121
NC1-31	5.88	2.96	155	86	1155
NC1-32	5.88	3.012	194	113	1348
NC1-33	5.86	2.974	194	114	1350
Average pH =	6.11				
Std. Dev. =	0.291				

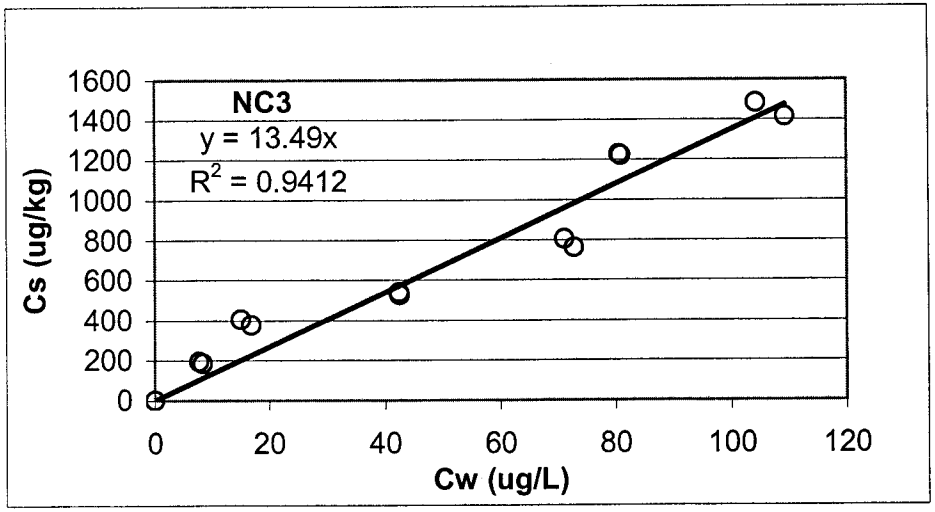


Chromium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC2-20	4.35	2.997	0	0	0
NC2-21	4.35	3.012	0	0	0
NC2-22	4.33	3.001	19	1	315
NC2-23	4.32	3.011	19	1	312
NC2-24	4.30	2.968	39	1	650
NC2-25	4.33	2.974	39	1	651
NC2-26	4.33	2.991	74	2	1212
NC2-27	4.33	2.981	74	2	1215
NC2-28	4.33	3.031	119	3	1909
NC2-29	4.32	3.002	119	3	1932
NC2-30	4.33	3.022	155	5	2478
NC2-31	4.34	3.009	155	5	2488
NC2-32	4.33	3	194	7	3126
NC2-33	4.33	3.01	194	7	3117
Average pH =	4.33				
Std. Dev. =	0.012				

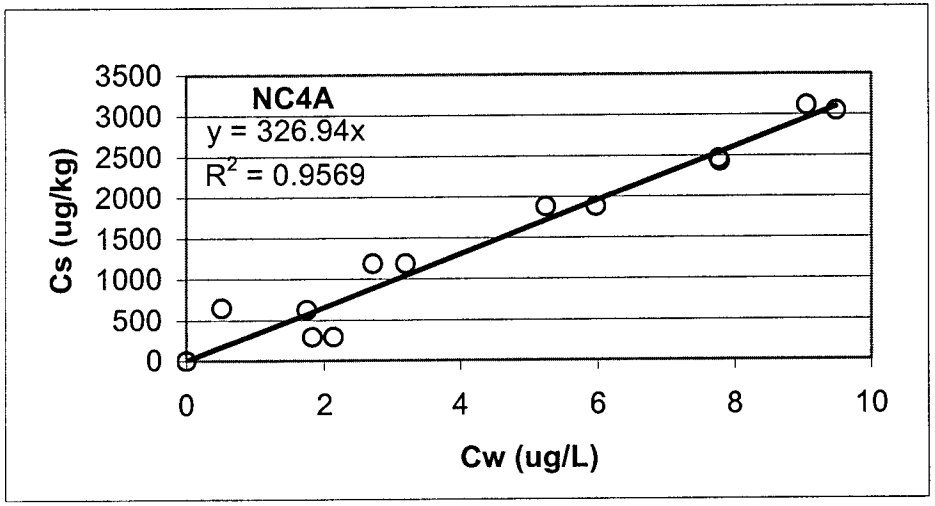


Sample	pH	g	Ci	Cw*	Cs
NC3-20	5.61	2.999	0	0	0
NC3-21	5.75	3.015	0	0	0
NC3-22	5.79	2.993	19	8	186
NC3-23	5.82	3.018	19	8	195
NC3-24	5.84	2.992	39	17	379
NC3-25	5.80	3.015	39	15	405
NC3-26	5.84	2.97	74	42	540
NC3-27	5.86	3.02	74	42	528
NC3-28	5.87	3.023	119	73	761
NC3-29	5.87	2.972	119	71	803
NC3-30	5.82	3.021	155	81	1227
NC3-31	5.85	3.017	155	81	1223
NC3-32	5.87	3.004	194	109	1415
NC3-33	5.89	3.037	194	104	1484
Average pH =	5.82				
Std. Dev. =	0.071				

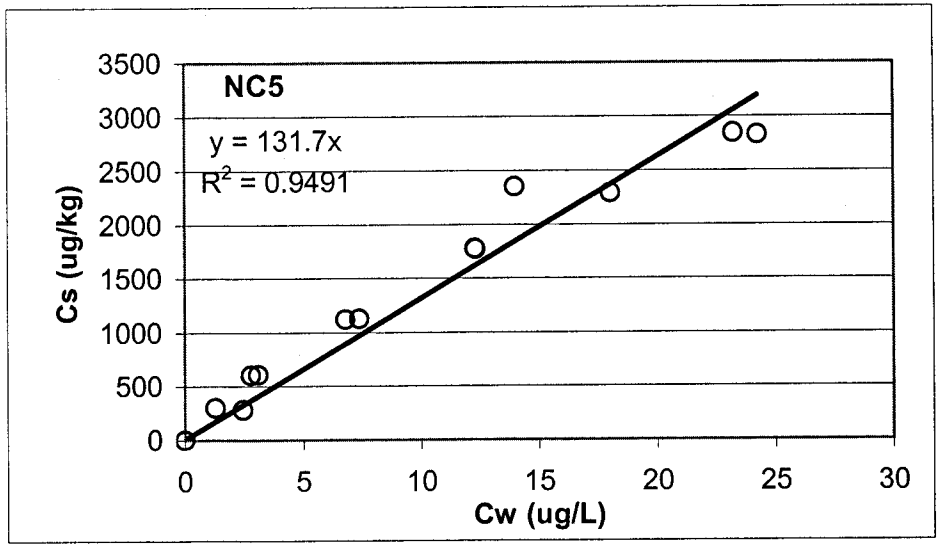


Chromium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC4a-20	4.38	2.992	0	0	0
NC4a-21	4.33	2.99	0	0	0
NC4a-22	4.34	3.033	19	2	291
NC4a-23	4.35	2.983	19	2	290
NC4a-24	4.33	3.008	39	2	627
NC4a-25	4.35	2.997	39	1	650
NC4a-26	4.36	2.992	74	3	1190
NC4a-27	4.35	3.019	74	3	1187
NC4a-28	4.36	2.998	119	6	1882
NC4a-29	4.37	3.017	119	5	1882
NC4a-30	4.37	2.99	155	8	2457
NC4a-31	4.35	3.024	155	8	2429
NC4a-32	4.35	2.975	194	9	3115
NC4a-33	4.35	3.038	194	9	3043
Average pH =	4.35				
Std. Dev. =	0.014				



Sample	pH	g	Ci	Cw*	Cs
NC5-20	4.65	3.019	0	0	0
NC5-21	4.52	2.991	0	0	0
NC5-22	4.50	3.014	19	1	302
NC5-23	4.46	2.988	19	2	285
NC5-24	4.45	2.985	39	3	609
NC5-25	4.43	3.05	39	3	602
NC5-26	4.47	3.011	74	7	1123
NC5-27	4.46	2.961	74	7	1132
NC5-28	4.46	3.005	119	12	1772
NC5-29	4.47	2.994	119	12	1779
NC5-30	4.49	2.987	155	14	2356
NC5-31	4.47	2.985	155	18	2290
NC5-32	4.46	3.007	194	24	2830
NC5-33	4.50	3.009	194	23	2844
Average pH =	4.49				
Std. Dev. =	0.053				

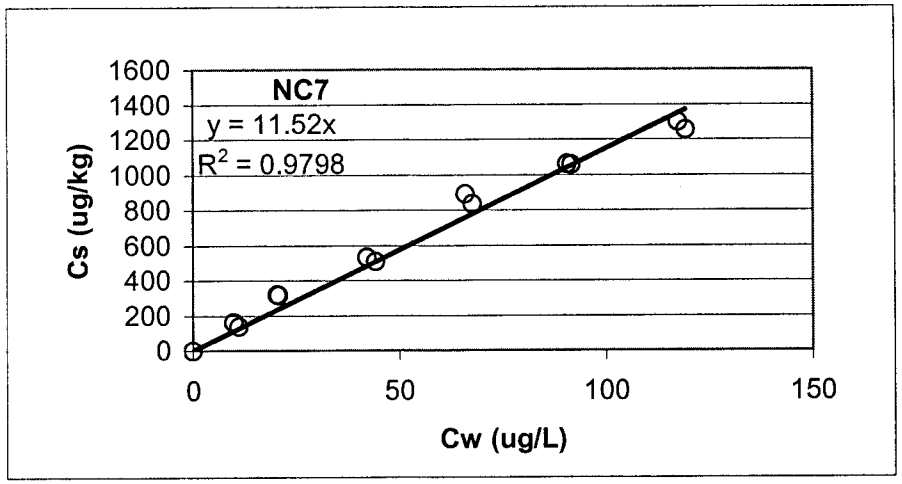


Chromium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC6-20	5.57	2.994	0	0	0
NC6-21	5.60	3.012	0	0	0
NC6-22	5.52	3.029	19	0	321
NC6-23	5.46	3.034	19	0	321
NC6-24	5.41	2.942	39	0	671
NC6-25	5.38	3.025	39	0	652
NC6-26	5.40	3.035	74	0	1226
NC6-27	5.33	2.98	74	0	1248
NC6-28	5.31	2.973	119	0	1998
NC6-29	5.28	2.972	119	0	1999
NC6-30	5.27	3.015	155	0	2566
NC6-31	5.27	3.004	155		2575
NC6-32	5.25	3.023	194	7	3094
NC6-33	5.25	3.023	194	8	3079
Average pH =	5.38				
Std. Dev. =	0.12				

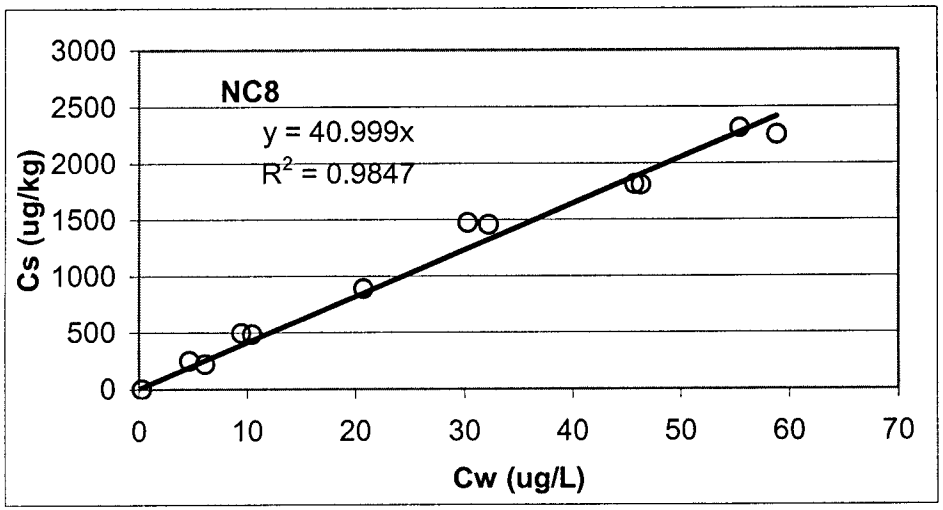
Single Point Kd estimate:
421
373
397 Ave.

Sample	pH	g	Ci	Cw*	Cs
NC7-20	6.62	3.007	0	0	0
NC7-21	6.61	2.953	0	0	0
NC7-22	6.56	2.978	19	10	163
NC7-23	6.50	3.001	19	11	139
NC7-24	6.44	2.974	39	21	316
NC7-25	6.40	2.985	39	20	320
NC7-26	6.37	3.039	74	42	532
NC7-27	6.32	2.977	74	44	508
NC7-28	6.30	2.953	119	66	893
NC7-29	6.39	3.049	119	68	837
NC7-30	6.34	3.014	155	91	1062
NC7-31	6.30	2.985	155	92	1057
NC7-32	6.27	2.962	194	117	1300
NC7-33	6.25	2.994	194	119	1256
Average pH =	6.41				
Std. Dev. =	0.124				

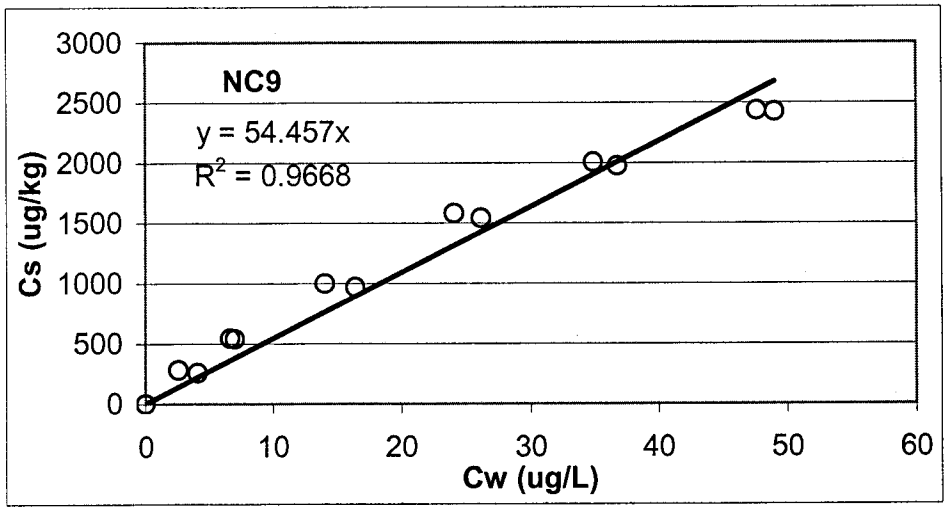


Chromium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC8-20	6.13	2.986	0	0	0
NC8-21	6.06	2.995	0	0	0
NC8-22	5.98	2.993	19	6	223
NC8-23	5.91	3.007	19	5	246
NC8-24	5.90	2.983	39	10	486
NC8-25	5.81	3.011	39	9	498
NC8-26	5.79	3.004	74	21	893
NC8-27	5.72	3.014	74	21	890
NC8-28	5.72	3.013	119	30	1469
NC8-29	5.70	2.976	119	32	1455
NC8-30	5.68	3.013	155	46	1809
NC8-31	5.72	3.008	155	46	1802
NC8-32	5.69	3.01	194	55	2310
NC8-33	5.80	3.012	194	59	2251
Average pH =	5.83				
Std. Dev. =	0.145				

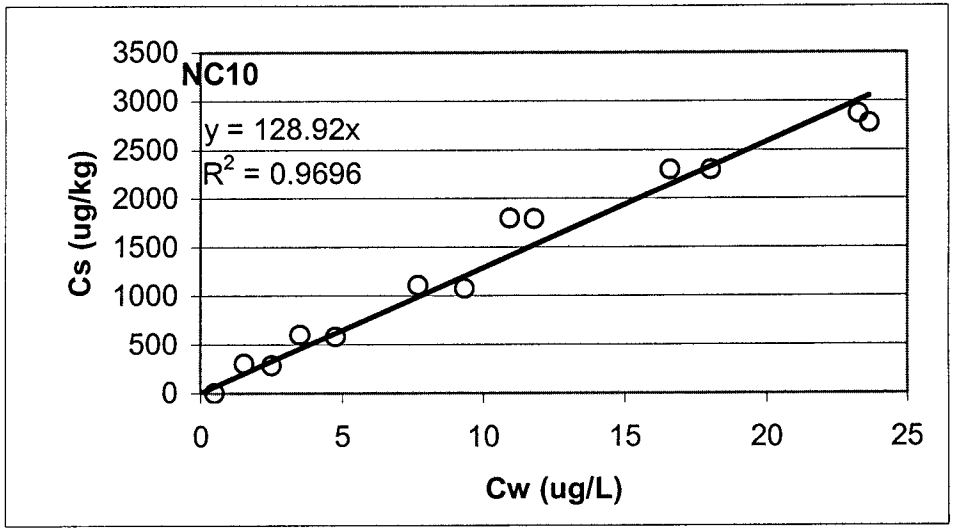


Sample	pH	g	Ci	Cw*	Cs
NC9-20	5.78	2.989	0	0	0
NC9-21	5.09	3.016	0	0	0
NC9-22	5.06	3.004	19	3	281
NC9-23	5.07	2.996	19	4	257
NC9-24	5.05	3.002	39	7	547
NC9-25	5.03	2.998	39	7	541
NC9-26	5.03	3.011	74	14	1002
NC9-27	5.04	2.983	74	16	972
NC9-28	5.02	2.993	119	24	1583
NC9-29	5.04	3.008	119	26	1540
NC9-30	5.02	2.988	155	37	1973
NC9-31	5.03	2.986	155	35	2006
NC9-32	5.00	3.013	194	48	2435
NC9-33	5.00	3	194	49	2423
Average pH =	5.09				
Std. Dev. =	0.2				



Chromium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC10-20	5.44	3.017	0	0	0
NC10-21	5.29	2.998	0	0	0
NC10-22	5.19	2.987	19	2	300
NC10-23	5.10	3.013	19	3	281
NC10-24	5.06	3	39	4	599
NC10-25	4.99	2.995	39	5	579
NC10-26	5.00	3	74	8	1112
NC10-27	5.13	3.012	74	9	1080
NC10-28	5.03	3.005	119	11	1795
NC10-29	4.99	2.988	119	12	1790
NC10-30	4.97	2.976	155	18	2296
NC10-31	4.97	3.011	155	17	2294
NC10-32	4.97	3.079	194	24	2773
NC10-33	4.97	2.984	194	23	2868
Average pH =	5.08				
Std. Dev. =	0.142				



Iron (III)

Jan. 29, 2001 AA Analysis
Bellows Creek Soils

Ci (ug/L) = Initial solution concentrations
Cw (ug/L) = Concentration measured at equilibrium

n.d. = not determined

Purdue ID	Duke ID
NC1	BC3 40-50'
NC2	BC3 50-60'
NC3	BC3 0-10'
NC4A	BC6 0-10'
NC4B	BC6 8.8-10.3'
NC5	BC6 10-20'
NC6	BC6 20-24'
NC7	MW-2-1 35-45'
NC8	MW-2-2 30-40'
NC9	MW6 28-38'
NC10	MW6 38-48'

Sample ID	pH	Soil mass (g)	Ci	Cw		
NC1-40		2.985			**Average**	**SD**
NC1-41	6.34	2.915	0	340	404	184
NC1-42	6.29	3.011	240	770		
NC1-43	6.16	3.093	240	445		
NC1-44	6.05	3.095	480	405		
NC1-45	5.95	2.946	480	150		
NC1-46	5.89	2.983	960	360		
NC1-47	5.81	2.984	960	485		
NC1-48	5.76	3.025	1200	180		
NC1-49	5.80	2.929	1200	500		
Average pH =	6.01					
Std. Dev. =	0.22					
NC2-41	4.36	2.964	0	270	**Average**	**SD**
NC2-42	4.34	2.929	240	135	207	64
NC2-43	4.34	3.07	240	220		
NC2-44	4.30	3.032	480	90		
NC2-45	4.31	2.961	480	215		
NC2-46	4.30	3.005	**960**	**265**		
NC2-47	4.28	3.031	960	170		
NC2-48	4.29	3.031	1200	275		
NC2-49	4.27	3.026	1200	220		
Average pH =	4.31					
Std. Dev. =	0.03					

Iron (continued)

Sample ID	pH	(g)	Ci	Cw		
NC3-41	5.60	3.079	0	175	**Average**	**SD**
NC3-42	5.68	2.962	240	335	223	69
NC3-43	5.71	2.955	240	285		
NC3-44	5.75	2.995	480	160		
NC3-45	5.68	2.995	480	155		
NC3-46	5.67	3.004	960	285		
NC3-47	5.66	2.991	960	245		
NC3-48	5.68	3.084	1200	220		
NC3-49	5.81	2.925	1200	145		
Average pH =	5.69					
Std. Dev. =	0.06					
NC4A-41	4.42	2.95	0	180	**Average**	**SD**
NC4A-42	4.40	3.016	240	250	270	94
NC4A-43	4.38	2.94	240	185		
NC4A-44	4.37	3.098	**480**	**240**		
NC4A-45	4.36	3.001	480	350		
NC4A-46	4.36	3.078	960	200		
NC4A-47	4.36	3.054	960	230		
NC4A-48	4.34	2.963	1200	330		
NC4A-49	4.38	3.095	1200	465		
Average pH =	4.37					
Std. Dev. =	0.02					
NC5-41	4.47	2.994	0	225	**Average**	**SD**
NC5-42	4.49	2.931	240	175	344	280
NC5-43	4.48	2.992	240	235		
NC5-44	4.47	2.929	480	200		
NC5-45	4.46	3.002	480	230		
NC5-46	4.45	2.996	960	1055		
NC5-47	4.45	3.028	960	225		
NC5-48	4.43	3.003	1200	470		
NC5-49	4.49	2.94	1200	285		
Average pH =	4.47					
Std. Dev. =	0.02					

Iron (continued)

Sample ID	pH	(g)	**Ci**	**Cw**		
NC6-41	5.19	2.942	0	355	**Average**	**SD**
NC6-42	5.22	3.034	**240**	**465**	368	144
NC6-43	5.23	3.007	240	255		
NC6-44	5.22	3.032	480	440		
NC6-45	5.13	3.087	480	385		
NC6-46	5.13	2.983	960	165		
NC6-47	5.11	2.943	960	275		
NC6-48	5.08	3.045	1200	660		
NC6-49	5.17	3.05	1200	315		
Average pH =	5.16					
Std. Dev. =	0.05					
NC7-41	5.78	3.044	0	260	**Average**	**SD**
NC7-42	5.82	3.075	240	240	204	51
NC7-43	5.84	2.966	240	285		
NC7-44	5.83	3.051	480	150		
NC7-45	5.84	2.953	480	145		
NC7-46	5.83	2.96	960	180		
NC7-47	5.81	3.06	960	155		
NC7-48	5.80	3.052	1200	200		
NC7-49	5.90	3.051	1200	225		
Average pH =	5.83					
Std. Dev. =	0.03					
NC8-41	5.65	2.999	0	180	**Average**	**SD**
NC8-42	5.62	3.034	240	265	249	91
NC8-43	5.57	3.042	240	155		
NC8-44	5.57	2.94	480	275		
NC8-45	5.51	2.978	480	120		
NC8-46	5.42	3.036	960	330		
NC8-47	5.44	2.947	960	350		
NC8-48	5.43	2.994	1200	375		
NC8-49	5.50	3.033	1200	195		
Average pH =	5.52					
Std. Dev. =	0.08					

Iron (continued)

Sample ID	pH	(g)	**Ci**	**Cw**		
NC9-41	5.19	2.942	0	355	**Average**	**SD**
NC9-42	5.05	2.964	240	175	144	110
NC9-43	5.01	3.001	240	30		
NC9-44	4.98	2.981	480	80		
NC9-45	4.94	2.94	480	195		
NC9-46	4.92	2.99	960	110		
NC9-47	4.89	3.006	960	20		
NC9-48	4.87	3.018	1200	250		
NC9-49	4.97	2.962	1200	85		
Average pH =	4.98					
Std. Dev. =	0.10					
NC10-41	4.91	3.011	0	630	**Average**	**SD**
NC10-42	4.94	3.035	240	365	207	188
NC10-43	4.92	3.016	240	150		
NC10-44	4.92	3.056	480	65		
NC10-45	4.89	2.982	480	240		
NC10-46	4.90	2.996	960	100		
NC10-47	4.89	2.937	960	100		
NC10-48	4.87	3.082	1200	175		
NC10-49	4.93	2.976	1200	35		
Average pH =	4.91					
Std. Dev. =	0.02					

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Manganese (II)

Ci (ug/L) = Initial solution concentrations
Cw (ug/L) = Concentration measured at equilibrium

n.d. = not determined

Purdue ID	Duke ID
NC1	BC3 40-50'
NC2	BC3 50-60'
NC3	BC3 0-10'
NC4A	BC6 0-10'
NC4B	BC6 8.8-10.3'
NC5	BC6 10-20'
NC6	BC6 20-24'
NC7	MW-2-1 35-45'
NC8	MW-2-2 30-40'
NC9	MW6 28-38'
NC10	MW6 38-48'

Sample	pH	Soil mass g	**Ci**	**Cw**
NC1-20	6.62	3.017	7	1147
NC1-21	6.19	2.99	24	1187
NC1-22	6.14	3.062	49	1172
NC1-23	6.13	3.087	87	1233
NC1-24	6.04	3.024	122	1308
NC1-25	5.98	2.969	167	1316
NC1-26	5.95	2.963	224	1333
NC1-27	6.23	2.996	5	1224
NC1-28	6.17	3.077	18	1218
NC1-29	6.1	3.057	57	1244
NC1-30	6.04	2.932	105	1272
NC1-31	5.99	2.983	157	1301
NC1-32	5.98	3.026	209	1452
NC1-33	5.96	2.984	250	1436
Average pH =	6.11			
Std. Dev. =	0.174			

Average	**SD**
1275	91

Manganese (continued)

Sample	pH	g	Ci	Cw	Average	SD
NC2-20	4.34	3.076	5	609	662	111
NC2-21	4.31	2.934	18	554		
NC2-22	4.31	2.947	57	581		
NC2-23	4.3	3.071	105	664		
NC2-24	4.3	2.999	157	711		
NC2-25	4.31	3.039	209	784		
NC2-26	4.34	3.057	250	832		
NC2-27	4.31	2.912	5	499		
NC2-28	4.29	2.923	18	536		
NC2-29	4.3	2.977	57	565		
NC2-30	4.29	3.051	105	636		
NC2-31	4.28	3.037	157	685		
NC2-32	4.29	2.988	209	775		
NC2-33	4.28	3.059	250	831		
Average pH =	4.30					
Std. Dev. =	0.019					

Sample	pH	g	Ci	Cw	Average	SD
NC3-20	4.31	3.01	7	550	635	96
NC3-21	4.32	3.003	24	563		
NC3-22	4.29	2.992	49	563		
NC3-23	4.3	2.959	87	605		
NC3-24	4.31	2.9457	122	685		
NC3-25	4.33	3.037	167	744		
NC3-26	4.31	3.0141	224	809		
NC3-27	4.32	2.756	7	503		
NC3-28	4.28	3.044	24	558		
NC3-29	4.3	2.715	49	534		
NC3-30	4.42	2.903	87	637		
NC3-31	4.32	2.966	122	673		
NC3-32	4.35	2.73	167	710		
NC3-33	4.3	2.917	224	761		
Average pH =	4.32					
Std. Dev. =	0.034					

Manganese (continued)

Sample	pH	g	**Ci**	**Cw**
NC4a-20	4.36	3.025	7	694
NC4a-21	4.36	3.015	24	744
NC4a-22	4.37	2.9885	49	770
NC4a-23	4.37	3.2434	87	846
NC4a-24	4.38	2.8647	122	820
NC4a-25	4.36	3.228	167	931
NC4a-26	4.38	3.2029	224	974
NC4a-27	4.35	3.034	7	705
NC4a-28	4.34	3.028	24	722
NC4a-29	4.34	3.007	49	782
NC4a-30	4.33	3.01	87	789
NC4a-31	4.33	2.995	122	832
NC4a-32	4.34	3.037	167	910
NC4a-33	4.34	3.034	224	963
Average pH =	4.35			
Std. Dev. =	0.017			

Sample	pH	g	**Ci**	**Cw**
NC5-20	4.47	3.071	5	1164
NC5-21	4.47	2.978	18	1225
NC5-22	4.47	2.995	57	1243
NC5-23	4.48	2.989	105	1296
NC5-24	4.48	2.9211	157	1306
NC5-25	4.48	3.0876	209	1423
NC5-26	4.45	3.0088	250	1463
NC5-27	4.43	3.018	5	1196
NC5-28	4.43	2.938	18	1194
NC5-29	4.45	3.002	57	1224
NC5-30	4.44	3.054	105	1290
NC5-31	4.44	2.948	157	1334
NC5-32	4.44	3.025	209	1398
NC5-33	4.45	2.951	250	1441
Average pH =	4.46			
Std. Dev. =	0.019			

Average	**SD**
1300	99

Manganese (continued)

Sample	pH	g	Ci	Cw
NC6-20	5.14	3.043	5	1498
NC6-21	5.03	3.2441	18	1616
NC6-22	5.19	2.9761	57	1631
NC6-23	5.18	3.2351	105	1666
NC6-24	5.22	3.0626	157	1778
NC6-25	5.27	3.0105	209	1758
NC6-26	5.24	3.1158	250	1684
NC6-27	5.2	3.006	5	1464
NC6-28	5.77	3.064	18	1349
NC6-29	5.28	3.026	57	1604
NC6-30	5.24	3.016	105	1553
NC6-31	5.26	3.057	157	1731
NC6-32	5.24	3.023	209	1671
NC6-33	5.17	3.051	250	1726
Average pH =	5.25			
Std. Dev. =	0.164			

Average	SD
1624	122

Sample	pH	g	Ci	Cw
NC7-20	5.96	2.98	5	1587
NC7-21	5.88	3.427	18	1759
NC7-22	5.97	3.1551	57	1725
NC7-23	6.02	2.8303	105	1604
NC7-24	6.05	3.0191	157	1748
NC7-25	6.06	2.9803	209	1721
NC7-26	6	3.0963	250	1847
NC7-27	6.05	3.02	5	1605
NC7-28	6.07	2.967	18	1592
NC7-29	6.06	2.93	57	1600
NC7-30	6.07	2.982	105	1635
NC7-31	6.14	2.966	157	1626
NC7-32	6.16	3.046	209	1799
NC7-33	6.05	2.946	250	1748
Average pH =	6.04			
Std. Dev. =	0.071			

Average	SD
1685	88

Manganese (continued)

Sample	pH	g	Ci	Cw	Average	SD
NC8-20	5.68	3.057	5	2145	2207	81
NC8-21	5.48	2.997	18	2113		
NC8-22	5.51	3.033	57	2192		
NC8-23	5.55	3.128	105	2220		
NC8-24	5.58	3.014	157	2203		
NC8-25	5.6	2.986	209	2228		
NC8-26	n.d.	3.127	250	n.d.		
NC8-27	5.6	2.953	5	2133		
NC8-28	5.6	2.983	18	2125		
NC8-29	5.59	3.032	57	2176		
NC8-30	5.58	3.043	105	2241		
NC8-31	5.58	3.024	157	2366		
NC8-32	5.6	2.952	209	2345		
NC8-33	5.66	2.989	250			
Average pH =	5.59					
Std. Dev. =	0.053					

Sample	pH	g	Ci	Cw	Average	SD
NC9-20	5.05	3.073	5	2041	2196	91
NC9-21	5.36	2.98	18	2131		
NC9-22	5.06	2.984	57	2154		
NC9-23	5.04	2.962	105	2184		
NC9-24	5.05	2.9541	157	2193		
NC9-25	5.14	2.9594	209	2357		
NC9-26	5.11	3.0172	250	2314		
NC9-27	5.02	3.032	5	2116		
NC9-28	5.17	2.997	18	2091		
NC9-29	5.03	2.975	57	2147		
NC9-30	5.02	3.014	105	2221		
NC9-31	5.04	2.989	157	2229		
NC9-32	5.04	2.927	209	2291		
NC9-33	5.14	3.001	250	2279		
Average pH =	5.09					
Std. Dev. =	0.092					

Manganese (continued)

Sample	pH	g	**Ci**	**Cw**
NC10-20	4.94	2.971	5	2852
NC10-21	5.13	2.997	18	3113
NC10-22	5.02	3.018	57	3176
NC10-23	5.1	3.016	105	3120
NC10-24	5.05	3.0654	157	3151
NC10-25	5.02	3.102	209	3134
NC10-26	5.01	3.1042	250	3318
NC10-27	4.94	3.087	5	3134
NC10-28	4.95	3.124	18	3168
NC10-29	4.95	3.04	57	3142
NC10-30	4.95	2.942	105	3070
NC10-31	4.94	2.956	157	3194
NC10-32	4.96	3.003	209	3272
NC10-33	4.95	3.085	250	3424
Average pH =	4.99			
Std. Dev. =	0.063			

Average	**SD**
3162	129

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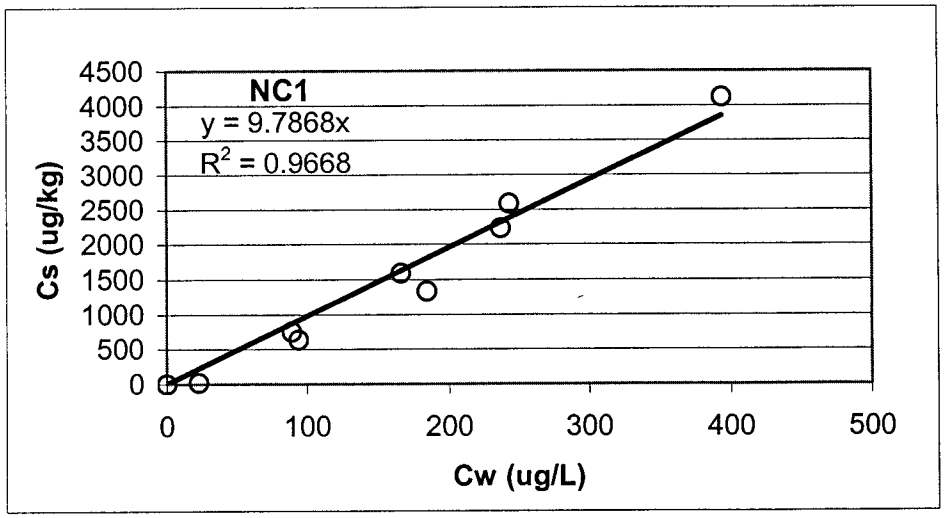
Selenium (VI)

Ci (ug/L) = Initial solution concentrations after matrix correction
Cw* (ug/L) = Equilibrium solution concentrations corrected for background
Cs (ug/kg) = Loss to soil calculated by difference: (Ci-Cw*)(V/m)
m = soil mass (kg)
V = solution volume (0.050 L)
n.d. = not determined
Blank cells = bad data

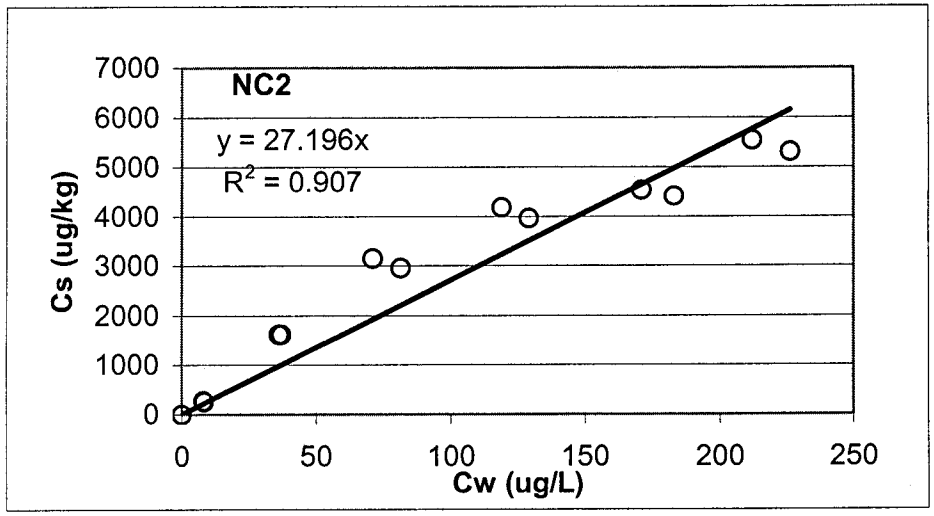
Purdue ID	Duke ID
NC1	BC3 40-50'
NC2	BC3 50-60'
NC3	BC3 0-10'
NC4A	BC6 0-10'
NC4B	BC6 8.8-10.3'
NC5	BC6 10-20'
NC6	BC6 20-24'
NC7	MW-2-1 35-45'
NC8	MW-2-2 30-40'
NC9	MW6 28-38'
NC10	MW6 38-48'

Sample	pH	Soil mass g	Ci	Cw*	Cs
NC1-20	6.62	3.017	0	0	0
NC1-21	6.19	2.99	26		
NC1-22	6.14	3.062	135	89	754
NC1-23	6.13	3.087	264	166	1590
NC1-24	6.04	3.024	399	243	2582
NC1-25	5.98	2.969	618		
NC1-26	5.95	2.963	638	394	4120
NC1-27	6.23	2.996	0	0	0
NC1-28	6.17	3.077	24	23	17
NC1-29	6.1	3.057	132	94	634
NC1-30	6.04	2.932	263	185	1334
NC1-31	5.99	2.983	370	237	2232
NC1-32	5.98	3.026	447		
NC1-33	5.96	2.984	551		
Average pH =	6.11				
Std. Dev. =	0.174				

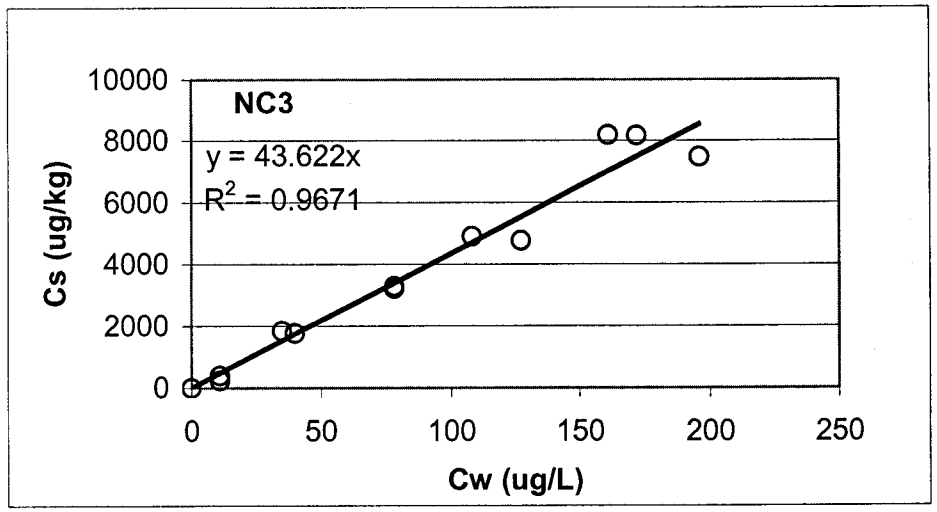


Selenium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC2-20	4.34	3.076	0	0	0
NC2-21	4.31	2.934	24	8	260
NC2-22	4.31	2.947	132	37	1617
NC2-23	4.3	3.071	263	81	2957
NC2-24	4.3	2.999	370	119	4180
NC2-25	4.31	3.039	447	171	4536
NC2-26	4.34	3.057	551	212	5540
NC2-27	4.31	2.912	0	0	0
NC2-28	4.29	2.923	24	8	265
NC2-29	4.3	2.977	132	36	1616
NC2-30	4.29	3.051	263	71	3146
NC2-31	4.28	3.037	370	129	3960
NC2-32	4.29	2.988	447	183	4410
NC2-33	4.28	3.059	551	226	5305
Average pH =	4.30				
Std. Dev. =	0.019				

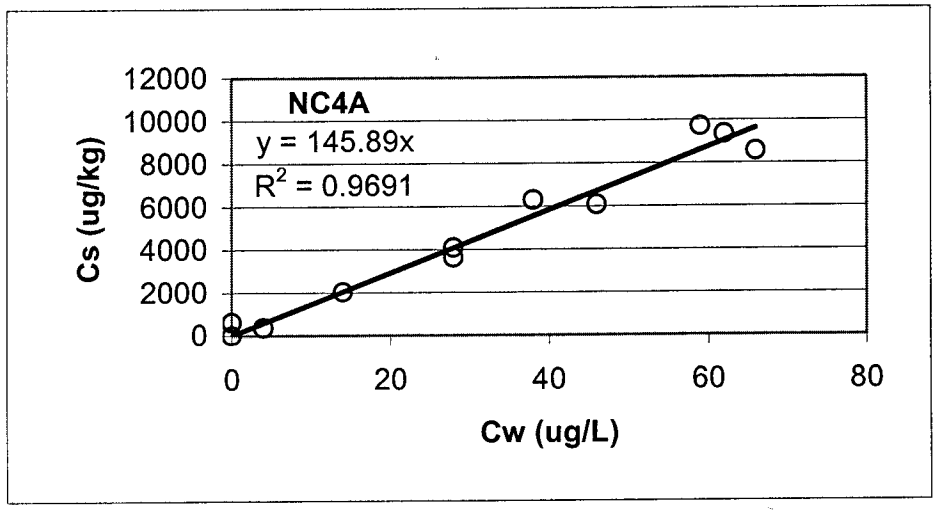


Sample	pH	g	Ci	Cw*	Cs
NC3-20	4.31	3.01	0	0	0
NC3-21	4.32	3.003	26	11	398
NC3-22	4.29	2.992	135	35	1825
NC3-23	4.3	2.959	264	78	3298
NC3-24	4.31	2.9457	399	127	4773
NC3-25	4.33	3.037	618		
NC3-26	4.31	3.0141	638	196	7484
NC3-27	4.32	2.756	0	0	0
NC3-28	4.28	3.044	26	11	244
NC3-29	4.3	2.715	135	40	1753
NC3-30	4.42	2.903	264	78	3207
NC3-31	4.32	2.966	399	108	4909
NC3-32	4.35	2.73	618	172	8172
NC3-33	4.3	2.917	638	161	8179
Average pH =	4.32				
Std. Dev. =	0.034				

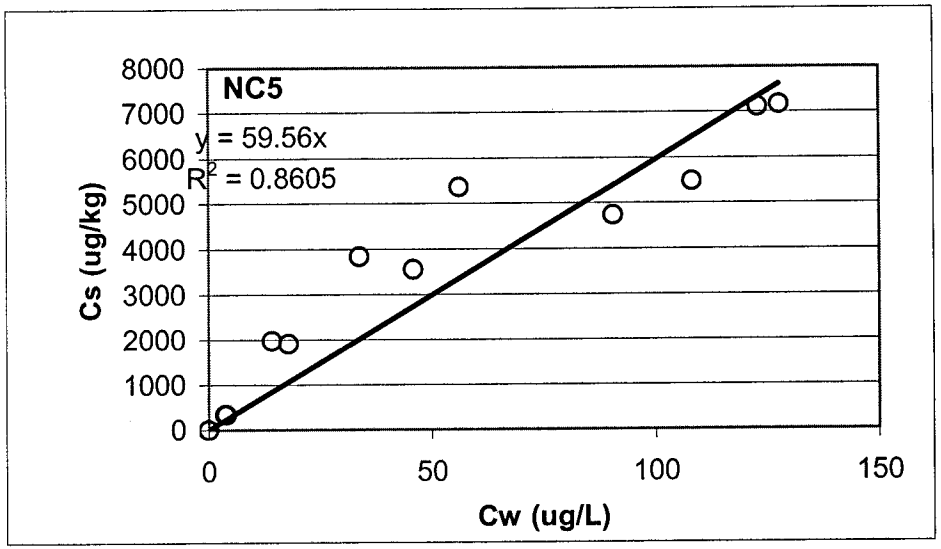


Selenium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC4a-20	4.36	3.025	0	0	0
NC4a-21	4.36	3.015	26	4	363
NC4a-22	4.37	2.9885	135	14	2027
NC4a-23	4.37	3.2434	264	28	3641
NC4a-24	4.38	2.8647	399	38	6304
NC4a-25	4.36	3.228	618	66	8553
NC4a-26	4.38	3.2029	638		
NC4a-27	4.35	3.034	0		
NC4a-28	4.34	3.028	26	0	609
NC4a-29	4.34	3.007	135		
NC4a-30	4.33	3.01	264	28	4106
NC4a-31	4.33	2.995	399	46	6080
NC4a-32	4.34	3.037	618	62	9338
NC4a-33	4.34	3.034	638	59	9726
Average pH =	4.35				
Std. Dev. =	0.017				

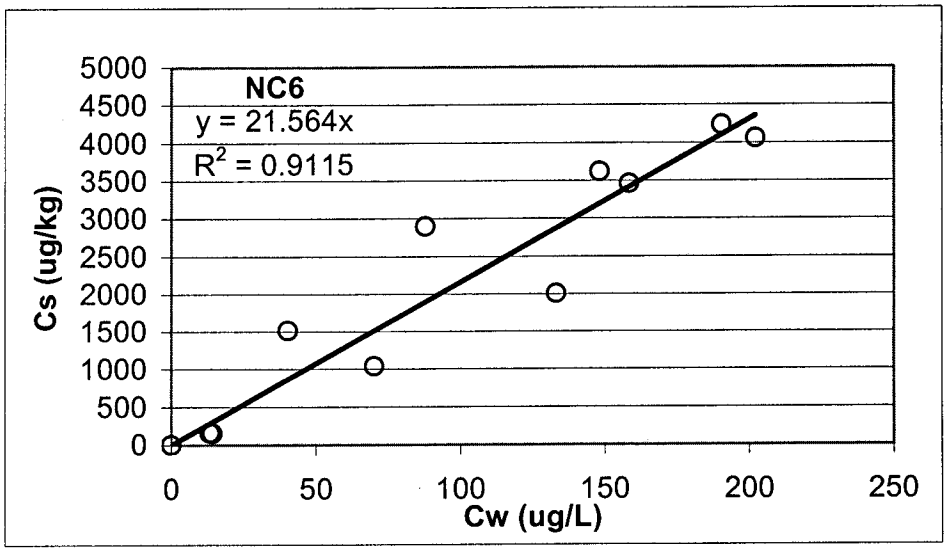


Sample	pH	g	Ci	Cw*	Cs
NC5-20	4.47	3.071	0	0	0
NC5-21	4.47	2.978	24	4	334
NC5-22	4.47	2.995	132	14	1972
NC5-23	4.48	2.989	263	34	3832
NC5-24	4.48	2.9211	370	56	5368
NC5-25	4.48	3.0876	447	108	5483
NC5-26	4.45	3.0088	551	123	7107
NC5-27	4.43	3.018	0	0	0
NC5-28	4.43	2.938	24	4	335
NC5-29	4.45	3.002	132	18	1908
NC5-30	4.44	3.054	263	46	3552
NC5-31	4.44	2.948	370	90	4736
NC5-32	4.44	3.025	447		
NC5-33	4.45	2.951	551	128	7168
Average pH =	4.46				
Std. Dev. =	0.019				

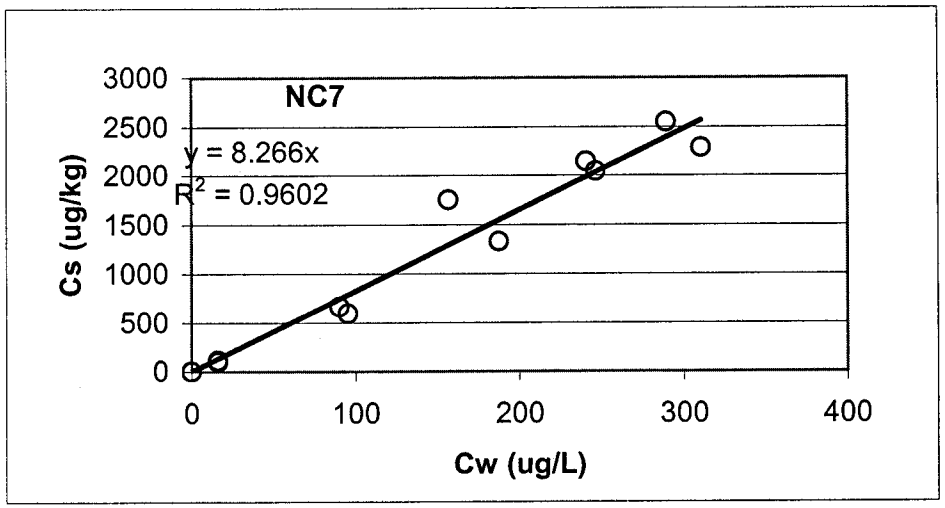


Selenium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC6-20	5.14	3.043	0	0	0
NC6-21	5.03	3.2441	24	13	160
NC6-22	5.19	2.9761	132	70	1043
NC6-23	5.18	3.2351	263	133	2006
NC6-24	5.22	3.0626	370	148	3619
NC6-25	5.27	3.0105	447	202	4064
NC6-26	5.24	3.1158	551		
NC6-27	5.2	3.006	0	0	0
NC6-28	5.77	3.064	24	14	156
NC6-29	5.28	3.026	132	40	1518
NC6-30	5.24	3.016	263	88	2900
NC6-31	5.26	3.057	370	158	3457
NC6-32	5.24	3.023	447	190	4240
NC6-33	5.17	3.051	551		
Average pH =	5.25				
Std. Dev. =	0.164				

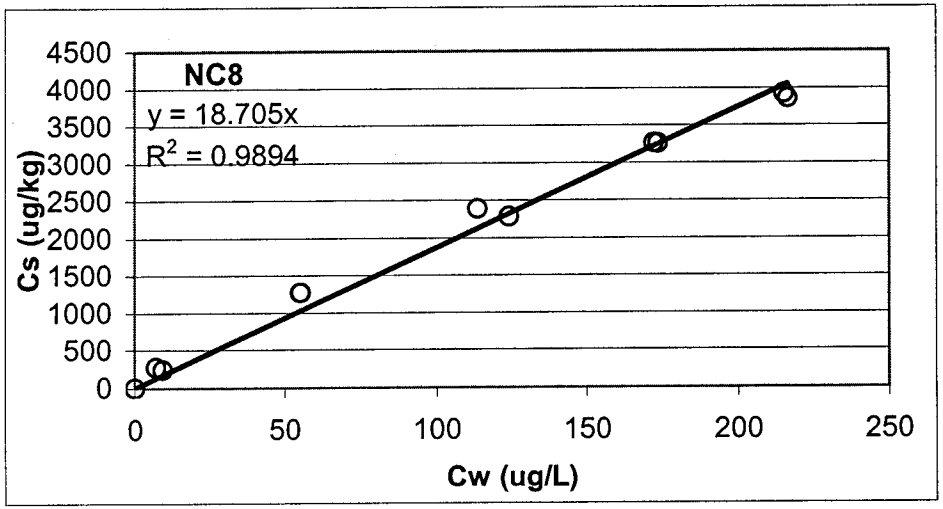


Sample	pH	g	Ci	Cw*	Cs
NC7-20	5.96	2.98	0	0	0
NC7-21	5.88	3.427	24	16	114
NC7-22	5.97	3.1551	132	90	666
NC7-23	6.02	2.8303	263	187	1331
NC7-24	6.05	3.0191	370	246	2041
NC7-25	6.06	2.9803	447	310	2285
NC7-26	6	3.0963	551		
NC7-27	6.05	3.02	0	0	0
NC7-28	6.07	2.967	24	16	98
NC7-29	6.06	2.93	132	95	595
NC7-30	6.07	2.982	263	156	1749
NC7-31	6.14	2.966	370	240	2145
NC7-32	6.16	3.046	447	289	2548
NC7-33	6.05	2.946	551		
Average pH =	6.04				
Std. Dev. =	0.071				

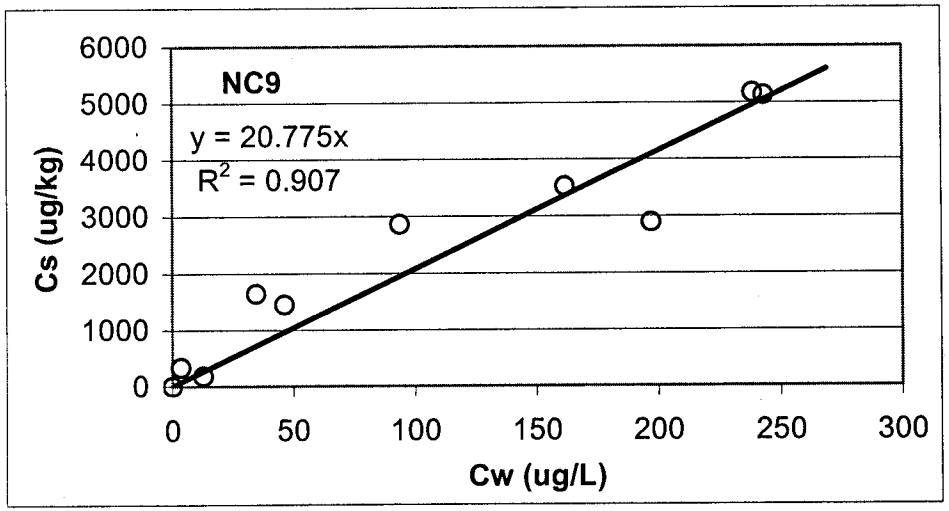


Selenium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC8-20	5.68	3.057	0	0	0
NC8-21	5.48	2.997	24	9	241
NC8-22	5.51	3.033	132	55	1276
NC8-23	5.55	3.128	263	113	2387
NC8-24	5.58	3.014	370	173	3255
NC8-25	5.6	2.986	447	216	3855
NC8-26	n.d.	3.127	551		
NC8-27	5.6	2.953	0	0	0
NC8-28	5.6	2.983	24	7	277
NC8-29	5.59	3.032	132	55	1273
NC8-30	5.58	3.043	263	124	2279
NC8-31	5.58	3.024	370	172	3267
NC8-32	5.6	2.952	447	215	3923
NC8-33	5.66	2.989	551		
Average pH =	5.59				
Std. Dev. =	0.053				

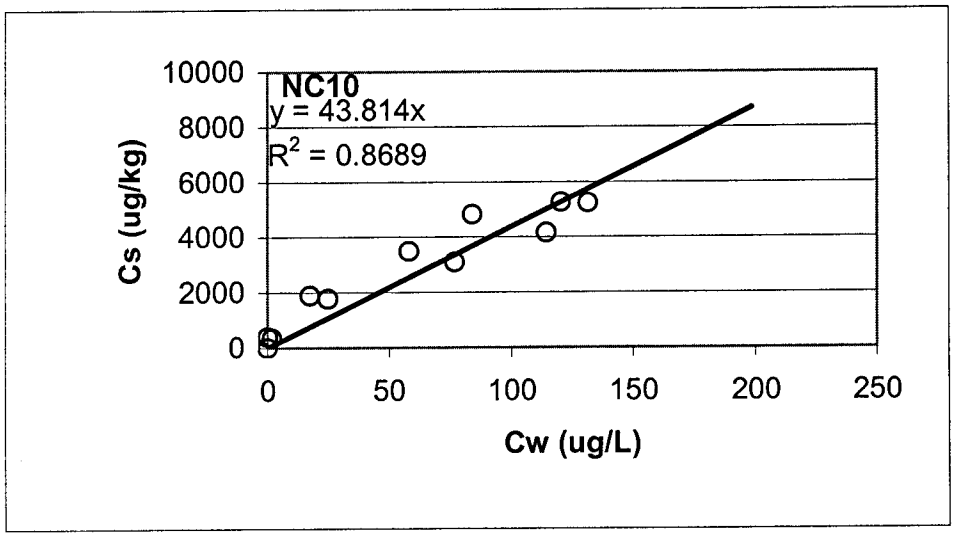


Sample	pH	g	Ci	Cw*	Cs
NC9-20	5.05	3.073	0	0	0
NC9-21	5.36	2.98	24	3	338
NC9-22	5.06	2.984	132	34	1639
NC9-23	5.04	2.962	263	93	2858
NC9-24	5.05	2.9541	370	161	3524
NC9-25	5.14	2.9594	447	253	
NC9-26	5.11	3.0172	551	238	5174
NC9-27	5.02	3.032	0	0	0
NC9-28	5.17	2.997	24	13	179
NC9-29	5.03	2.975	132	46	1446
NC9-30	5.02	3.014	263	56	
NC9-31	5.04	2.989	370	197	2888
NC9-32	5.04	2.927	447	269	
NC9-33	5.14	3.001	551	243	5125
Average pH =	5.09				
Std. Dev. =	0.092				



Selenium (continued)

Sample	pH	g	Ci	Cw*	Cs
NC10-20	4.94	2.971	0	0	
NC10-21	5.13	2.997	24	0	392
NC10-22	5.02	3.018	132	25	1781
NC10-23	5.1	3.016	263	77	3086
NC10-24	5.05	3.0654	370	114	4163
NC10-25	5.02	3.102	447	120	5258
NC10-26	5.01	3.1042	551	183	
NC10-27	4.94	3.087	0	0	0
NC10-28	4.95	3.124	24	2	349
NC10-29	4.95	3.04	132	17	1890
NC10-30	4.95	2.942	263	58	3479
NC10-31	4.94	2.956	370	84	4833
NC10-32	4.96	3.003	447	131	5248
NC10-33	4.95	3.085	551	198	
Average pH =	4.99				
Std. Dev. =	0.063				



Appendix 3

Appendix 3

Soil Sample Laboratory Report
Belews Creek Ash Landfill
S&ME Project 1264-00-157
December 4, 2001

S&ME

December 4, 2001

Mr. William M. Miller, P.E.
Senior Engineer
Duke Power – Mail Code EC12ZB
Post Office Box 1006
Charlotte, North Carolina 28201-1006

Reference: **SOIL SAMPLE LABORATORY REPORT**
Belew's Creek Ash Landfill
Belews Creek, North Carolina
S&ME Project 1264-00-157

Dear Mr. Miller:

S&ME, Inc. is pleased to present you this report of the soil sample testing conducted for the Belews Creek Ash Landfill associated with the Belews Creek Steam Station in Belews Creek North Carolina. You will find this report consists of Table 1, *Laboratory Data Summary for Undisturbed Samples*, followed by the individual test reports for those samples, and Table 2, *Laboratory Data Summary of Bulk and Split-Spoon Samples*, followed by the individual test report for those samples. This submittal should be considered to replace the prior individual reports submitted June 9, June 26, June 29, and July 7, 2000.

S&ME, Inc. appreciates this and every opportunity to be of service to you and Duke Power. If you have questions about this information or need additional assistance, please contact us.

Very truly yours,

S&ME, Inc.

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

File: S:\env2000\Overall Updated Soil Report (2001)

S&ME, Inc.
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TABLE 1
LABORATORY DATA SUMMARY
FOR UNDISTURBED SAMPLES
DUKE POWER COMPANY- BELEWS CREEK ASH LANDFILL

S&ME Project No. 1264-00-157

SAMPLE ID	DEPTH (feet)		USCS Classif.	ATTERBURG LIMITS		GRAIN SIZE DISTRIB.		Standard Proctor Compaction ASTM (D-698)		IN-SITU CONDITIONS			Porosity	Hydraulic Conductivity k (cm/sec)
	From	To		LL	PI	% Finer than #200	% Coarser than #200	Max. Dry Dens. (pcf)	Optimum M.C. (%)	Unit Weight (pcf)	Natural Moist. (%)	Specific Gravity		
MW 2-1 UD#2	9.5	11.5	CH	51	38	94.4	5.6	----	----	64.7	30.7	2.88	0.64	2.80×10^{-6}
MW 2-2 UD#3	24.1	25.5	ML	NP	NP	58.3	41.7	----	----	89.8	18.0	2.65	0.46	1.81×10^{-4}
MW 2-2 UD #5	34.1	36.1	ML	48	19	59.5	40.5	----	----	86.1	33.1	2.73	0.49	6.63×10^{-5}
MW 2-3 UD#4	29.0	30.6	ML	NP	NP	64.1	35.9	----	----	93.8	17.5	2.72	0.45	5.58×10^{-5}
MW 2-4 UD#2	19.0	21.0	ML	NP	NP	70.6	29.4	----	----	82.1	21.1	2.67	0.51	BAD SAMPLE
BC-4 UD-1	5.0	6.7	ML	NP	NP	53.3	46.7	----	----	79.4	16.1	2.73	0.53	2.51×10^{-4}
BC-5 UD-1	9.5	11.5	ML	NP	NP	55.6	44.4	----	----	72.5	23.4	2.64	0.56	3.61×10^{-4}

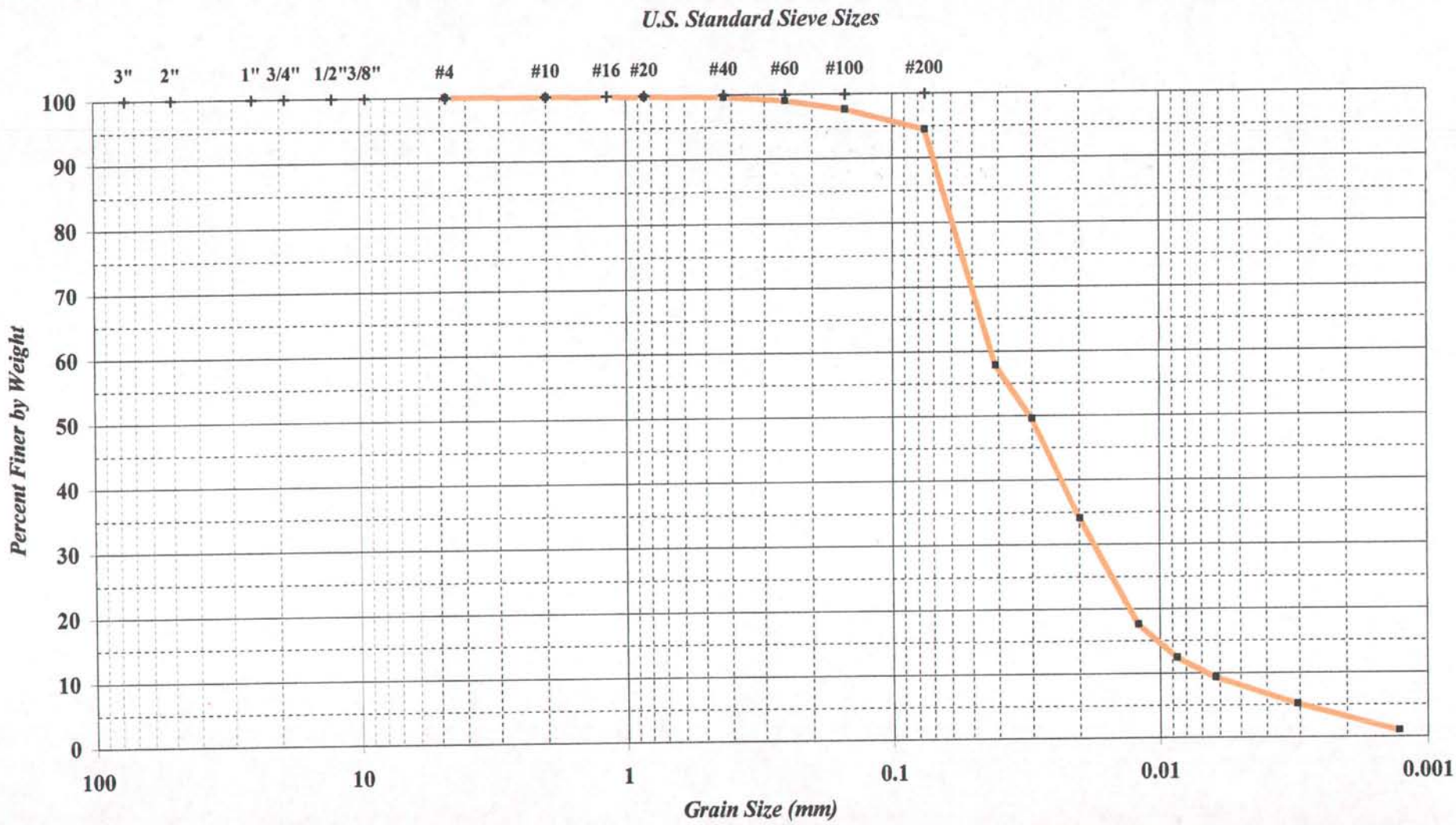
LEGEND
NP - Indicates Non-Plastic
- - - - Indicates not analyzed

TABLE 1
LABORATORY DATA SUMMARY
FOR UNDISTURBED SAMPLES
DUKE POWER COMPANY- BELEWS CREEK ASH LANDFILL

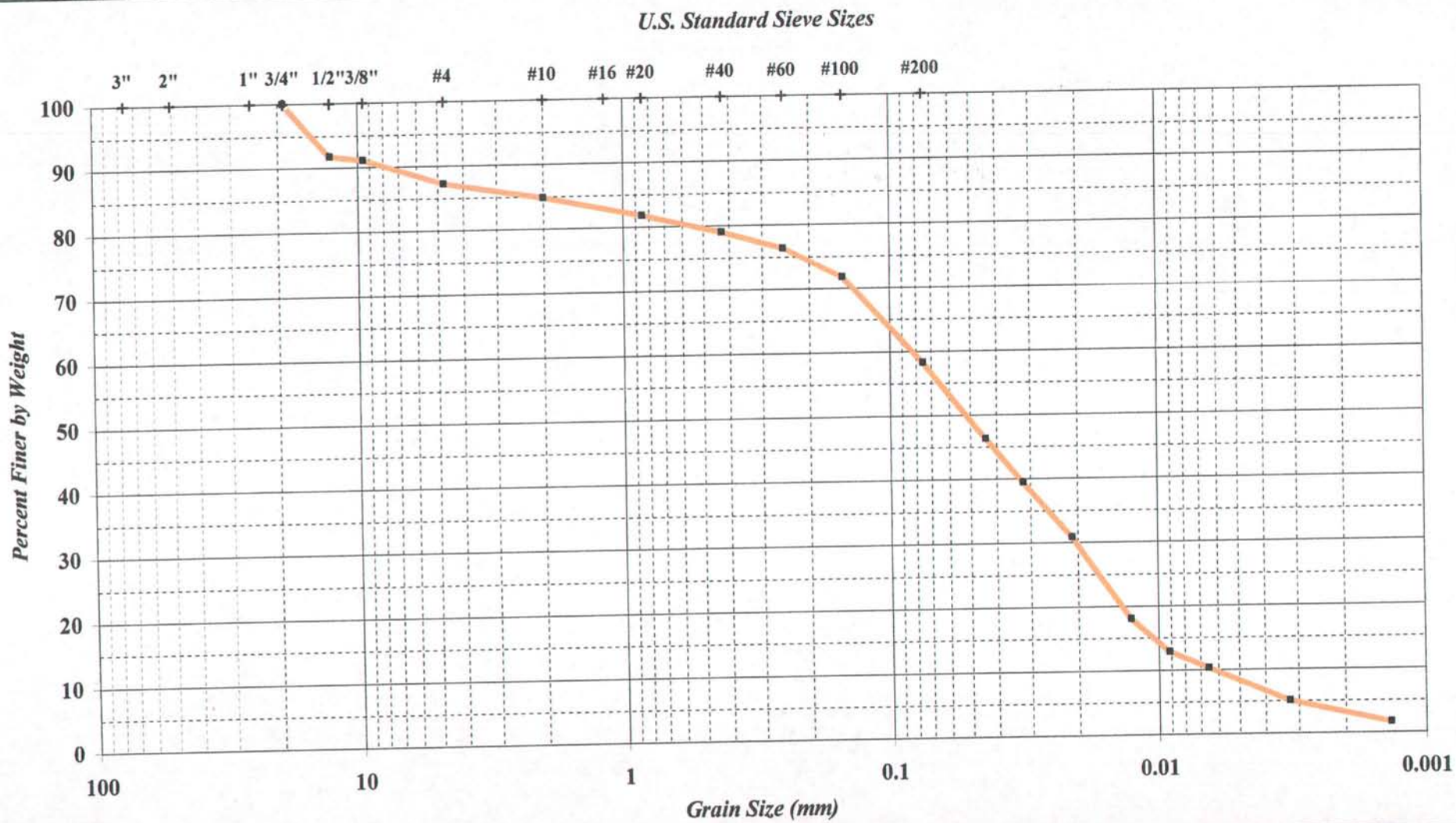
S&ME Project No. 1264-00-157

SAMPLE ID	DEPTH (feet)		USCS Classif.	ATTERBURG LIMITS		GRAIN SIZE DISTRIB.		Standard Proctor Compaction ASTM (D-698)		IN-SITU CONDITIONS			Porosity	Hydraulic Conductivity k (cm/sec)
	From	To		LL	PI	% Finer than #200	% Coarser than #200	Max. Dry Dens. (pcf)	Optimum M.C. (%)	Unit Weight (pcf)	Natural Moist. (%)	Specific Gravity		
MW 2-1 UD#2	9.5	11.5	CH	51	38	94.4	5.6	----	----	64.7	30.7	2.88	0.64	2.80×10^{-6}
MW 2-2 UD#3	24.1	25.5	ML	NP	NP	58.3	41.7	----	----	89.8	18.0	2.65	0.46	1.81×10^{-4}
MW 2-2 UD #5	34.1	36.1	ML	48	19	59.5	40.5	----	----	86.1	33.1	2.73	0.49	6.63×10^{-5}
MW 2-3 UD#4	29.0	30.6	ML	NP	NP	64.1	35.9	----	----	93.8	17.5	2.72	0.45	5.58×10^{-5}
MW 2-4 UD#2	19.0	21.0	ML	NP	NP	70.6	29.4	----	----	82.1	21.1	2.67	0.51	BAD SAMPLE
BC-4 UD-1	5.0	6.7	ML	NP	NP	53.3	46.7	----	----	79.4	16.1	2.73	0.53	2.51×10^{-4}
BC-5 UD-1	9.5	11.5	ML	NP	NP	55.6	44.4	----	----	72.5	23.4	2.64	0.56	3.61×10^{-4}

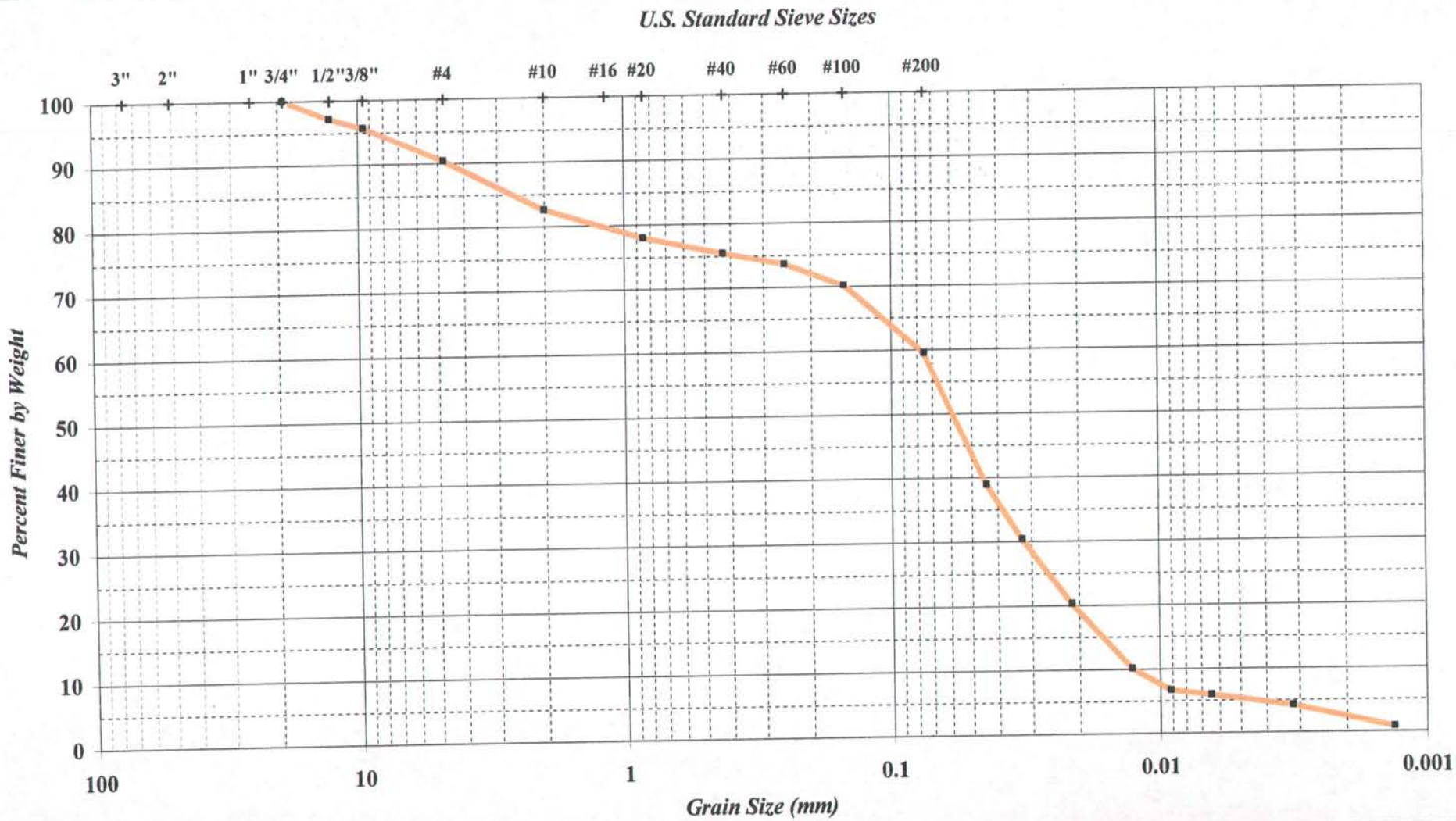
LEGEND
NP - Indicates Non-Plastic
---- Indicates not analyzed



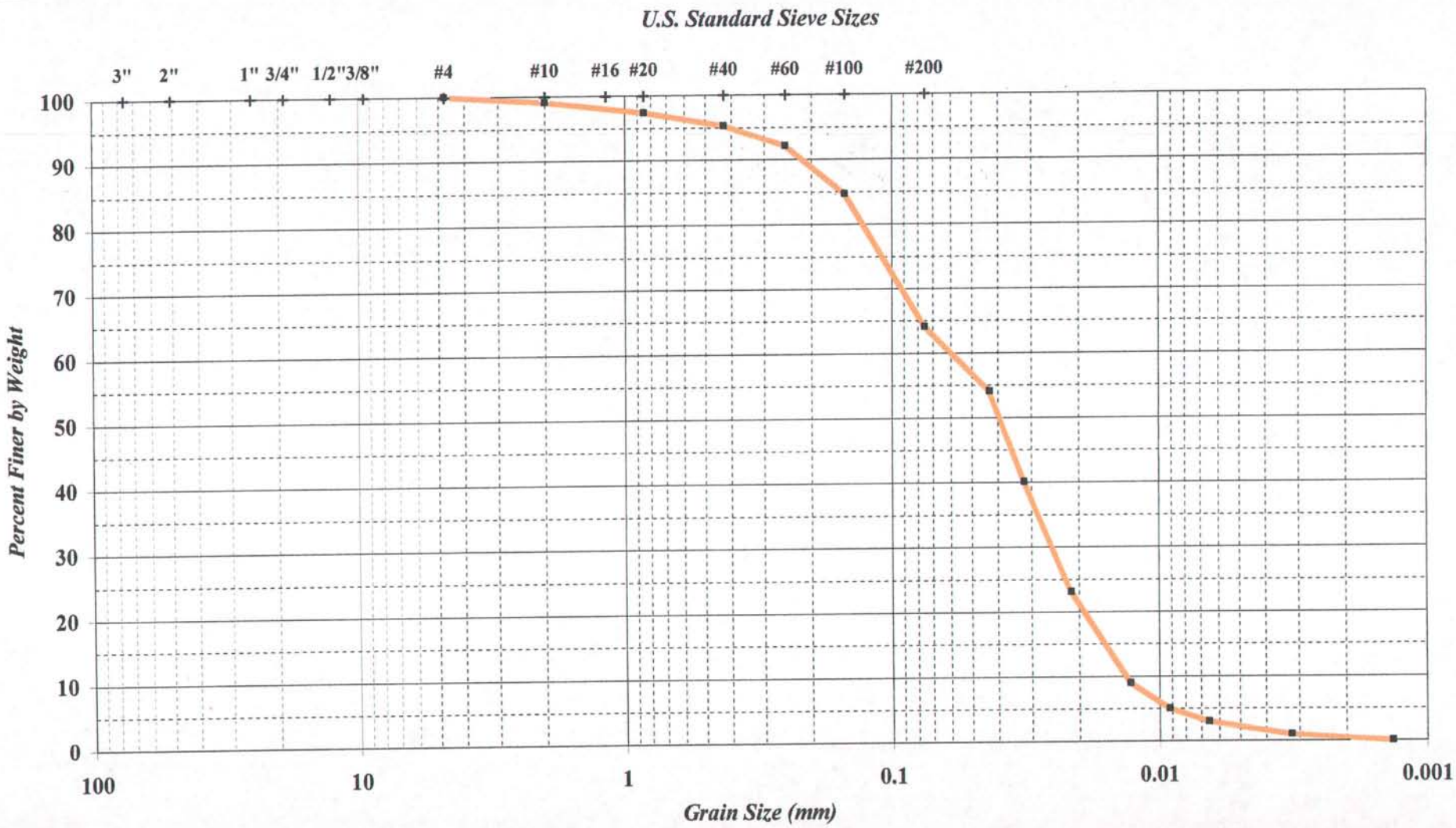
Job Name	Belew's Creek Ash Landfill	Depth	9.5-11.5 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	30.7 %	*ASTM D-421 and 422*
		Gs	2.88	
Job Location	Greensboro, North Carolina	% Finer #200	94.4	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	51	
Job Number	1264-00-157	PI	38	
Boring No.	Soil Description/Classification			
MW 2-1; UD#2	Orange Tan Gray fat CLAY (CH)			



Job Name	Belew's Creek Ash Landfill	Depth	24.1-25.5 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	18 %	*ASTM D-421 and 422*
		Gs	2.65	
Job Location	Greensboro, North Carolina	% Finer #200	58.3	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	NP	
Job Number	1264-00-157	PI	NP	
Boring No.	Soil Description/Classification			
MW 2-2; UD#3	Black Yellow Orange sandy SILT (ML)			

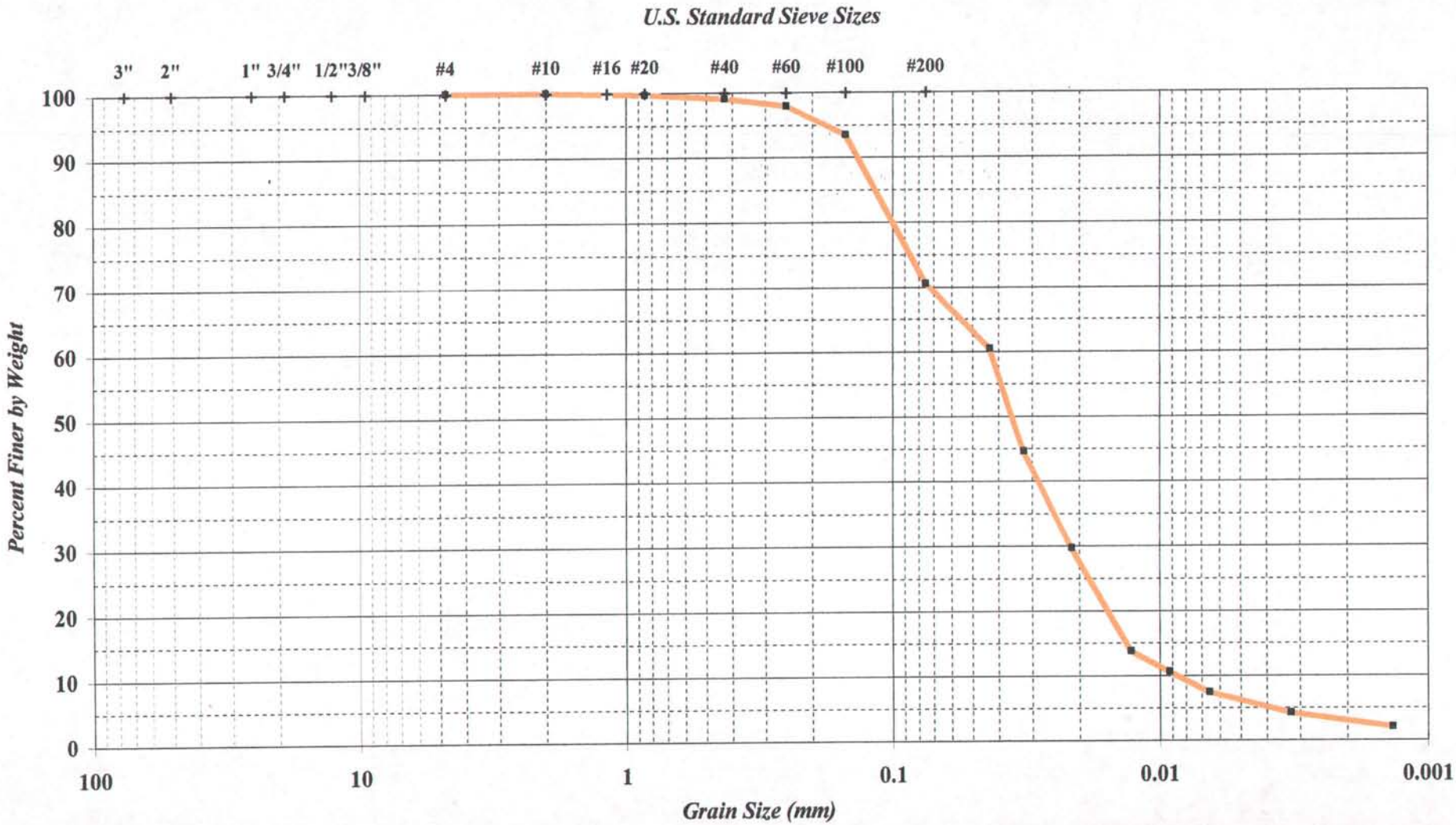


Job Name	Belew's Creek Ash Landfill	Depth	34.1-36.1 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	33.1 %	*ASTM D-421 and 422*
		Gs	2.73	
Job Location	Greensboro, North Carolina	% Finer #200	59.5	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	48	
Job Number	1264-00-157	PI	19	
Boring No.	Soil Description/Classification			
MW 2-2; UD#5	Black Orange Tan sandy SILT (ML)			



Job Name	Belew's Creek Ash Landfill	Depth	29.0-30.6 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	17.5 %	*ASTM D-421 and 422*
Job Location	Greensboro, North Carolina	Gs	2.72	
		% Finer #200	64.1	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
Job Number	1264-00-157	LL	NP	
		PI	NP	

Boring No.	Soil Description/Classification
MW 2-3; UD#4	Orange Gray Tan sandy SILT (ML)



Job Name	Belew's Creek Ash Landfill	Depth	19-21 *feet*
		Nat. Moist.	21.1 %
		Gs	2.67
Job Location	Greensboro, North Carolina	% Finer #200	70.6
		LL	NP
Job Number	1264-00-157	PI	NP

Boring No.	Soil Description/Classification
MW 2-4; UD#2	Orange Tan Gray SILT with sand (ML)

GRAIN SIZE DISTRIBUTION

ASTM D-421 and 422

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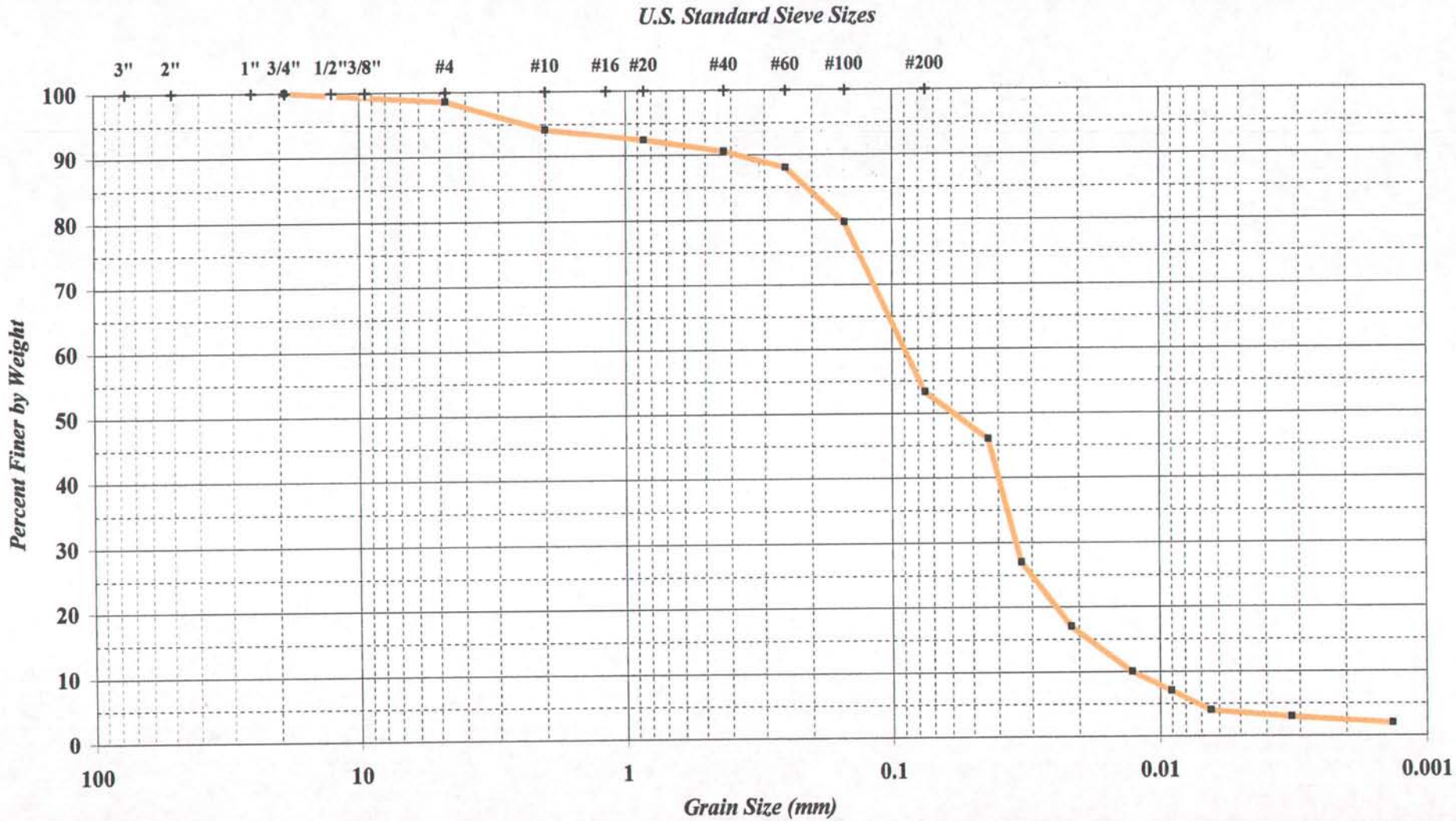
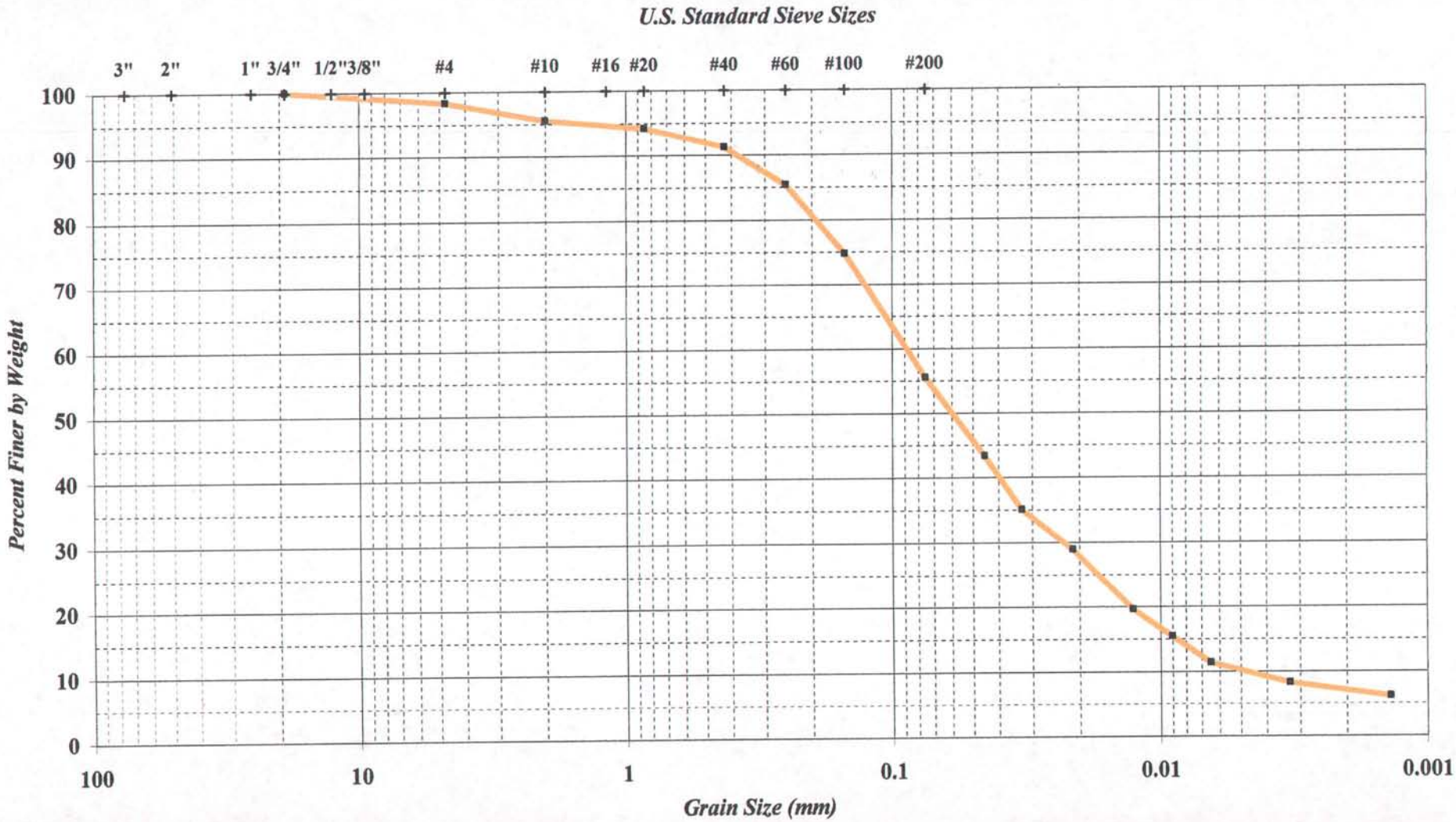
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



Job Name	Belew's Creek Ash Landfill	Depth	5-6.7' *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	16.1 %	*ASTM D-421 and 422*
		Gs	2.73	
Job Location	Greensboro, North Carolina	% Finer #200	53.3	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	NP	
Job Number	1264-00-157	PI	NP	
Boring No.	Soil Description/Classification			
BC-4 UD#1	Black Tan fine to medium sandy SILT (ML)			



Job Name	Belew's Creek Ash Landfill	Depth	9.5-11.5 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	23.4 %	*ASTM D-421 and 422*
		Gs	2.64	
Job Location	Greensboro, North Carolina	% Finer #200	55.6	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	NP	
Job Number	1264-00-157	PI	NP	
Boring No.	Soil Description/Classification			
BC-5 UD#1	Black Tan fine to medium sandy SILT (ML)			

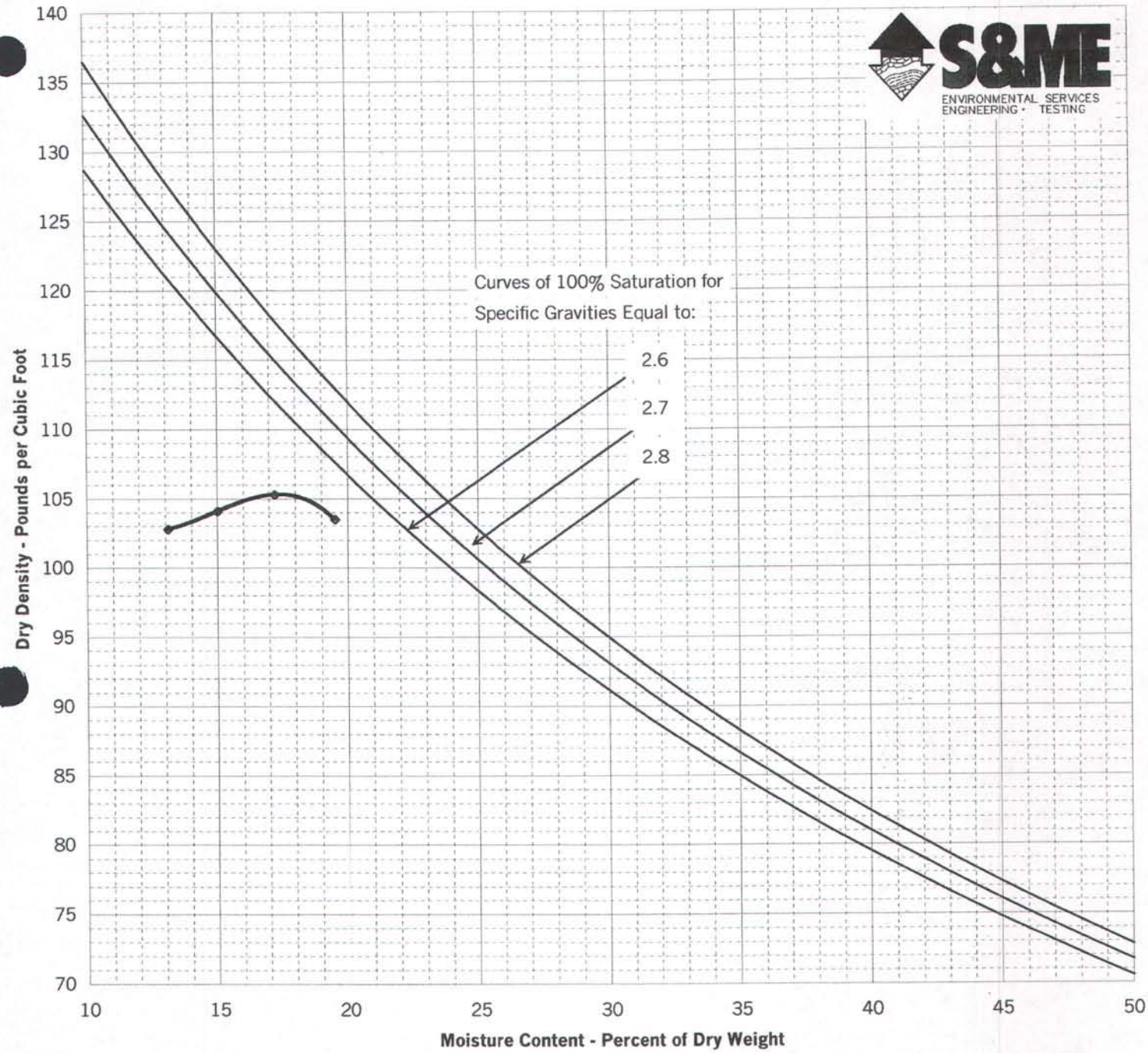
TABLE 2
LABORATORY DATA SUMMARY
FOR BULK AND SPLIT SPOON SAMPLES
DUKE POWER COMPANY- BELEWS CREEK ASH LANDFILL

S&ME Project No. 1264-00-157

SAMPLE ID	DEPTH (feet)		USCS Classif.	ATTERBURG LIMITS		GRAIN SIZE DISTRIB.		Standard Proctor Compaction ASTM (D-698)		REMOLDED CONDITIONS				Porosity	Hydraulic Conductivity, k (cm/sec)
						% Finer than #200	% Coarser than #200	Max. Dry Dens. (pcf)	Optimum M.C. (%)	Unit Weight (pcf)	Natural Moist. (%)	% M.C. from optimum	Specific Gravity		
	From	To		LL	PI										
BC-1	0.0	10.0	ML	29	4	57.8	42.2	105.5	17.5	94.8	17.6	+0.1	2.69	0.44	5.64×10^{-5}
BC-3	0.0	10.0	SM	20	2	43.5	56.5	115.0	12.0	103.4	11.9	-0.1	2.63	0.37	3.47×10^{-4}
BC-4	0.0	10.0	ML	29	6	62.0	38.0	107.0	15.0	96.1	14.9	-0.1	2.66	0.42	5.54×10^{-5}
BC-5	0.0	10.0	ML	32	4	58.3	41.7	104.0	18.5	93.0	18.3	-0.2	2.66	0.44	6.47×10^{-5}
BC-6	0.0	10.0	ML	39	4	64.9	35.1	98.0	22.5	87.7	23.2	+0.7	2.73	0.49	5.31×10^{-5}
BC-1A SS#2	54.2	55.1	SM	27.0	2.0	34.1	65.9	----	----	----	----	----	----	----	----
BC-2 SS#9	29.5	31.0	SM	32.0	2.0	42.4	57.6	----	----	----	----	----	----	----	----
BC-4 SS#3	15.0	16.5	GM	NP	NP	14.8	85.2	----	----	----	----	----	----	----	----
BC-4 SS#5	25.0	25.5	SC	33.0	12.0	39.0	61.0	----	----	----	----	----	----	----	----
BC-5 SS#3	14.5	16.0	SM	31.0	5.0	46.6	53.4	----	----	----	----	----	----	----	----
BC-6 SS#3	14.3	15.8	SM	31.0	2.0	39.7	60.3	----	----	----	----	----	----	----	----
MW 2-1 SS#7	34.5	35.7	SM	30.0	2.0	45.5	54.5	----	----	----	----	----	----	----	----
MW 2-2 SS#9	44.1	45.6	SM	36.0	5.0	49.2	50.8	----	----	----	----	----	----	----	----
MW 2-3 SS#1	4.0	5.5	ML	34.0	8.0	71.8	28.2	----	----	----	----	----	----	----	----
MW 2-3 SS#7	34.0	35.4	SM	32.0	3.0	46.6	53.4	----	----	----	----	----	----	----	----
MW 2-4 SS#1	4.0	5.5	MH	53.0	15.0	79.5	20.5	----	----	----	----	----	----	----	----
MW 2-4 SS#5	26.0	27.5	ML	32.0	4.0	59.3	40.7	----	----	----	----	----	----	----	----

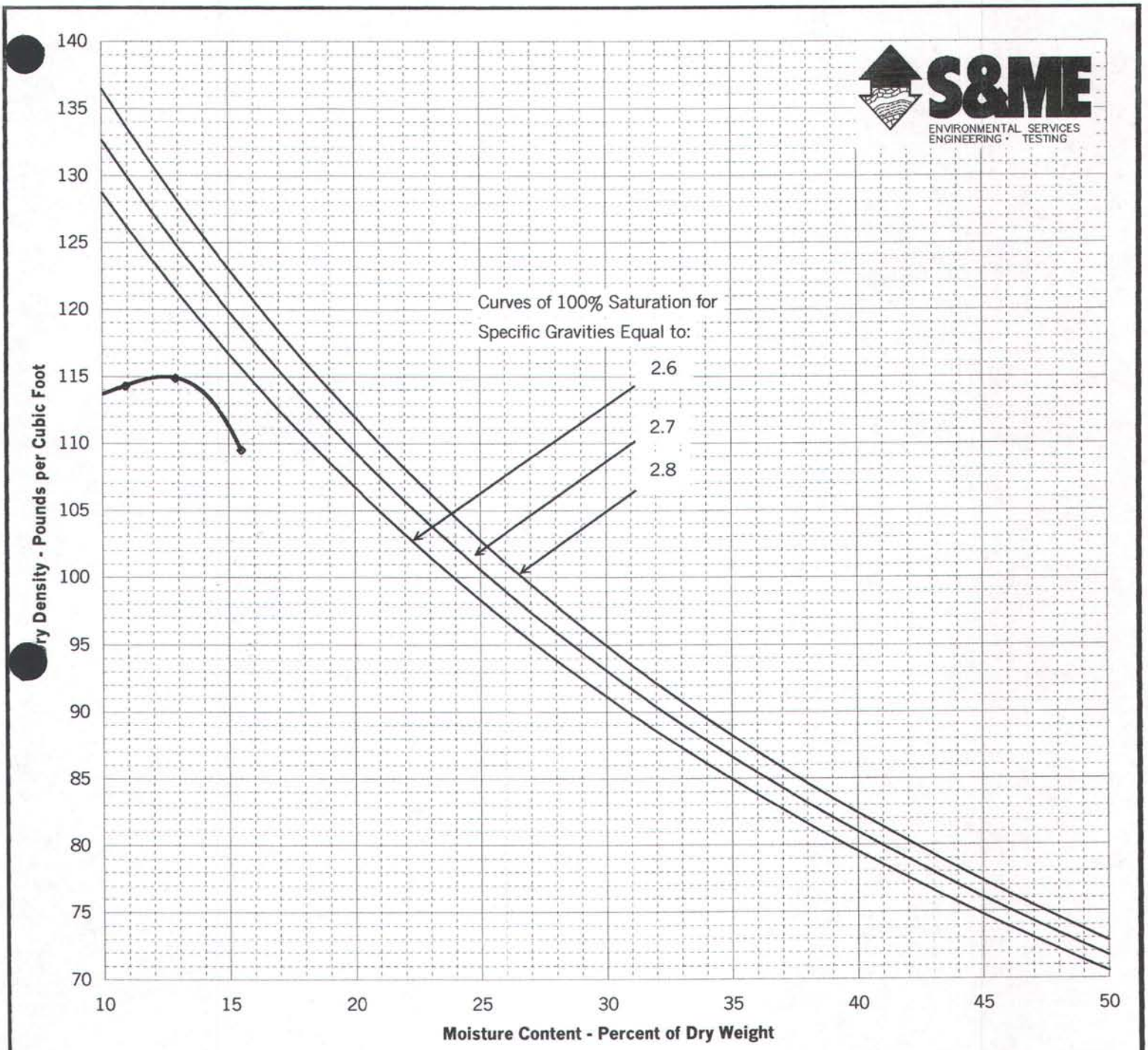
LEGEND

NP - Indicates Non-Plastic
---- Indicates not analyzed



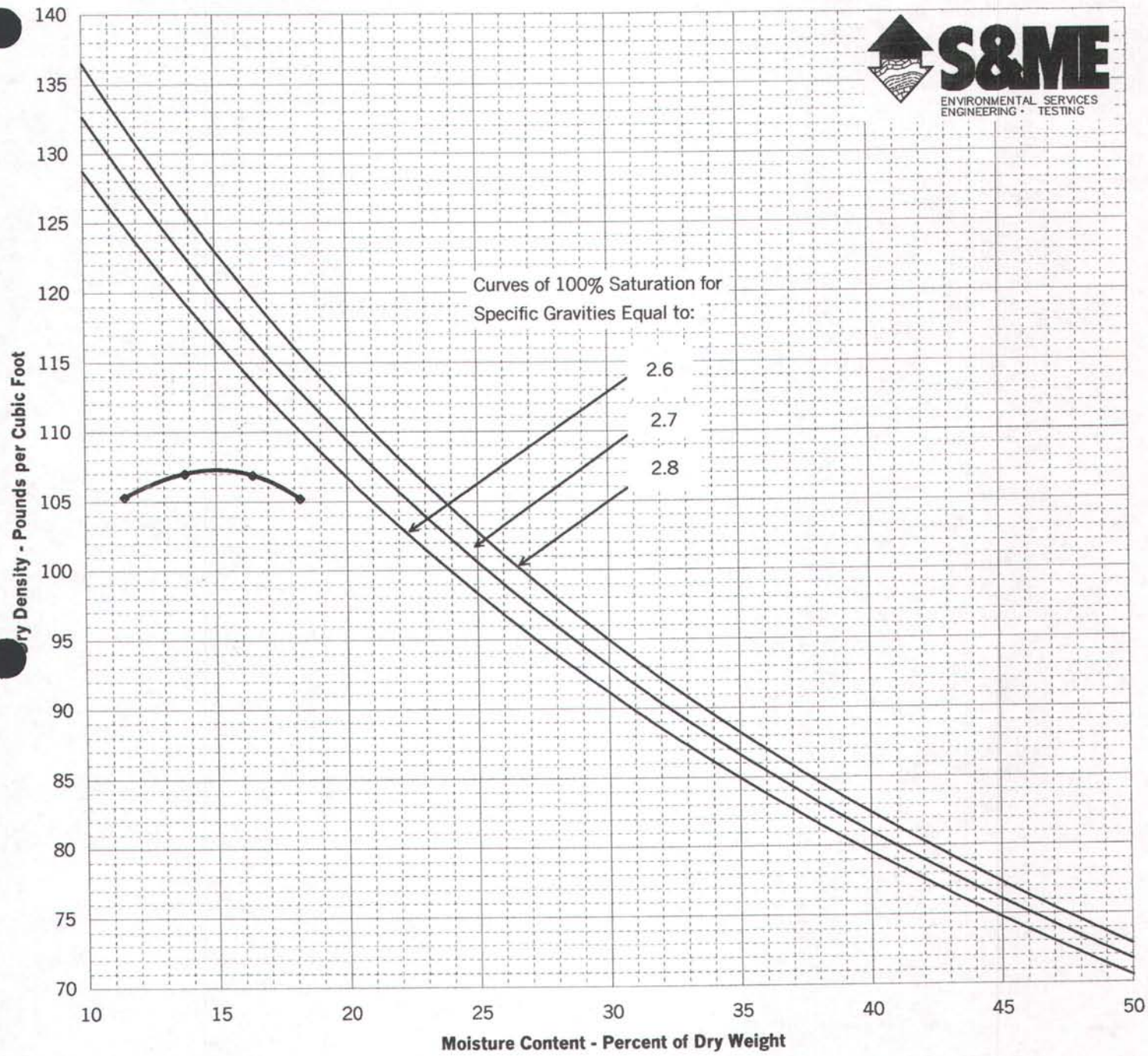
S&ME, Inc. Job Name	Belew's Creek Ash Landfill	**Date Performed**	4/28/00	
		S&ME Lab No.	169	
S&ME, Inc. Job Number	1264-00-157	**LL**	29	
		PI	4	
Sample ID	BC-1 0-10'	**% finer #200**	57.8	%
		Max. Dry Density	105.5	pcf
Soil Description	Tan coarse to fine sandy SILT (ML)	**Opt. Moist. Content**	17.5	%
		Nat. Moist. Content	na	%

Filename: 1264-00-157 (169)



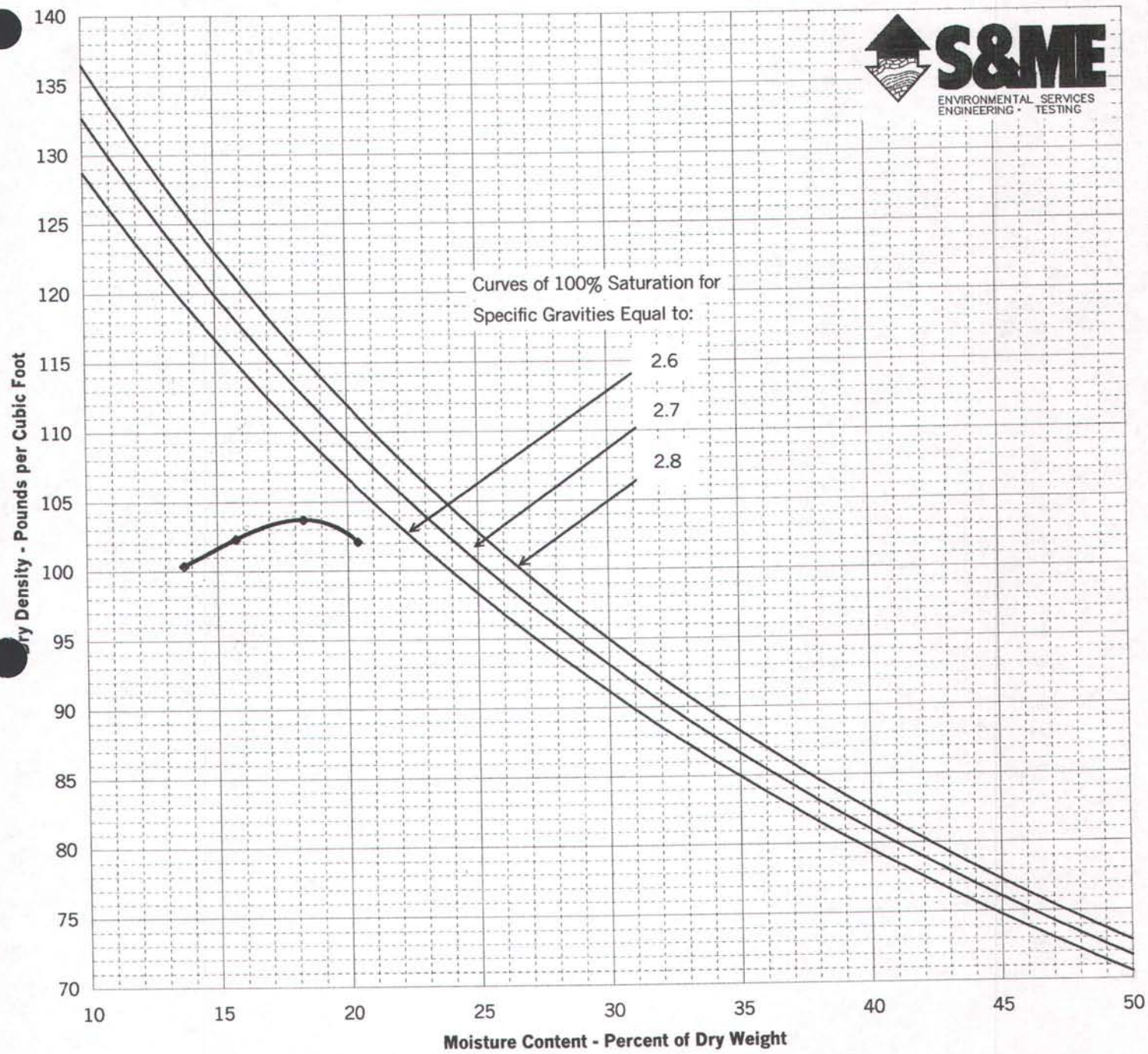
S&ME, Inc.		**Date Performed**	4/28/00	
Job Name	Belew's Creek Ash Landfill	**S&ME Lab No.**	170	
S&ME, Inc.		**LL**	20	
Job Number	1264-00-157	**PI**	2	
		% finer #200	43.5	%
Sample ID	BC-3 0'-10'	**Max. Dry Density**	115.0	pcf
		Opt. Moist. Content	12.0	%
l Description	Tan green silty coarse to fine SAND (SM) with fine gravel	**Nat. Moist. Content**	na	%

Filename: 1264-00-157 (170).XLS



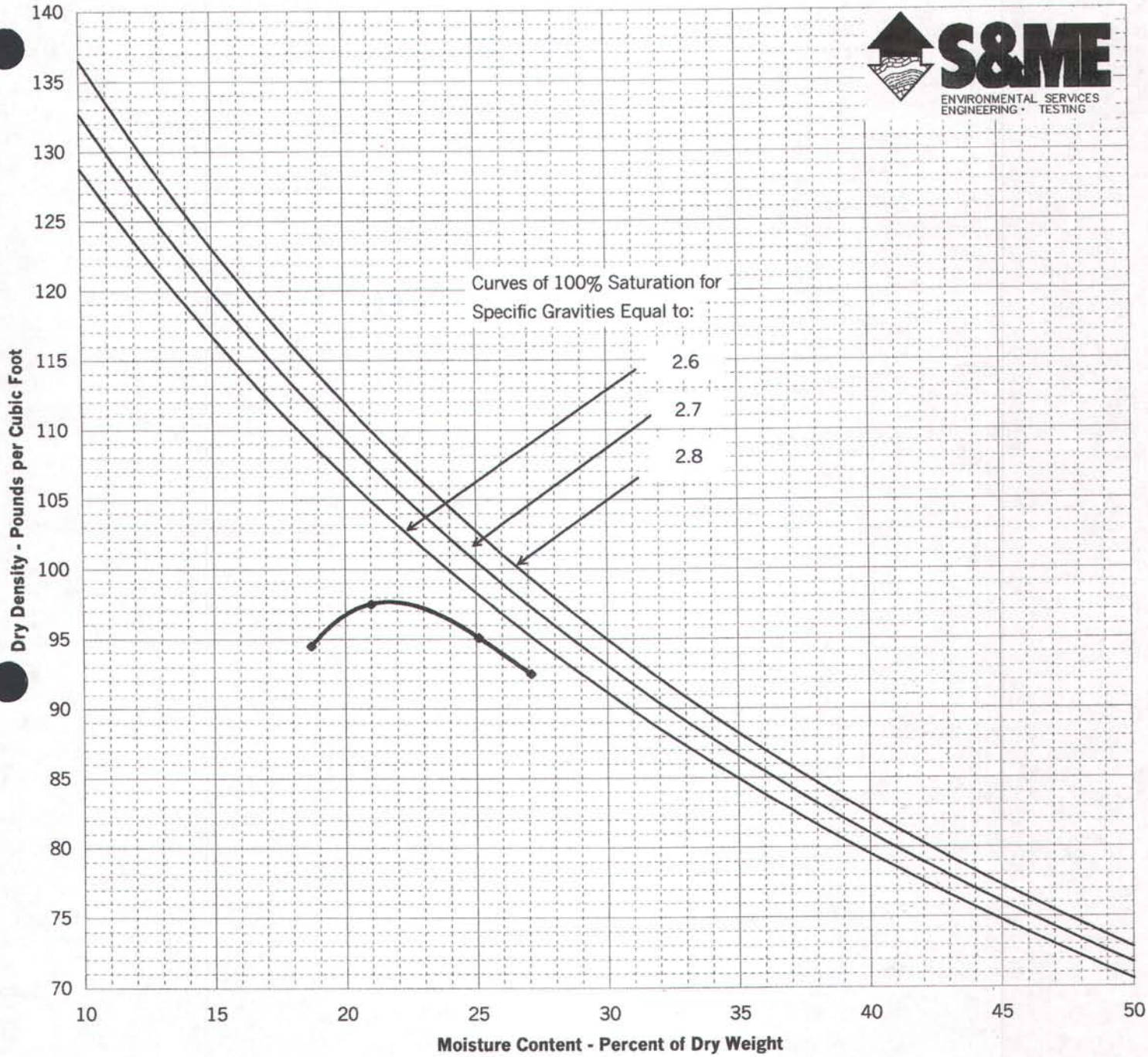
S&ME, Inc.		**Date Performed**	5/1/00	
Job Name	Belew's Creek Ash Landfill	**S&ME Lab No.**	171	
S&ME, Inc.		**LL**	29	
Job Number	1264-00-157	**PI**	6	
		% finer #200	62	%
Sample ID	BC-4 0'-10'	**Max. Dry Density**	107.0	pcf
		Opt. Moist. Content	15.0	%
Soil Description	Tan coarse to fine sandy SILT (ML)	**Nat. Moist. Content**	na	%

Filename: 1264-00-157 (171).XLS



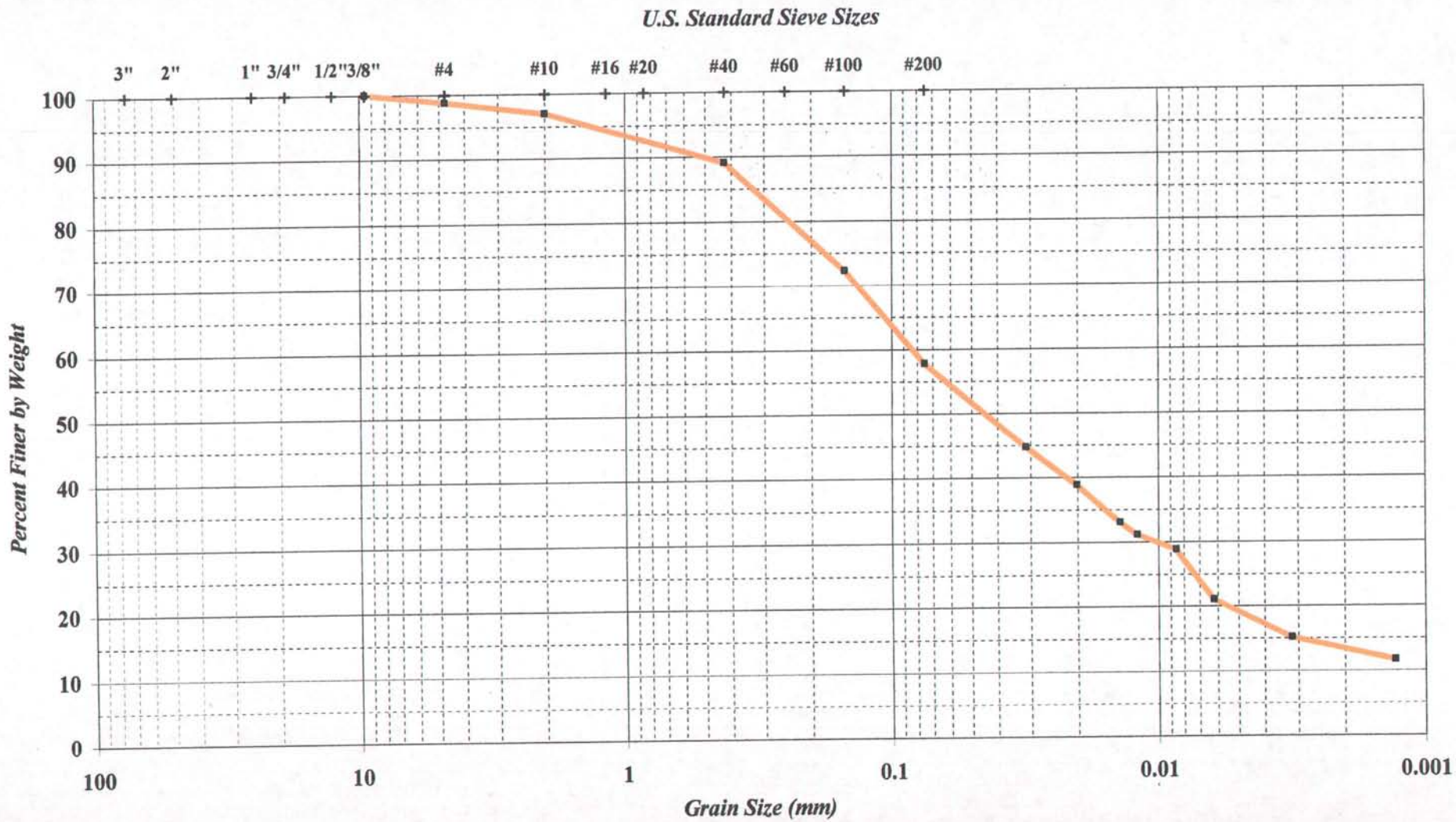
S&ME, Inc. Job Name	Belew's Creek Ash Landfill	Date Performed	5/1/00	
		S&ME Lab No.	172	
S&ME, Inc. Job Number	1264-00-157	LL	32	
		PI	4	
		% finer #200	58.3	%
Sample ID	BC-5 0'-10'	Max. Dry Density	104.0	pcf
		Opt. Moist. Content	18.5	%
Soil Description	Tan coarse to fine sandy SILT (ML)	Nat. Moist. Content	na	%

Filename: 1264-00-157 (172).XLS

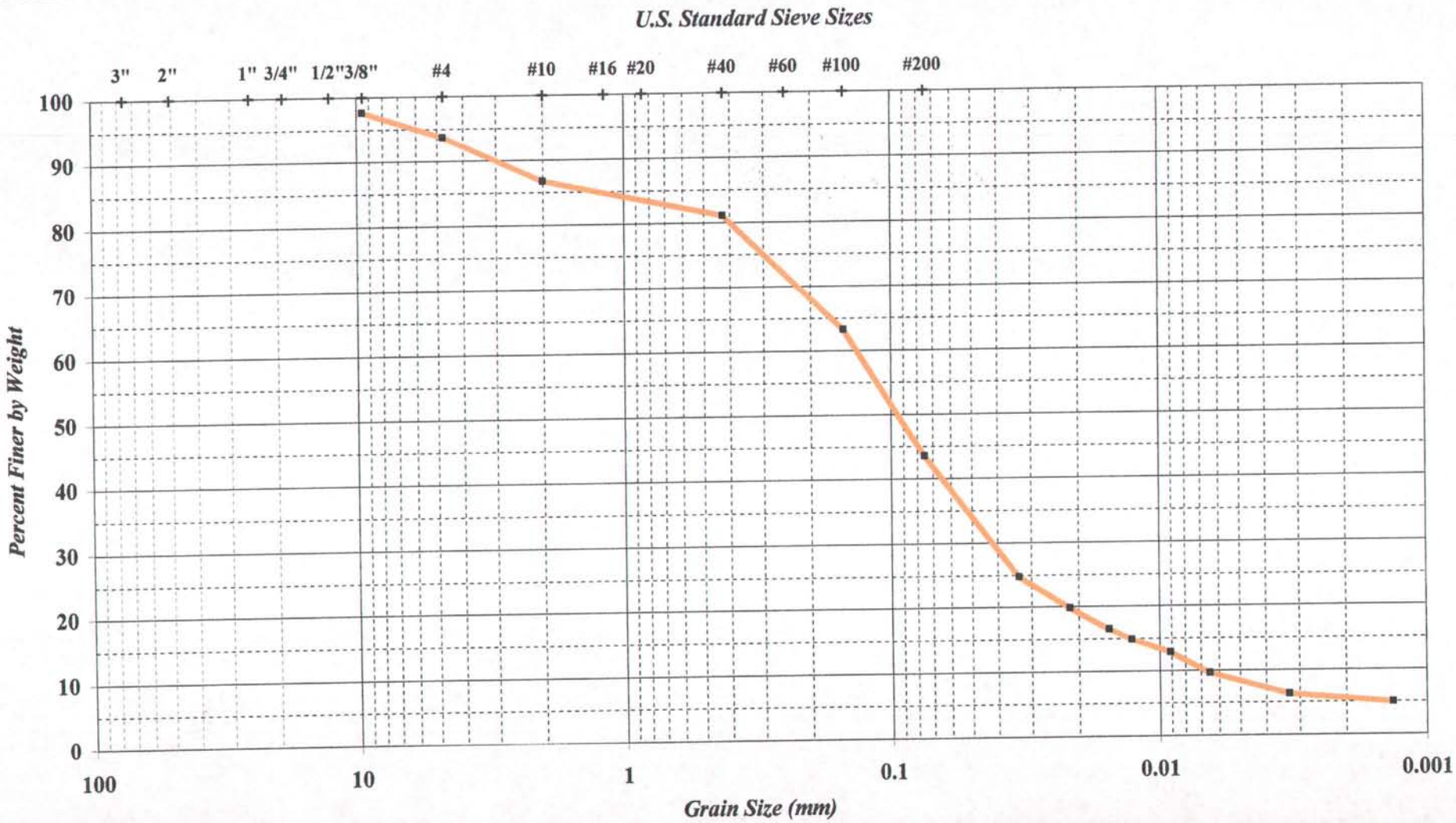


S&ME, Inc.		**Date Performed**	5/1/00	
Job Name	Belew's Creek Ash Landfill	**S&ME Lab No.**	173	
S&ME, Inc.		**LL**	39	
Job Number	1264-00-157	**PI**	4	
		% finer #200	64.9	%
Sample ID	BC-6 0'-10'	**Max. Dry Density**	98.0	pcf
		Opt. Moist. Content	22.5	%
Soil Description	Orange tan coarse to fine sandy SILT (ML)	**Nat. Moist. Content**	na	%

Filename: 1264-00-157 (173).XLS

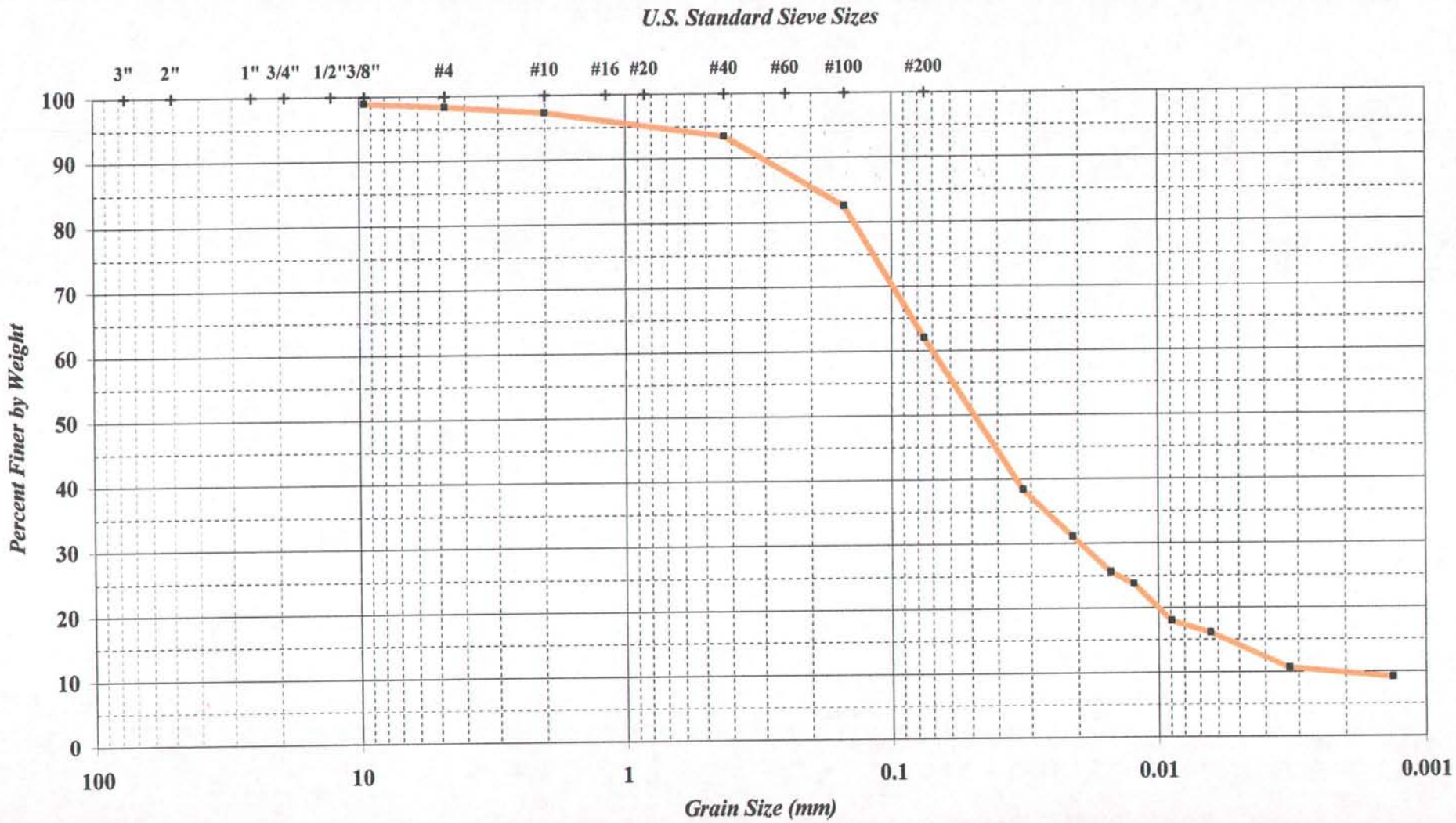


Job Name	Belew's Creek Ash Landfill	Depth	0-10 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
		Gs	2.69	
Job Location	Greensboro, North Carolina	% Finer #200	57.8	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	29	
Job Number	1264-00-157	PI	4	
Boring No.	Soil Description/Classification			
BC-1	Tan coarse to fine sandy SILT (ML)			



Job Name	Belew's Creek Ash Landfill	Depth	0-10 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
Job Location	Greensboro, North Carolina	Gs	2.63	
		% Finer #200	43.5	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
Job Number	1264-00-157	LL	20	
		PI	2	

Boring No.	Soil Description/Classification
BC-3	Tan green silty coarse to fine SAND (SM) with fine gravel



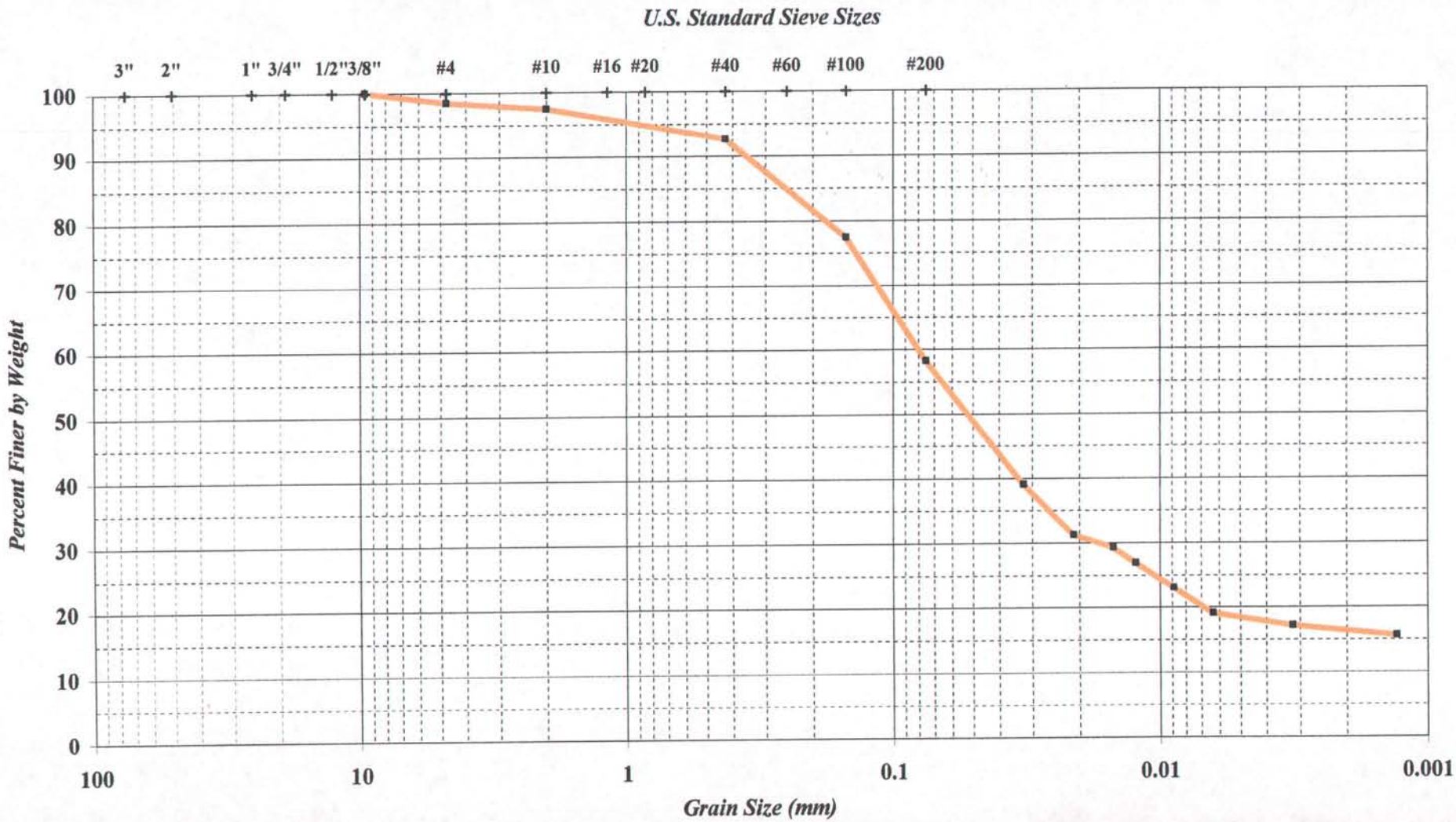
Job Name	Belew's Creek Ash Landfill	Depth	0-10 *feet*
		Nat. Moist.	na %
		Gs	2.66
Job Location	Greensboro, North Carolina	% Finer #200	62
		LL	29
Job Number	1264-00-157	PI	6

Boring No.	Soil Description/Classification
BC-4	Tan coarse to fine sandy SILT (ML)

GRAIN SIZE DISTRIBUTION

ASTM D-421 and 422

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



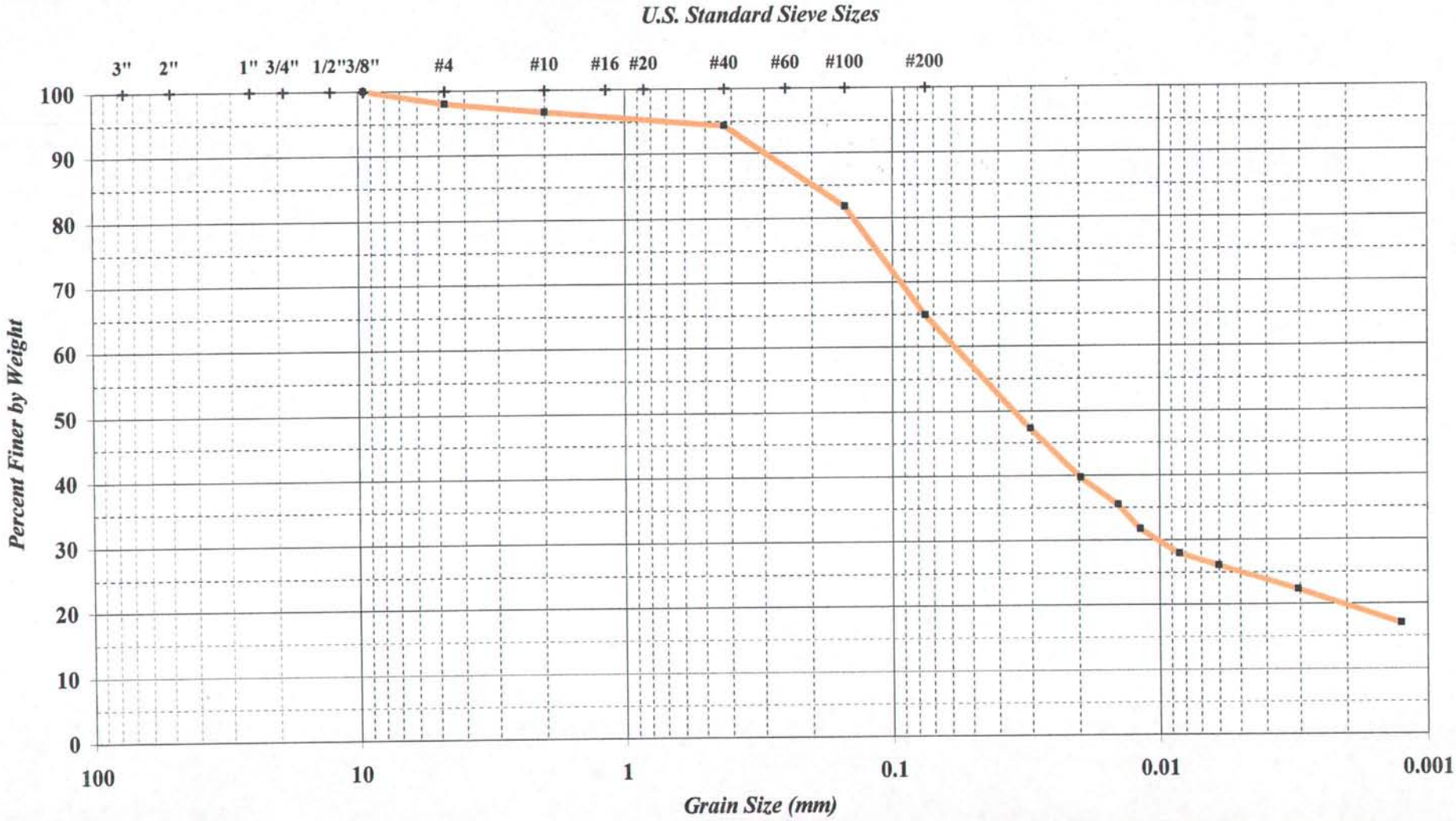
Job Name	Belew's Creek Ash Landfill	Depth	0-10 *feet*
		Nat. Moist.	na %
		Gs	2.66
Job Location	Greensboro, North Carolina	% Finer #200	58.3
		LL	32
Job Number	1264-00-157	PI	4

Boring No.	Soil Description/Classification
BC-5	Tan coarse to fine sandy SILT (ML)

GRAIN SIZE DISTRIBUTION

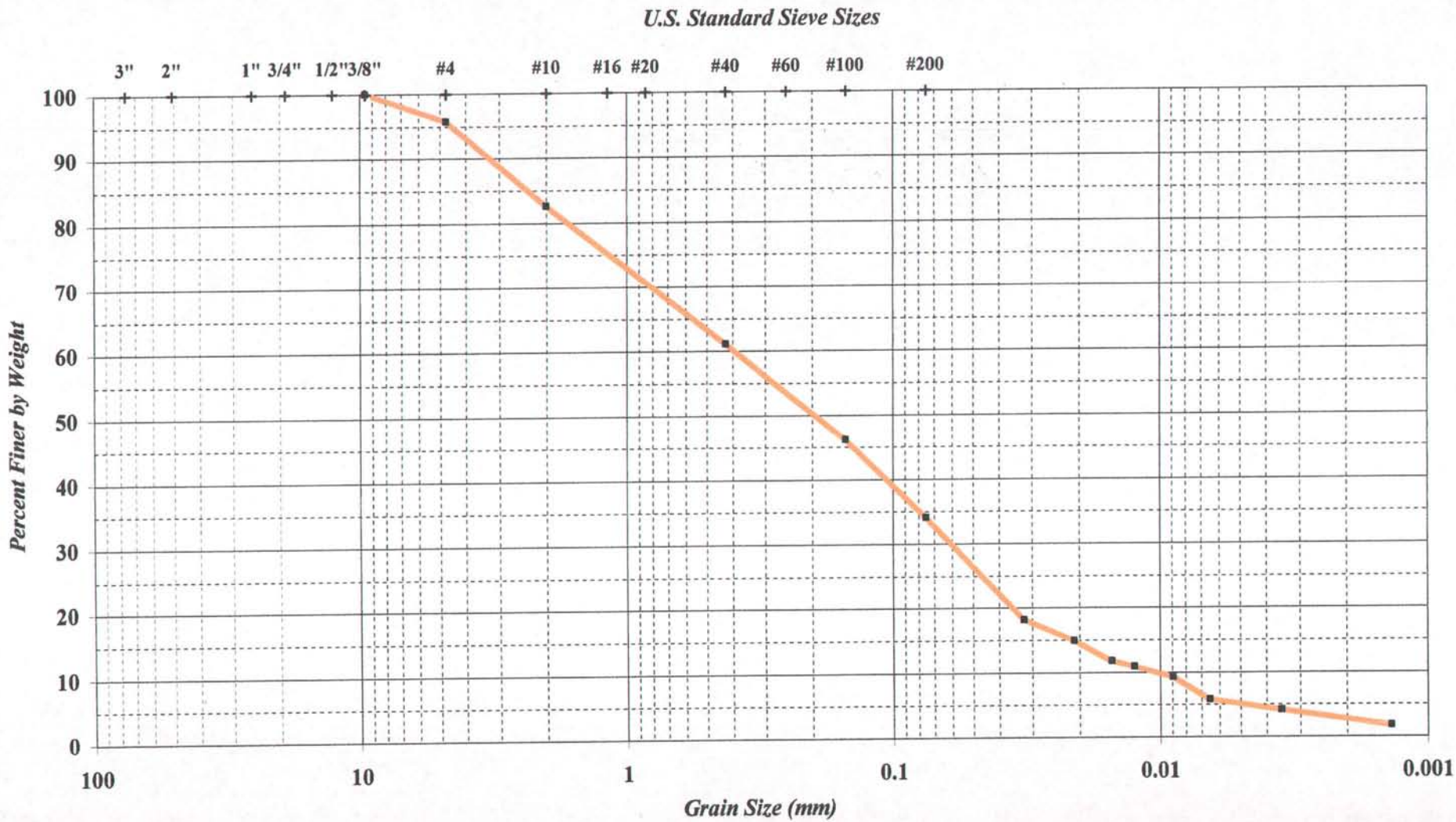
ASTM D-421 and 422

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



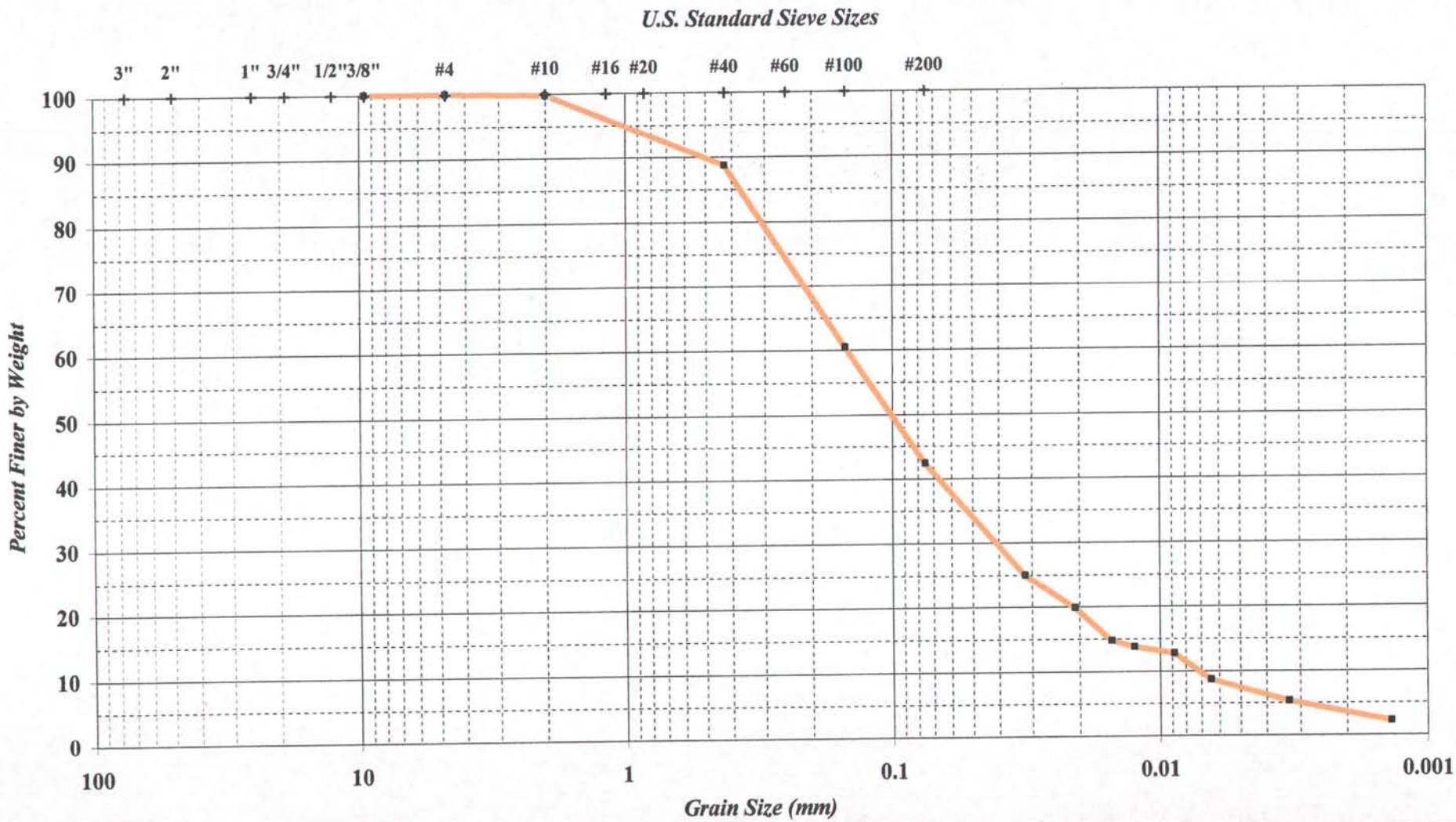
Job Name	Belew's Creek Ash Landfill	Depth	0-10 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
		Gs	2.73	
Job Location	Greensboro, North Carolina	% Finer #200	64.9	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	39	
Job Number	1264-00-157	PI	4	
Boring No.	Soil Description/Classification			
BC-6	Orange Tan coarse to fine sandy SILT (ML)			

Filename: BC-1A SS#2



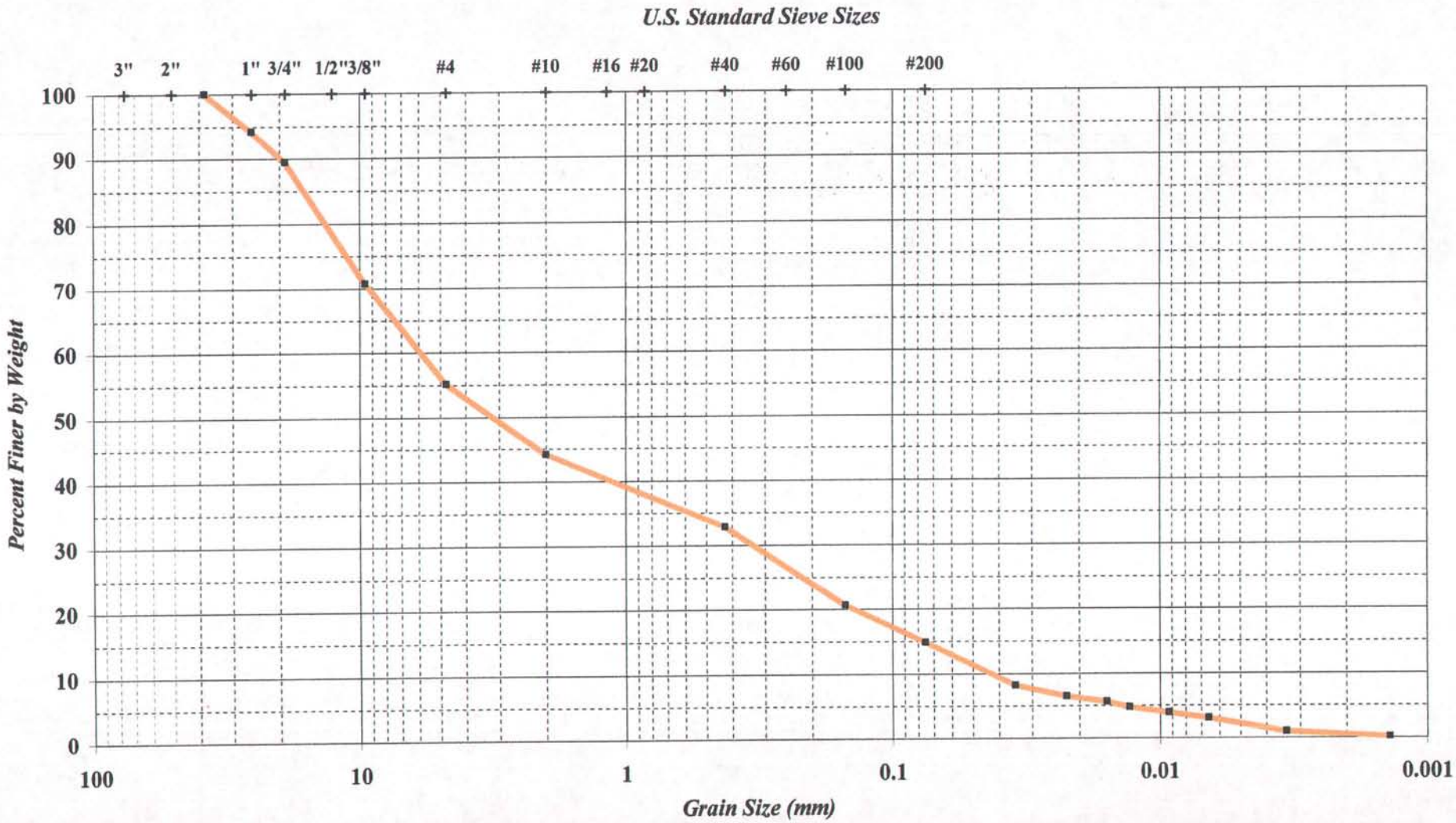
Job Name	Belew's Creek Ash Landfill	Depth	54.2-55.1 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
		Gs	2.62	
Job Location	Greensboro, North Carolina	% Finer #200	34.1	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	27	
Job Number	1264-00-157	PI	2	
Boring No.	Soil Description/Classification			
BC-1A SS#2	Light Brown silty coarse to fine SAND (SM)			

Filename: BC-2 SS#9



Job Name	Belew's Creek Ash Landfill	Depth	29.5-31 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
Job Location	Greensboro, North Carolina	Gs	2.6	
		% Finer #200	42.4	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
Job Number	1264-00-157	LL	32	
		PI	2	

Boring No.	Soil Description/Classification
BC-2 SS#9	Light Yellow-Tan silty medium to fine SAND (SM)



Job Name	Belew's Creek Ash Landfill	Depth	15-16.5 *feet*
		Nat. Moist.	na %
Job Location	Greensboro, North Carolina	Gs	2.6
		% Finer #200	14.8
Job Number	1264-00-157	LL	NP
		PI	NP

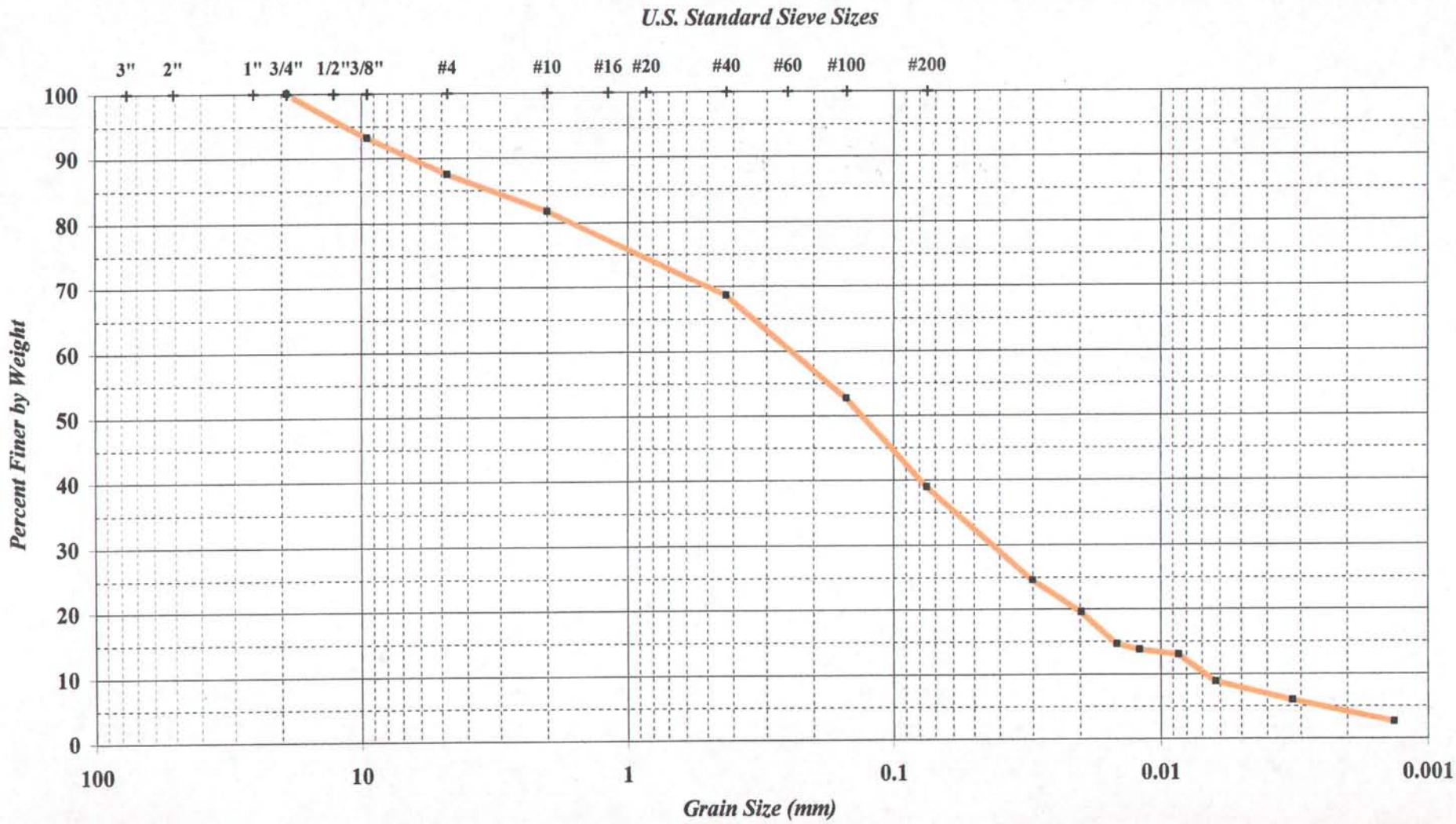
Boring No.	Soil Description/Classification
BC-4 SS#3	Orange-Tan slightly silty coarse to fine sandy GRAVEL (GM)

GRAIN SIZE DISTRIBUTION

ASTM D-421 and 422

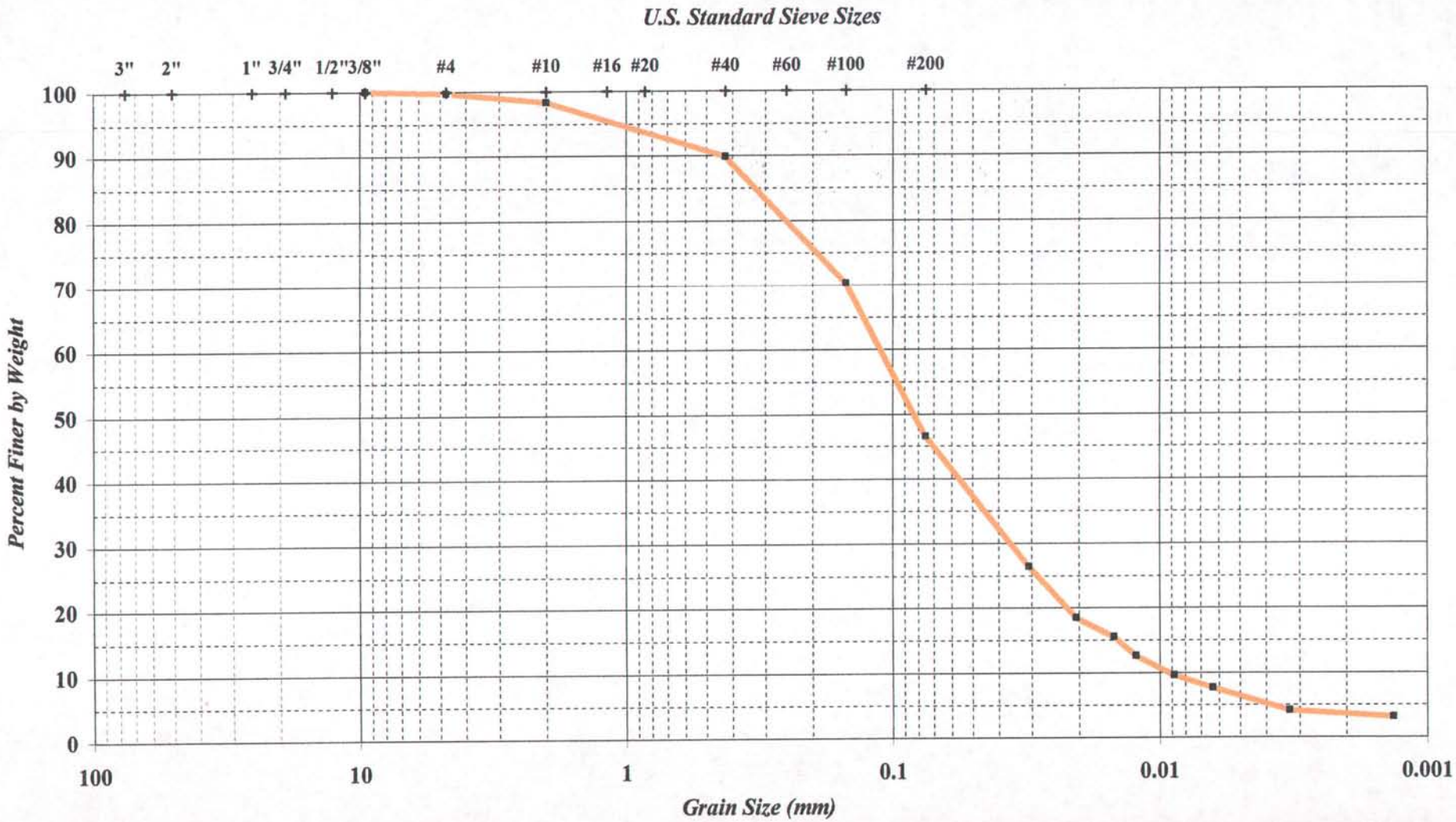
S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING

Filename: BC-4 SS#5



Job Name	Belew's Creek Ash Landfill	Depth	25-25.5 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
		Gs	2.64	
Job Location	Greensboro, North Carolina	% Finer #200	39	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	33	
Job Number	1264-00-157	PI	12	

Boring No.	Soil Description/Classification
BC-4 SS#5	Yellow-Tan clayey coarse to fine SAND (SC) with some gravel



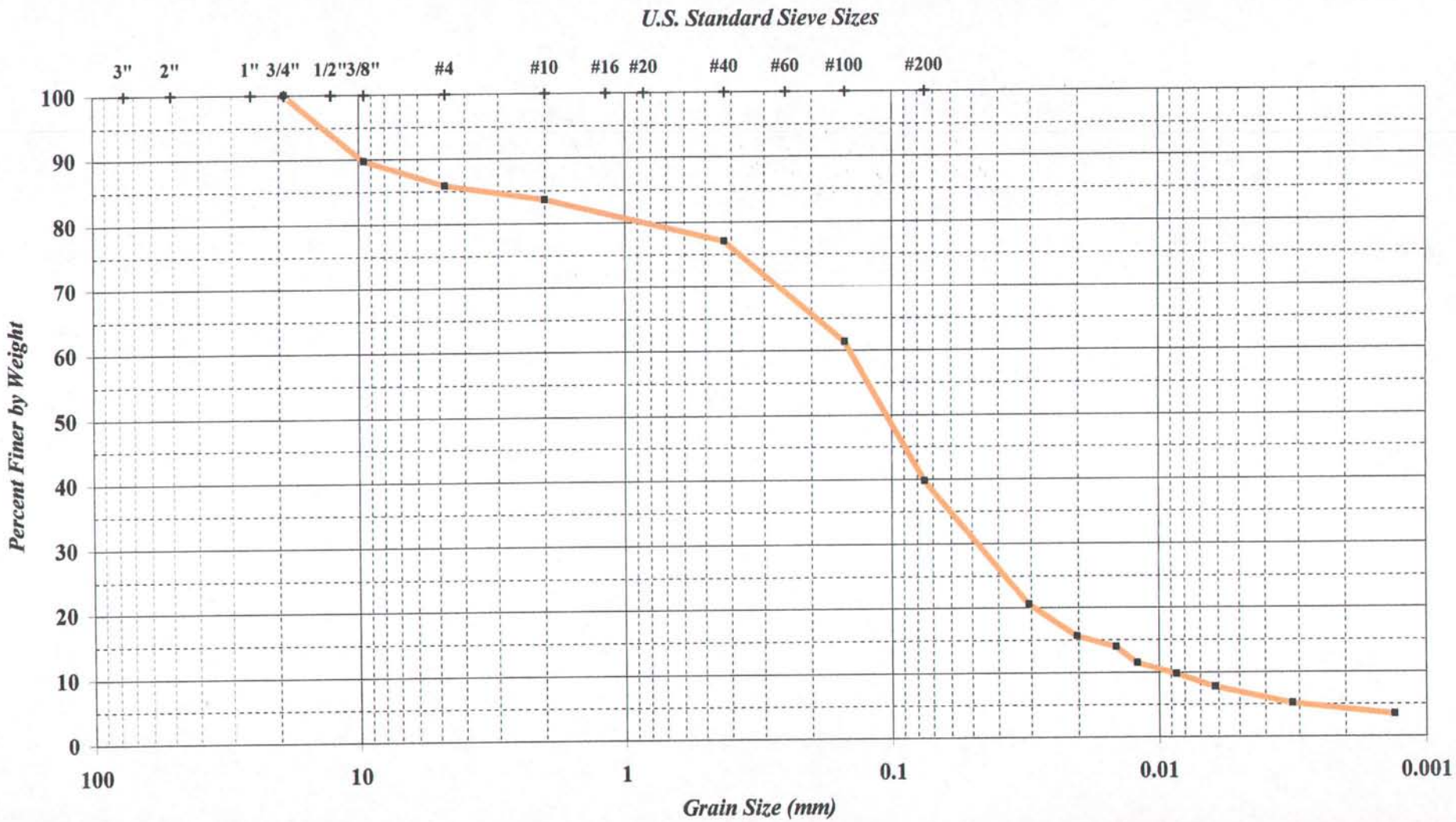
Job Name	Belew's Creek Ash Landfill	Depth	14.5-16 *feet*
		Nat. Moist.	na %
Job Location	Greensboro, North Carolina	Gs	2.63
		% Finer #200	46.6
Job Number	1264-00-157	LL	31
		PI	5

Boring No.	Soil Description/Classification
BC-5 SS#3	Light Green-Tan silty medium to fine SAND (SM)

GRAIN SIZE DISTRIBUTION

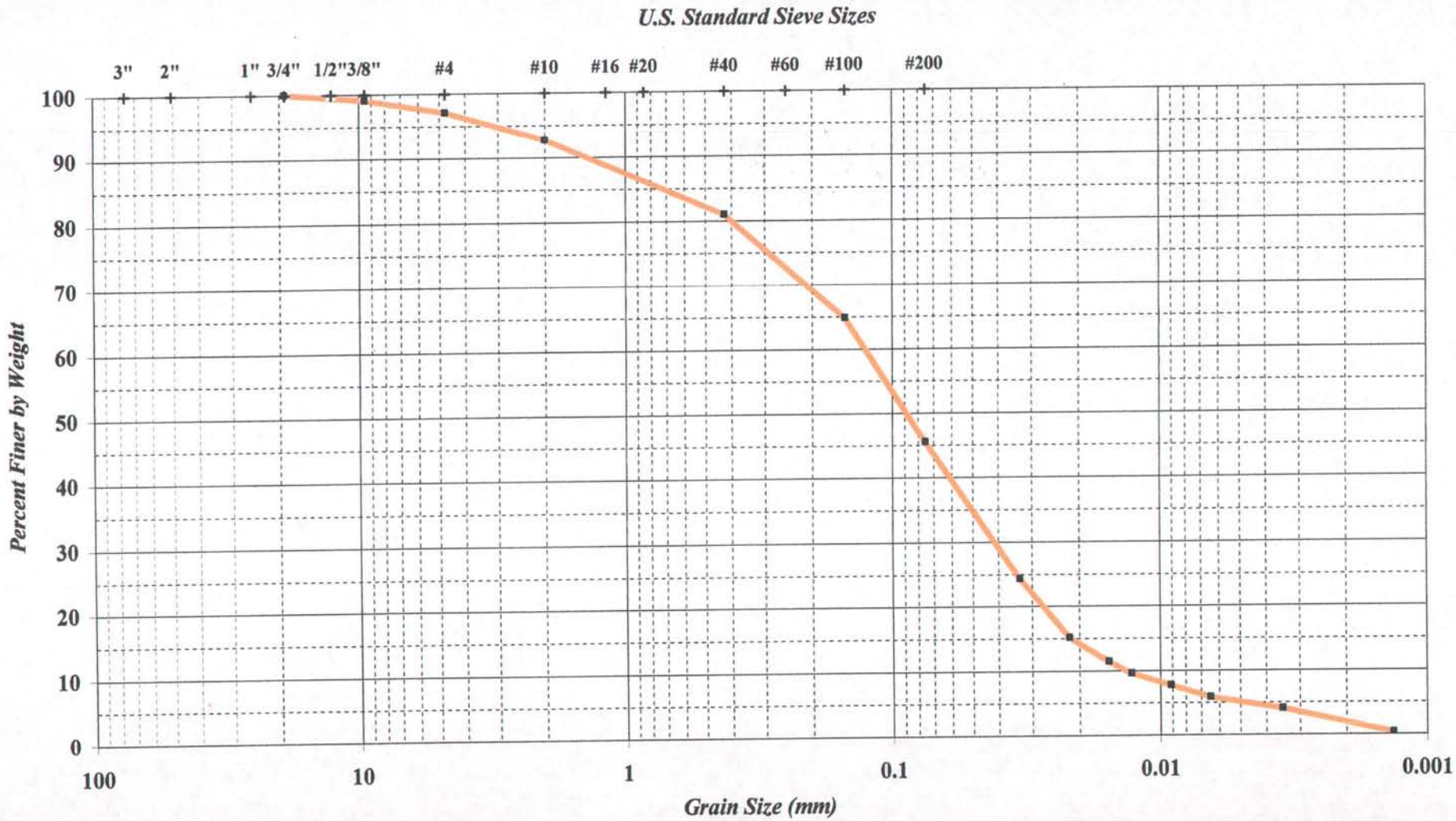
ASTM D-421 and 422

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



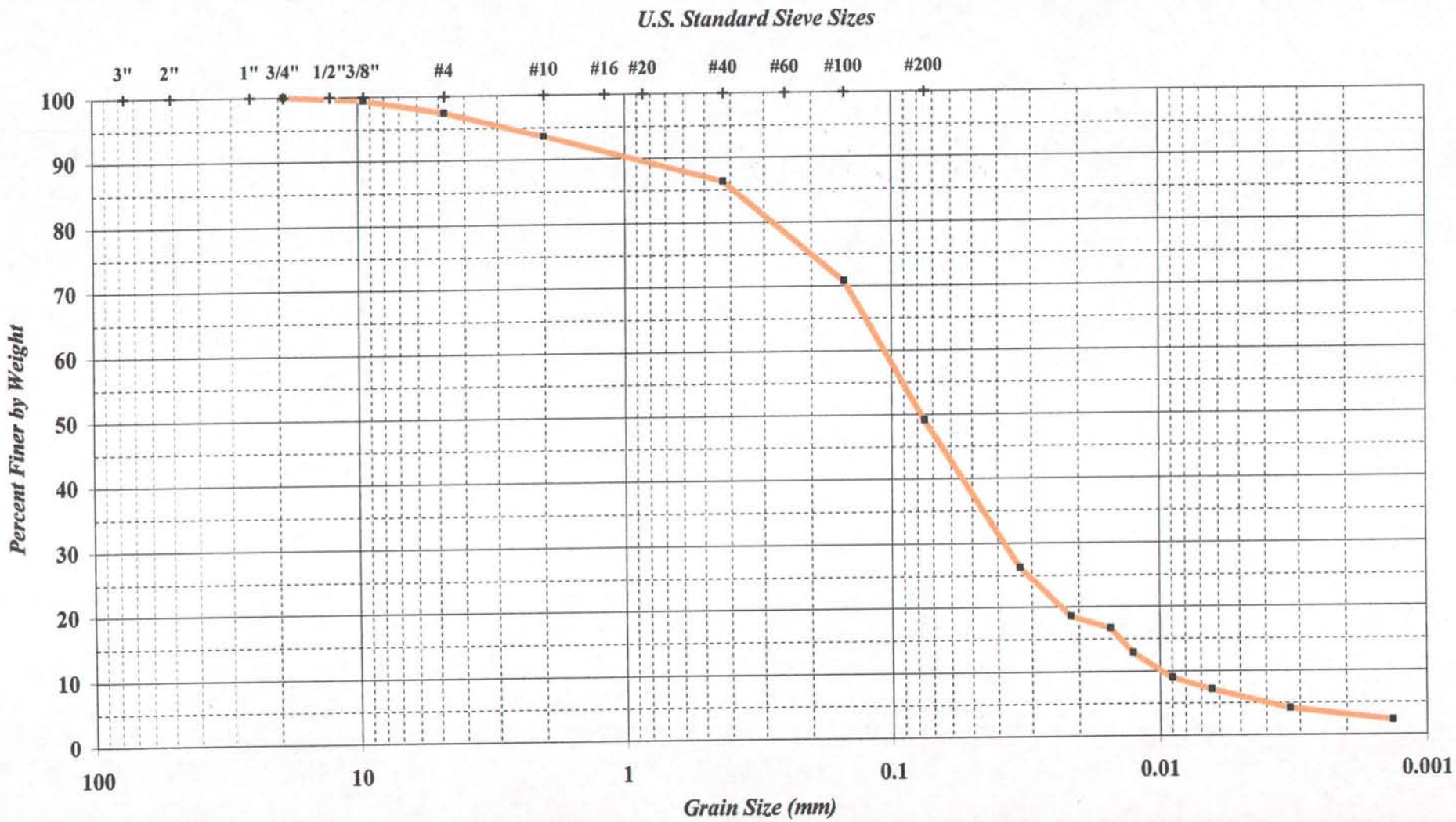
Job Name	Belew's Creek Ash Landfill	Depth	14.3-15.8 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
		Gs	2.68	
Job Location	Greensboro, North Carolina	% Finer #200	39.7	S&ME
		LL	31	
Job Number	1264-00-157	PI	2	ENVIRONMENTAL SERVICES ENGINEERING • TESTING

Boring No.	Soil Description/Classification
BC-6 SS#3	Dark Grey silty coarse to fine SAND (SM) with some gravel



Job Name	Belew's Creek Ash Landfill	Depth	34.5-35.7 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
		Gs	2.68	
Job Location	Greensboro, North Carolina	% Finer #200	45.5	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
		LL	30	
Job Number	1264-00-157	PI	2	

Boring No.	Soil Description/Classification
MW 2-1 SS#7	Tan silty coarse to fine SAND (SM)



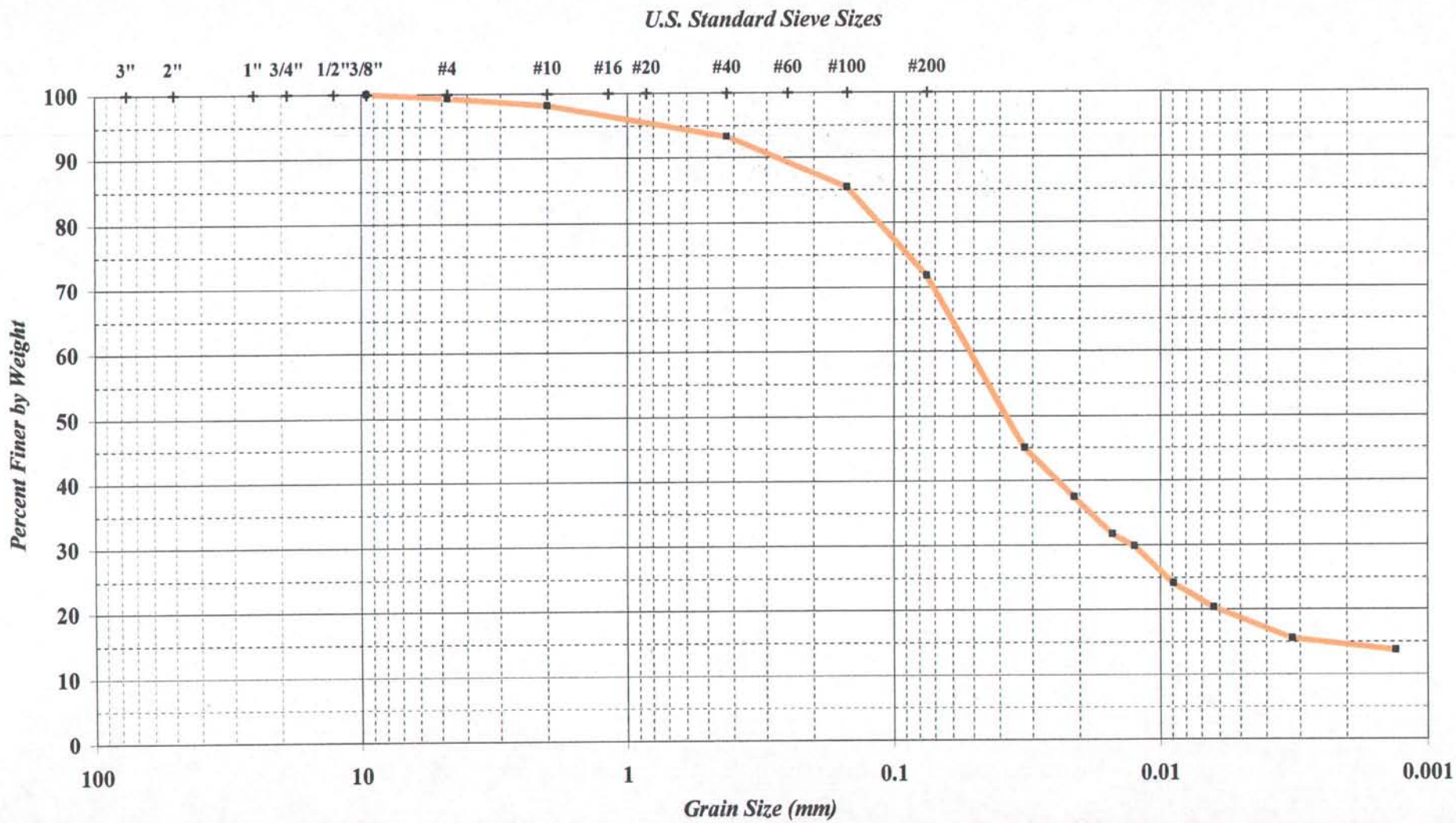
Job Name	Belew's Creek Ash Landfill	Depth	44.1-45.6 *feet*
		Nat. Moist.	na %
		Gs	2.71
Job Location	Greensboro, North Carolina	% Finer #200	49.2
		LL	36
Job Number	1264-00-157	PI	5

Boring No.	Soil Description/Classification
MW 2-2 SS#9	Green-Tan very silty coarse to fine SAND (SM)

GRAIN SIZE DISTRIBUTION

ASTM D-421 and 422

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



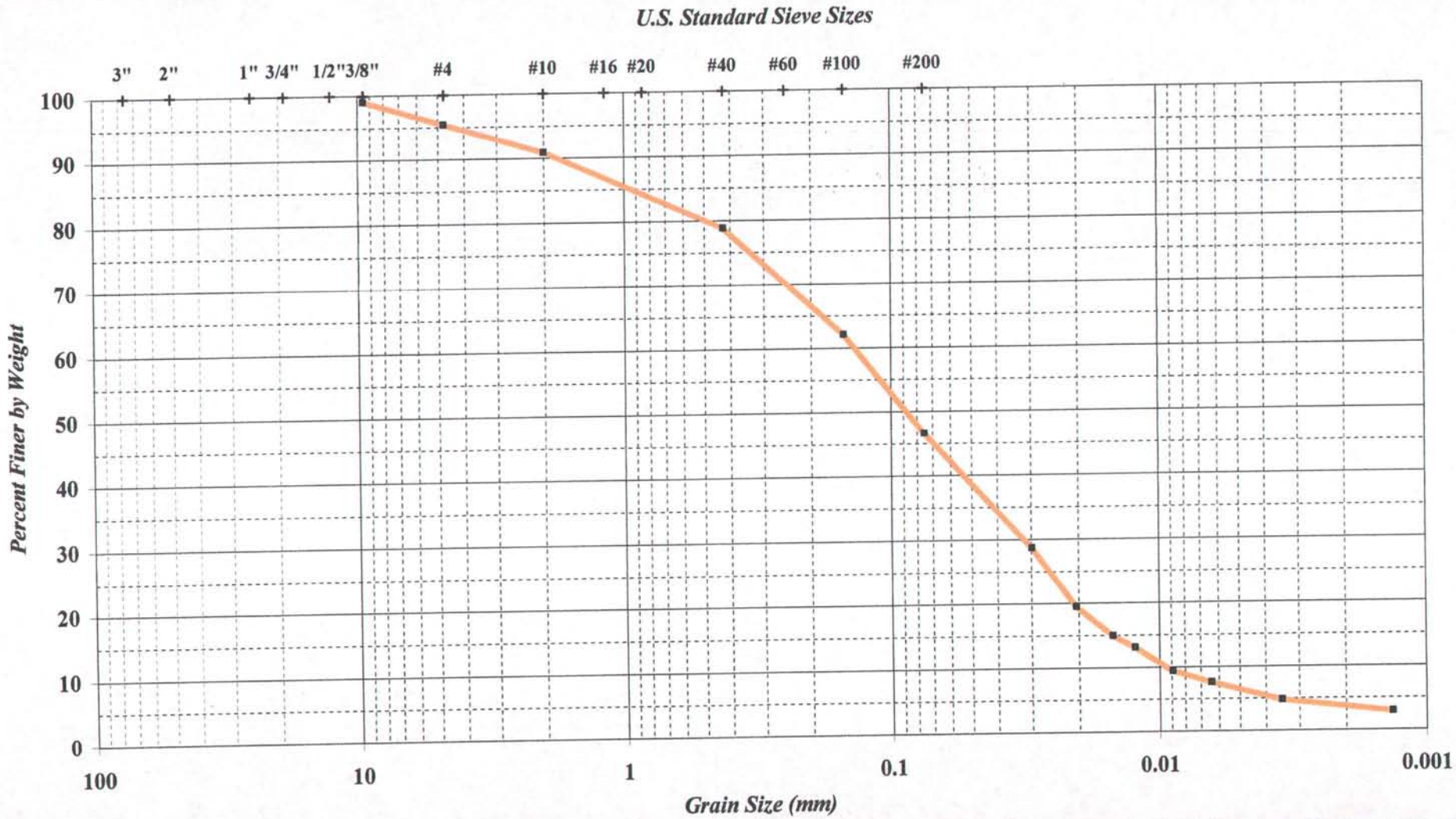
Job Name	Belew's Creek Ash Landfill	Depth	4-5.5 *feet*
		Nat. Moist.	na %
		Gs	2.6
Job Location	Greensboro, North Carolina	% Finer #200	71.8
		LL	34
Job Number	1264-00-157	PI	8

Boring No.	Soil Description/Classification
MW 2-3 SS#1	Dark Yellow-Tan medium to fine sandy SILT (ML)

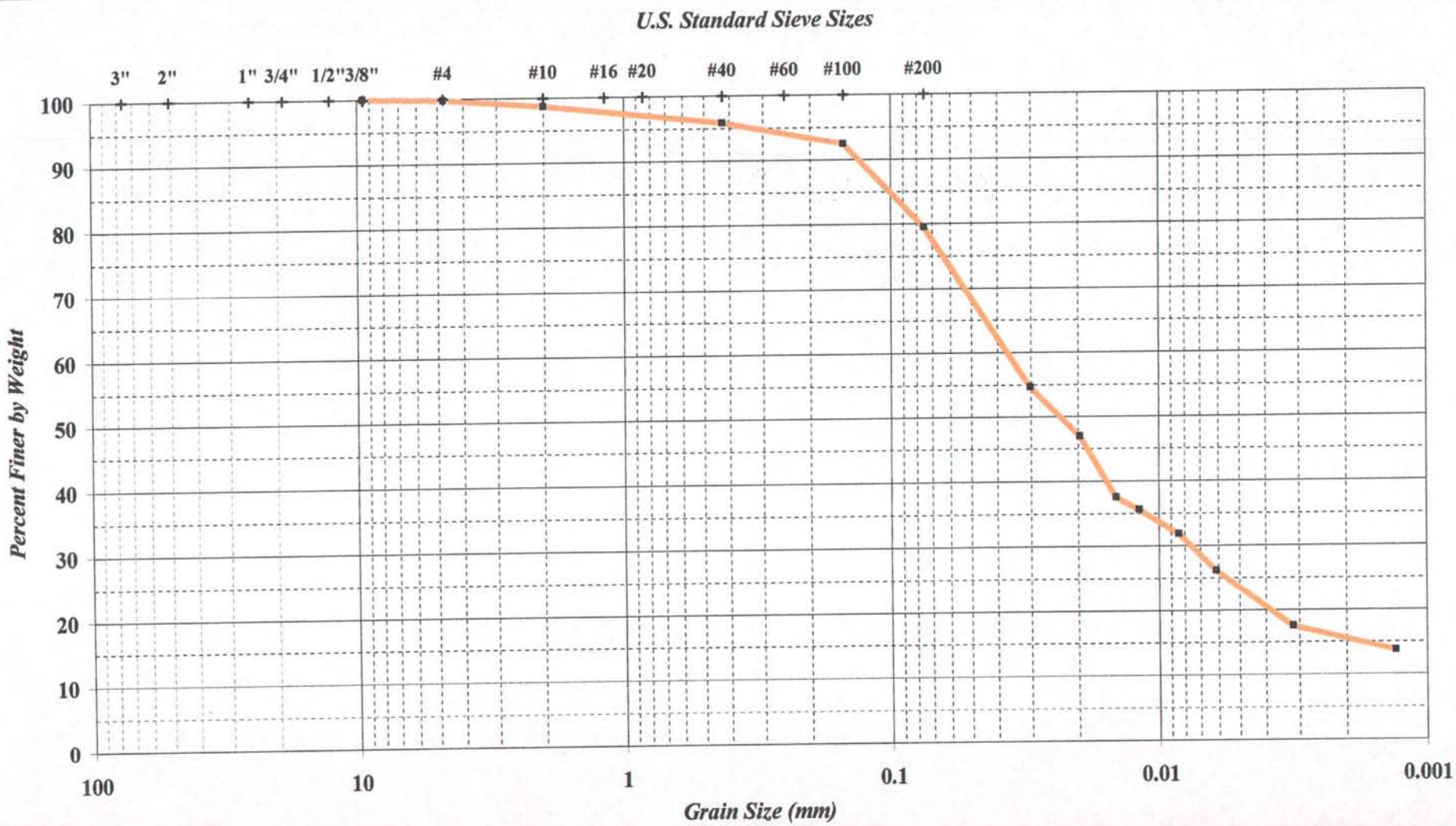
GRAIN SIZE DISTRIBUTION

ASTM D-421 and 422

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



Job Name	Belew's Creek Ash Landfill	Depth	34-35.4 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
Job Location	Greensboro, North Carolina	Gs	2.67	
		% Finer #200	46.6	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
Job Number	1264-00-157	LL	32	
		PI	3	
Boring No.	**Soil Description/Classification**			
MW 2-3 SS#7	Light Brown silty coarse to fine SAND (SM)			



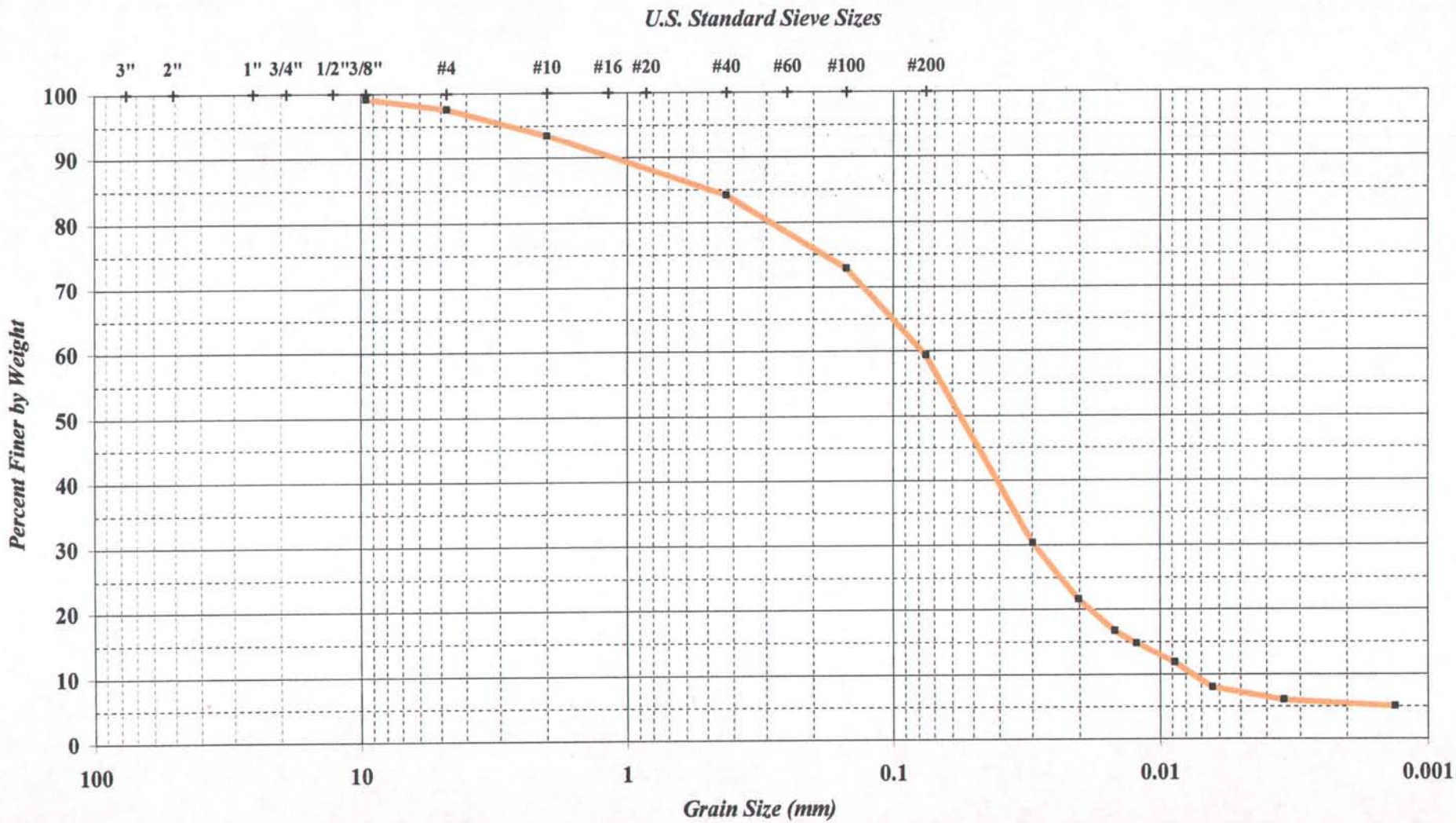
Job Name	Belew's Creek Ash Landfill	Depth	4-5.5 *feet*
		Nat. Moist.	na %
Job Location	Greensboro, North Carolina	Gs	2.64
		% Finer #200	79.5
Job Number	1264-00-157	LL	53
		PI	15

Boring No.	Soil Description/Classification
MW 2-4 SS#1	Light Orange-Brown medium to fine sandy elastic SILT (MH)

GRAIN SIZE DISTRIBUTION

ASTM D-421 and 422

S&ME
ENVIRONMENTAL SERVICES
ENGINEERING • TESTING



Job Name	Belew's Creek Ash Landfill	Depth	26-27.5 *feet*	**GRAIN SIZE DISTRIBUTION**
		Nat. Moist.	na %	*ASTM D-421 and 422*
Job Location	Greensboro, North Carolina	Gs	2.64	
		% Finer #200	59.3	S&ME ENVIRONMENTAL SERVICES ENGINEERING • TESTING
Job Number	1264-00-157	LL	32	
		PI	4	

Boring No.	Soil Description/Classification
MW 2-4 SS#5	Tan coarse to fine sandy SILT (ML)

Appendix 4

Appendix 4

HELP Model Runs

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**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04    (10 APRIL 1995)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:      C:\HELP3\PRE-5.D4
TEMPERATURE DATA FILE:        C:\HELP3\TEMP-5.D7
SOLAR RADIATION DATA FILE:    C:\HELP3\RAD-5.D13
EVAPOTRANSPIRATION DATA:      C:\HELP3\ET-5.D11
SOIL AND DESIGN DATA FILE:    C:\HELP3\4FTSOIL.D10
OUTPUT DATA FILE:             C:\HELP3\4FTSOIL.OUT


TIME:   7:24     DATE:  12/ 4/2001


******************************************************************************

     TITLE:  Belews Creek Landfill - Infiltration into Soil Only (4'Soil)

******************************************************************************


     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  96
          THICKNESS                    =     12.00   INCHES
          POROSITY                     =      0.5200 VOL/VOL
          FIELD CAPACITY               =      0.1960 VOL/VOL
          WILTING POINT                =      0.0610 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.2280 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.304999994000E-03 CM/SEC
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 98

THICKNESS	=	36.00	INCHES
POROSITY	=	0.5200	VOL/VOL
FIELD CAPACITY	=	0.1960	VOL/VOL
WILTING POINT	=	0.0610	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.2280	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.153000001000E-03	CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

Max SPLP.

SCS RUNOFF CURVE NUMBER	=	72.00	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	1.000	ACRES
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
INITIAL WATER IN EVAPORATIVE ZONE	=	2.052	INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.680	INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.549	INCHES
INITIAL SNOW WATER	=	0.000	INCHES
INITIAL WATER IN LAYER MATERIALS	=	10.944	INCHES
TOTAL INITIAL WATER	=	10.944	INCHES
TOTAL SUBSURFACE INFLOW	=	0.00	INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

STATION LATITUDE	=	35.13	DEGREES
MAXIMUM LEAF AREA INDEX	=	0.00	
START OF GROWING SEASON (JULIAN DATE)	=	90	
END OF GROWING SEASON (JULIAN DATE)	=	305	
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
AVERAGE ANNUAL WIND SPEED	=	7.60	MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	66.00	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	68.00	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	74.00	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	70.00	%

NOTE: PRECIPITATION DATA FOR GREENSBORO NORTH CAROLINA
WAS ENTERED FROM THE DEFAULT DATA FILE.

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
34.30	37.70	46.00	56.00	63.90	71.40
75.30	74.20	68.00	56.70	47.50	38.40

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

****

AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1974 THROUGH 1978

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	4.54	1.88	4.38	2.21	4.14	2.73
	5.32	4.79	5.44	3.60	2.36	3.98
STD. DEVIATIONS	2.16	1.22	2.58	1.21	2.31	1.09
	5.09	3.03	2.32	3.18	0.62	0.26
RUNOFF						
TOTALS	0.110	0.173	0.115	0.050	0.042	0.000
	0.350	0.133	0.351	0.228	0.000	0.003
STD. DEVIATIONS	0.172	0.386	0.258	0.112	0.094	0.000
	0.479	0.125	0.590	0.459	0.000	0.007
EVAPOTRANSPIRATION						
TOTALS	1.195	1.814	2.709	2.226	3.169	2.757
	2.959	2.719	2.765	2.099	1.511	1.283
STD. DEVIATIONS	0.361	0.389	0.625	0.626	1.838	1.051
	1.810	0.777	0.836	1.063	0.464	0.196

PERCOLATION/LEAKAGE THROUGH LAYER 2

TOTALS	2.0182	1.9978	1.6532	0.8394	1.0083	0.6399
	1.3636	1.9517	1.5754	1.2633	0.9621	0.9374
STD. DEVIATIONS	1.7238	0.9321	1.4502	0.6973	0.9579	0.3939
	1.5774	1.8829	1.6942	0.7017	0.6614	0.3485

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AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1974 THROUGH 1978

	INCHES		CU. FEET	PERCENT
PRECIPITATION	45.37	(10.898)	164693.1	100.00
RUNOFF	1.555	(0.8222)	5644.42	3.427
EVAPOTRANSPIRATION	27.206	(3.5059)	98759.48	59.966
PERCOLATION/LEAKAGE THROUGH LAYER 2	16.21022	(7.79065)	58843.102	35.72894
CHANGE IN WATER STORAGE	0.398	(1.3753)	1445.99	0.878

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PEAK DAILY VALUES FOR YEARS 1974 THROUGH 1978

	(INCHES)	(CU. FT.)
PRECIPITATION	4.73	17169.900
RUNOFF	1.387	5036.0254
PERCOLATION/LEAKAGE THROUGH LAYER 2	0.825121	2995.18799
SNOW WATER	2.69	9760.6875

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.5132
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0610

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FINAL WATER STORAGE AT END OF YEAR 1978

LAYER	(INCHES)	(VOL/VOL)
1	2.6111	0.2176
2	10.3246	0.2868
SNOW WATER	0.000	

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**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04   (10 APRIL 1995)                 **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:     C:\HELP3\PRE-5.D4
TEMPERATURE DATA FILE:       C:\HELP3\TEMP-5.D7
SOLAR RADIATION DATA FILE:   C:\HELP3\RAD-5.D13
EVAPOTRANSPIRATION DATA:     C:\HELP3\ET-5.D11
SOIL AND DESIGN DATA FILE:   C:\HELP3\AREA1-5.D10
OUTPUT DATA FILE:            C:\HELP3\AREA1-5.OUT


TIME:   7:14     DATE:  12/ 4/2001


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     TITLE:  BCS Landfill - Area 1 - Operational Period

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     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  99
          THICKNESS                    =    805.00   INCHES  67' Ash
          POROSITY                     =      0.4500 VOL/VOL
          FIELD CAPACITY               =      0.2150 VOL/VOL
          WILTING POINT                =      0.0570 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.1640 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.104999999000E-03 CM/SEC

                                          .000105 cm/sec =
                                          .012 ft/hr =
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 98

THICKNESS	=	48.00	INCHES
POROSITY	=	0.5200	VOL/VOL
FIELD CAPACITY	=	0.1960	VOL/VOL
WILTING POINT	=	0.0610	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.2280	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.153000001000E-03	CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

SCS RUNOFF CURVE NUMBER	=	72.00	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	19.600	ACRES
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
INITIAL WATER IN EVAPORATIVE ZONE	=	1.476	INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.050	INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.513	INCHES
INITIAL SNOW WATER	=	0.000	INCHES
INITIAL WATER IN LAYER MATERIALS	=	142.964	INCHES
TOTAL INITIAL WATER	=	142.964	INCHES
TOTAL SUBSURFACE INFLOW	=	0.00	INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

STATION LATITUDE	=	35.13	DEGREES
MAXIMUM LEAF AREA INDEX	=	0.00	
START OF GROWING SEASON (JULIAN DATE)	=	90	
END OF GROWING SEASON (JULIAN DATE)	=	305	
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
AVERAGE ANNUAL WIND SPEED	=	7.60	MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	66.00	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	68.00	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	74.00	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	70.00	%

NOTE: PRECIPITATION DATA FOR GREENSBORO NORTH CAROLINA
WAS ENTERED FROM THE DEFAULT DATA FILE.

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
34.30	37.70	46.00	56.00	63.90	71.40
75.30	74.20	68.00	56.70	47.50	38.40

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

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AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1974 THROUGH 1978

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	4.54	1.88	4.38	2.21	4.14	2.73
	5.32	4.79	5.44	3.60	2.36	3.98
STD. DEVIATIONS	2.16	1.22	2.58	1.21	2.31	1.09
	5.09	3.03	2.32	3.18	0.62	0.26
RUNOFF						
TOTALS	0.261	0.179	0.200	0.082	0.089	0.003
	0.629	0.348	0.649	0.378	0.000	0.060
STD. DEVIATIONS	0.359	0.401	0.448	0.184	0.188	0.004
	0.908	0.388	0.958	0.706	0.000	0.042
EVAPOTRANSPIRATION						
TOTALS	1.195	1.834	2.726	2.256	3.189	2.751
	2.971	2.726	2.798	2.097	1.529	1.284
STD. DEVIATIONS	0.361	0.384	0.620	0.637	1.859	1.040
	1.819	0.797	0.841	1.064	0.489	0.194

PERCOLATION/LEAKAGE THROUGH LAYER 2

TOTALS	0.1191	0.1096	0.1608	0.1003	0.1208	0.2777
	0.2499	0.3553	0.3190	0.2590	0.2184	0.4263
STD. DEVIATIONS	0.1800	0.1689	0.1994	0.1210	0.1137	0.3757
	0.2857	0.4194	0.4035	0.3643	0.3520	0.6752

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AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1974 THROUGH 1978

	INCHES		CU. FEET	PERCENT
PRECIPITATION	45.37	(10.898)	3227985.0	100.00
RUNOFF	2.879	(1.3643)	204836.47	6.346
EVAPOTRANSPIRATION	27.354	(3.4641)	1946174.87	60.291
PERCOLATION/LEAKAGE THROUGH LAYER 2	2.71632	(3.25355)	193260.844	5.98704
CHANGE IN WATER STORAGE	12.421	(6.5468)	883710.19	27.377

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PEAK DAILY VALUES FOR YEARS 1974 THROUGH 1978

	(INCHES)	(CU. FT.)
PRECIPITATION	4.73	336530.062
RUNOFF	2.292	163047.9690
PERCOLATION/LEAKAGE THROUGH LAYER 2	0.070161	4991.79346
SNOW WATER	2.69	191309.4840

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.4500
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0570

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FINAL WATER STORAGE AT END OF YEAR 1978

LAYER	(INCHES)	(VOL/VOL)
1	191.6786	0.2381
2	13.3890	0.2789
SNOW WATER	0.000	

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**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04    (10 APRIL 1995)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:      C:\HELP3\PRE-5.D4
TEMPERATURE DATA FILE:        C:\HELP3\TEMP-5.D7
SOLAR RADIATION DATA FILE:    C:\HELP3\RAD-5.D13
EVAPOTRANSPIRATION DATA:      C:\HELP3\ET-5.D11
SOIL AND DESIGN DATA FILE:    C:\HELP3\AREA2-5.D10
OUTPUT DATA FILE:             C:\HELP3\AREA2-5.OUT


TIME:   7:16     DATE:  12/ 4/2001


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     TITLE:  BCS Landfill - Area 2 - Operational Period

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     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  99
          THICKNESS                    =    988.00   INCHES
          POROSITY                     =      0.4500 VOL/VOL
          FIELD CAPACITY               =      0.2150 VOL/VOL
          WILTING POINT                =      0.0570 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.1640 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.104999999000E-03 CM/SEC
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 98

THICKNESS	=	48.00	INCHES
POROSITY	=	0.5200	VOL/VOL
FIELD CAPACITY	=	0.1960	VOL/VOL
WILTING POINT	=	0.0610	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.2280	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.153000001000E-03	CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

SCS RUNOFF CURVE NUMBER	=	72.00	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	27.500	ACRES
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
INITIAL WATER IN EVAPORATIVE ZONE	=	1.476	INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.050	INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.513	INCHES
INITIAL SNOW WATER	=	0.000	INCHES
INITIAL WATER IN LAYER MATERIALS	=	172.976	INCHES
TOTAL INITIAL WATER	=	172.976	INCHES
TOTAL SUBSURFACE INFLOW	=	0.00	INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

STATION LATITUDE	=	35.13	DEGREES
MAXIMUM LEAF AREA INDEX	=	0.00	
START OF GROWING SEASON (JULIAN DATE)	=	90	
END OF GROWING SEASON (JULIAN DATE)	=	305	
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
AVERAGE ANNUAL WIND SPEED	=	7.60	MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	66.00	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	68.00	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	74.00	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	70.00	%

NOTE: PRECIPITATION DATA FOR GREENSBORO NORTH CAROLINA
WAS ENTERED FROM THE DEFAULT DATA FILE.

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
34.30	37.70	46.00	56.00	63.90	71.40
75.30	74.20	68.00	56.70	47.50	38.40

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

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AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1974 THROUGH 1978

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	4.54	1.88	4.38	2.21	4.14	2.73
	5.32	4.79	5.44	3.60	2.36	3.98
STD. DEVIATIONS	2.16	1.22	2.58	1.21	2.31	1.09
	5.09	3.03	2.32	3.18	0.62	0.26
RUNOFF						
TOTALS	0.261	0.179	0.200	0.082	0.089	0.003
	0.629	0.348	0.649	0.376	0.000	0.060
STD. DEVIATIONS	0.359	0.401	0.448	0.184	0.188	0.004
	0.908	0.388	0.958	0.702	0.000	0.042
EVAPOTRANSPIRATION						
TOTALS	1.195	1.833	2.726	2.256	3.189	2.753
	2.967	2.722	2.797	2.097	1.526	1.285
STD. DEVIATIONS	0.361	0.384	0.619	0.637	1.859	1.041
	1.815	0.794	0.841	1.064	0.488	0.193

PERCOLATION/LEAKAGE THROUGH LAYER 2

TOTALS	0.0349	0.0324	0.0517	0.0641	0.0492	0.0699
	0.0862	0.1204	0.1445	0.1120	0.0420	0.2431
STD. DEVIATIONS	0.0671	0.0612	0.0884	0.1066	0.0960	0.0957
	0.1245	0.1932	0.2807	0.2505	0.0862	0.5295

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AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1974 THROUGH 1978

	INCHES		CU. FEET	PERCENT
PRECIPITATION	45.37	(10.898)	4529060.5	100.00
RUNOFF	2.877	(1.3660)	287239.87	6.342
EVAPOTRANSPIRATION	27.346	(3.4614)	2729791.25	60.273
PERCOLATION/LEAKAGE THROUGH LAYER 2	1.05028	(1.60923)	104844.523	2.31493
CHANGE IN WATER STORAGE	14.096	(5.7587)	1407181.25	31.070

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PEAK DAILY VALUES FOR YEARS 1974 THROUGH 1978

	(INCHES)	(CU. FT.)
PRECIPITATION	4.73	472172.250
RUNOFF	2.292	228766.3750
PERCOLATION/LEAKAGE THROUGH LAYER 2	0.059105	5900.15137
SNOW WATER	2.69	268418.9060

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.4500
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0570

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FINAL WATER STORAGE AT END OF YEAR 1978

LAYER	(INCHES)	(VOL/VOL)
1	230.2171	0.2330
2	13.2413	0.2759
SNOW WATER	0.000	

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**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04   (10 APRIL 1995)                 **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:     C:\HELP3\PRE-5.D4
TEMPERATURE DATA FILE:       C:\HELP3\TEMP-5.D7
SOLAR RADIATION DATA FILE:   C:\HELP3\RAD-5.D13
EVAPOTRANSPIRATION DATA:     C:\HELP3\ET-5.D11
SOIL AND DESIGN DATA FILE:   C:\HELP3\AREA3-5.D10
OUTPUT DATA FILE:            C:\HELP3\AREA3-5.OUT


TIME:   7:28     DATE:  12/ 4/2001


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     TITLE:  BCS Landfill - Area 3 - Operational Period

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     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                LAYER  1
                                --------

                 TYPE 1 - VERTICAL PERCOLATION LAYER
                     MATERIAL TEXTURE NUMBER  99
          THICKNESS                  =    431.00   INCHES
          POROSITY                   =      0.4500 VOL/VOL
          FIELD CAPACITY             =      0.2150 VOL/VOL
          WILTING POINT              =      0.0570 VOL/VOL
          INITIAL SOIL WATER CONTENT =      0.1640 VOL/VOL
          EFFECTIVE SAT. HYD. COND.  =  0.104999999000E-03 CM/SEC
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 98

THICKNESS	=	48.00	INCHES
POROSITY	=	0.5200	VOL/VOL
FIELD CAPACITY	=	0.1960	VOL/VOL
WILTING POINT	=	0.0610	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.2280	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.153000001000E-03	CM/SEC

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

SCS RUNOFF CURVE NUMBER	=	72.00	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	5.000	ACRES
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
INITIAL WATER IN EVAPORATIVE ZONE	=	1.476	INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.050	INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.513	INCHES
INITIAL SNOW WATER	=	0.000	INCHES
INITIAL WATER IN LAYER MATERIALS	=	81.628	INCHES
TOTAL INITIAL WATER	=	81.628	INCHES
TOTAL SUBSURFACE INFLOW	=	0.00	INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

STATION LATITUDE	=	35.13	DEGREES
MAXIMUM LEAF AREA INDEX	=	0.00	
START OF GROWING SEASON (JULIAN DATE)	=	90	
END OF GROWING SEASON (JULIAN DATE)	=	305	
EVAPORATIVE ZONE DEPTH	=	9.0	INCHES
AVERAGE ANNUAL WIND SPEED	=	7.60	MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	66.00	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	68.00	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	74.00	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	70.00	%

NOTE: PRECIPITATION DATA FOR GREENSBORO NORTH CAROLINA
WAS ENTERED FROM THE DEFAULT DATA FILE.

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
34.30	37.70	46.00	56.00	63.90	71.40
75.30	74.20	68.00	56.70	47.50	38.40

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

****

AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1974 THROUGH 1978

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	4.54	1.88	4.38	2.21	4.14	2.73
	5.32	4.79	5.44	3.60	2.36	3.98
STD. DEVIATIONS	2.16	1.22	2.58	1.21	2.31	1.09
	5.09	3.03	2.32	3.18	0.62	0.26
RUNOFF						
TOTALS	0.261	0.179	0.200	0.082	0.089	0.003
	0.629	0.348	0.649	0.378	0.000	0.060
STD. DEVIATIONS	0.359	0.401	0.448	0.184	0.188	0.004
	0.908	0.388	0.958	0.706	0.000	0.042
EVAPOTRANSPIRATION						
TOTALS	1.195	1.834	2.725	2.259	3.189	2.754
	2.960	2.731	2.791	2.097	1.529	1.283
STD. DEVIATIONS	0.361	0.384	0.608	0.635	1.859	1.041
	1.819	0.791	0.841	1.064	0.489	0.195

PERCOLATION/LEAKAGE THROUGH LAYER 2

TOTALS	0.5077	0.4368	0.3322	0.3667	0.8292	0.6048
	0.6607	0.7298	0.6214	0.7066	0.7827	0.9060
STD. DEVIATIONS	0.5697	0.3864	0.2938	0.2563	0.6521	0.5094
	0.4970	0.6180	0.4430	0.4451	0.8781	0.7556

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AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1974 THROUGH 1978

	INCHES		CU. FEET	PERCENT
PRECIPITATION	45.37	(10.898)	823465.6	100.00
RUNOFF	2.879	(1.3642)	52256.29	6.346
EVAPOTRANSPIRATION	27.346	(3.4590)	496331.22	60.273
PERCOLATION/LEAKAGE THROUGH LAYER 2	7.48465	(5.22519)	135846.359	16.49691
CHANGE IN WATER STORAGE	7.660	(9.3144)	139031.09	16.884

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PEAK DAILY VALUES FOR YEARS 1974 THROUGH 1978

	(INCHES)	(CU. FT.)
PRECIPITATION	4.73	85849.500
RUNOFF	2.292	41593.8477
PERCOLATION/LEAKAGE THROUGH LAYER 2	0.091176	1654.84937
SNOW WATER	2.69	48803.4414

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.4500
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0570

****

****

FINAL WATER STORAGE AT END OF YEAR 1978

LAYER	(INCHES)	(VOL/VOL)
1	106.3972	0.2469
2	13.5313	0.2819
SNOW WATER	0.000	

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**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04    (10 APRIL 1995)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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******************************************************************************


PRECIPITATION DATA FILE:     C:\HELP3\P100.D4
TEMPERATURE DATA FILE:       C:\HELP3\T100.D7
SOLAR RADIATION DATA FILE:   C:\HELP3\S100.D13
EVAPOTRANSPIRATION DATA:     C:\HELP3\ET100.D11
SOIL AND DESIGN DATA FILE:   C:\HELP3\AREA1PO.D10
OUTPUT DATA FILE:            C:\HELP3\AREA1PO.OUT


TIME:   9:23     DATE:  12/10/2001


******************************************************************************

     TITLE:  BCS Landfill - Area 1 - Post Operational Period

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     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  96
          THICKNESS                    =      9.00   INCHES
          POROSITY                     =      0.4300 VOL/VOL
          FIELD CAPACITY               =      0.2060 VOL/VOL
          WILTING POINT                =      0.0980 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.1720 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.345999986000E-03 CM/SEC
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 0

THICKNESS	=	15.00	INCHES
POROSITY	=	0.4300	VOL/VOL
FIELD CAPACITY	=	0.2060	VOL/VOL
WILTING POINT	=	0.0980	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.1720	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.115000003000E-03	CM/SEC

LAYER 3

TYPE 2 - LATERAL DRAINAGE LAYER
MATERIAL TEXTURE NUMBER 20

THICKNESS	=	0.20	INCHES
POROSITY	=	0.8500	VOL/VOL
FIELD CAPACITY	=	0.0100	VOL/VOL
WILTING POINT	=	0.0050	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	10.0000000000	CM/SEC
SLOPE	=	21.00	PERCENT
DRAINAGE LENGTH	=	800.0	FEET

25 = 4.76:1

LAYER 4

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 35

THICKNESS	=	0.04	INCHES
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.	=	0.199999996000E-12	CM/SEC
FML PINHOLE DENSITY	=	1.00	HOLES/ACRE
FML INSTALLATION DEFECTS	=	4.00	HOLES/ACRE
FML PLACEMENT QUALITY	=	3 - GOOD	

LAYER 5

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 99

```
THICKNESS                    =    806.00   INCHES
POROSITY                     =      0.4500 VOL/VOL
FIELD CAPACITY               =      0.2150 VOL/VOL
WILTING POINT                =      0.0570 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1640 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.104999999000E-03 CM/SEC
```

LAYER 6

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 97

```
THICKNESS                    =     48.00   INCHES
POROSITY                     =      0.5200 VOL/VOL
FIELD CAPACITY               =      0.1960 VOL/VOL
WILTING POINT                =      0.0610 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.2280 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.153000001000E-03 CM/SEC
```

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

```
SCS RUNOFF CURVE NUMBER              =     72.00
FRACTION OF AREA ALLOWING RUNOFF     =    100.0    PERCENT
AREA PROJECTED ON HORIZONTAL PLANE   =     19.600  ACRES
EVAPORATIVE ZONE DEPTH               =     18.0    INCHES
INITIAL WATER IN EVAPORATIVE ZONE    =      3.096  INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE   =      7.740  INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE   =      1.764  INCHES
INITIAL SNOW WATER                   =      0.000  INCHES
INITIAL WATER IN LAYER MATERIALS     =    147.256  INCHES
TOTAL INITIAL WATER                  =    147.256  INCHES
TOTAL SUBSURFACE INFLOW              =      0.00   INCHES/YEAR
```

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

```
STATION LATITUDE                          =  35.13 DEGREES
MAXIMUM LEAF AREA INDEX                   =   2.00
START OF GROWING SEASON (JULIAN DATE)     =     90
END OF GROWING SEASON (JULIAN DATE)       =    305
EVAPORATIVE ZONE DEPTH                    =  18.0  INCHES
```

AVERAGE ANNUAL WIND SPEED = 7.60 MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 66.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 68.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 74.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 70.00 %

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
3.51	3.37	3.88	3.16	3.37	3.93
4.27	4.19	3.64	3.18	2.59	3.38

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
37.50	39.90	48.00	58.30	66.50	73.50
77.20	76.30	69.90	58.40	48.50	40.20

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

****

AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 100

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	3.47	3.45	4.14	3.02	3.20	3.83
	4.43	4.33	3.83	3.11	2.68	3.18
STD. DEVIATIONS	1.75	1.75	1.93	1.43	1.66	2.04
	2.01	2.19	2.50	2.02	1.61	1.98
RUNOFF						

TOTALS	0.044	0.128	0.038	0.002	0.016	0.020
	0.009	0.026	0.072	0.033	0.011	0.053
STD. DEVIATIONS	0.198	0.441	0.136	0.007	0.063	0.092
	0.044	0.085	0.186	0.094	0.046	0.174

EVAPOTRANSPIRATION

TOTALS	1.287	1.641	2.785	3.048	3.653	3.827
	4.108	3.209	2.673	2.630	1.186	1.079
STD. DEVIATIONS	0.245	0.280	0.461	0.776	0.945	1.503
	1.498	1.072	0.805	0.832	0.332	0.225

LATERAL DRAINAGE COLLECTED FROM LAYER 3

TOTALS	1.8437	1.8335	1.7233	0.7521	0.4829	0.2482
	0.2288	0.3687	0.8211	0.7268	0.6894	1.3581
STD. DEVIATIONS	1.4833	1.4138	1.3396	0.6966	0.6865	0.3102
	0.4795	0.7278	1.1392	0.8922	1.1041	1.5043

PERCOLATION/LEAKAGE THROUGH LAYER 4

TOTALS	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001
	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002
STD. DEVIATIONS	0.0002	0.0001	0.0002	0.0001	0.0001	0.0000
	0.0001	0.0001	0.0002	0.0001	0.0001	0.0003

PERCOLATION/LEAKAGE THROUGH LAYER 6

TOTALS	0.0015	0.0014	0.0020	0.0025	0.0022	0.0017
	0.0016	0.0016	0.0008	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0154	0.0141	0.0204	0.0246	0.0220	0.0174
	0.0159	0.0158	0.0080	0.0000	0.0000	0.0000

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)

DAILY AVERAGE HEAD ON TOP OF LAYER 4

AVERAGES	0.0042	0.0047	0.0046	0.0018	0.0012	0.0006
	0.0006	0.0009	0.0031	0.0016	0.0017	0.0060
STD. DEVIATIONS	0.0036	0.0041	0.0082	0.0016	0.0021	0.0007
	0.0017	0.0021	0.0117	0.0020	0.0031	0.0251

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

	INCHES		CU. FEET	PERCENT
PRECIPITATION	42.67	(6.674)	3035871.2	100.00
RUNOFF	0.451	(0.5527)	32099.13	1.057
EVAPOTRANSPIRATION	31.127	(3.1654)	2214618.00	72.948
LATERAL DRAINAGE COLLECTED FROM LAYER 3	11.07664	(4.38230)	788080.875	25.95897
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.00159	(0.00058)	113.100	0.00373
AVERAGE HEAD ON TOP OF LAYER 4	0.003	(0.002)		
PERCOLATION/LEAKAGE THROUGH LAYER 6	0.01536	(0.15360)	1092.833	0.03600
CHANGE IN WATER STORAGE	-0.001	(1.2527)	-73.00	-0.002

****

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PEAK DAILY VALUES FOR YEARS 1 THROUGH 100

	(INCHES)	(CU. FT.)
PRECIPITATION	5.93	421907.625
RUNOFF	1.773	126142.3440
DRAINAGE COLLECTED FROM LAYER 3	2.00796	142862.23400
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.002078	147.87112
AVERAGE HEAD ON TOP OF LAYER 4	5.888	
MAXIMUM HEAD ON TOP OF LAYER 4	63.332	
PERCOLATION/LEAKAGE THROUGH LAYER 6	0.010563	751.50391
SNOW WATER	4.59	326645.1870

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.3927
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0980

*** MAXIMUM HEADS ARE COMPUTED USING THE MOUND EQUATION. ***

****

****

FINAL WATER STORAGE AT END OF YEAR 100

LAYER	(INCHES)	(VOL/VOL)
1	1.7866	0.1985
2	3.6138	0.2409
3	0.0020	0.0100
4	0.0000	0.0000
5	132.3430	0.1642
6	9.4080	0.1960
SNOW WATER	0.000	

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**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04    (10 APRIL 1995)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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PRECIPITATION DATA FILE:      C:\HELP3\P100.D4
TEMPERATURE DATA FILE:        C:\HELP3\T100.D7
SOLAR RADIATION DATA FILE:    C:\HELP3\S100.D13
EVAPOTRANSPIRATION DATA:      C:\HELP3\ET100.D11
SOIL AND DESIGN DATA FILE:    C:\HELP3\AREA2PO.D10
OUTPUT DATA FILE:             C:\HELP3\AREA2PO.OUT


TIME:   9:26     DATE:  12/10/2001


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     TITLE:  BCS Landfill - Area 2 - Post Operational Period

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     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  96
          THICKNESS                    =       9.00   INCHES
          POROSITY                     =       0.4300 VOL/VOL
          FIELD CAPACITY               =       0.2060 VOL/VOL
          WILTING POINT                =       0.0980 VOL/VOL
          INITIAL SOIL WATER CONTENT   =       0.1720 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.345999986000E-03 CM/SEC
```

top soil
soil

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 98

THICKNESS	=	15.00	INCHES
POROSITY	=	0.4300	VOL/VOL
FIELD CAPACITY	=	0.2060	VOL/VOL
WILTING POINT	=	0.0980	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.1720	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.115000003000E-03	CM/SEC

? 15" b cover ✓

LAYER 3

TYPE 2 - LATERAL DRAINAGE LAYER
MATERIAL TEXTURE NUMBER 20

THICKNESS	=	0.20	INCHES
POROSITY	=	0.8500	VOL/VOL
FIELD CAPACITY	=	0.0100	VOL/VOL
WILTING POINT	=	0.0050	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	10.0000000000	CM/SEC
SLOPE	=	27.00	PERCENT
DRAINAGE LENGTH	=	1000.0	FEET

LAYER 4

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 35

THICKNESS	=	0.04	INCHES
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.	=	0.199999996000E-12	CM/SEC
FML PINHOLE DENSITY	=	1.00	HOLES/ACRE
FML INSTALLATION DEFECTS	=	4.00	HOLES/ACRE
FML PLACEMENT QUALITY	=	3 - GOOD	

LAYER 5

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 99

```
THICKNESS                    =    988.00   INCHES
POROSITY                     =      0.4500 VOL/VOL
FIELD CAPACITY               =      0.2150 VOL/VOL
WILTING POINT                =      0.0570 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1640 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.104999999000E-03 CM/SEC
```

LAYER 6

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 97

```
THICKNESS                    =     48.00   INCHES
POROSITY                     =      0.5200 VOL/VOL
FIELD CAPACITY               =      0.1960 VOL/VOL
WILTING POINT                =      0.0610 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.2280 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.153000001000E-03 CM/SEC
```

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

```
SCS RUNOFF CURVE NUMBER              =     72.00
FRACTION OF AREA ALLOWING RUNOFF     =    100.0    PERCENT
AREA PROJECTED ON HORIZONTAL PLANE   =     27.400  ACRES
EVAPORATIVE ZONE DEPTH               =     18.0    INCHES
INITIAL WATER IN EVAPORATIVE ZONE    =      3.096  INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE   =      7.740  INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE   =      1.764  INCHES
INITIAL SNOW WATER                   =      0.000  INCHES
INITIAL WATER IN LAYER MATERIALS     =    177.104  INCHES
TOTAL INITIAL WATER                  =    177.104  INCHES
TOTAL SUBSURFACE INFLOW              =      0.00   INCHES/YEAR
```

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

```
STATION LATITUDE                          =  35.13 DEGREES
MAXIMUM LEAF AREA INDEX                   =   2.00
START OF GROWING SEASON (JULIAN DATE)     =     90
END OF GROWING SEASON (JULIAN DATE)       =    305
EVAPORATIVE ZONE DEPTH                    =  18.0  INCHES
```

AVERAGE ANNUAL WIND SPEED = 7.60 MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 66.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 68.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 74.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 70.00 %

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
3.51	3.37	3.88	3.16	3.37	3.93
4.27	4.19	3.64	3.18	2.59	3.38

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
37.50	39.90	48.00	58.30	66.50	73.50
77.20	76.30	69.90	58.40	48.50	40.20

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

****

AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 100

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	3.47	3.45	4.14	3.02	3.20	3.83
	4.43	4.33	3.83	3.11	2.68	3.18
STD. DEVIATIONS	1.75	1.75	1.93	1.43	1.66	2.04
	2.01	2.19	2.50	2.02	1.61	1.98
RUNOFF						

TOTALS	0.044	0.128	0.039	0.002	0.016	0.020
	0.009	0.026	0.073	0.033	0.011	0.053
STD. DEVIATIONS	0.198	0.442	0.137	0.007	0.063	0.092
	0.044	0.085	0.189	0.095	0.046	0.174

EVAPOTRANSPIRATION

TOTALS	1.288	1.642	2.787	3.050	3.648	3.817
	4.091	3.194	2.669	2.623	1.187	1.079
STD. DEVIATIONS	0.245	0.281	0.464	0.777	0.946	1.500
	1.497	1.074	0.810	0.836	0.333	0.226

LATERAL DRAINAGE COLLECTED FROM LAYER 3

TOTALS	1.8437	1.8321	1.7200	0.7529	0.4793	0.2554
	0.2393	0.3831	0.8293	0.7390	0.6930	1.3592
STD. DEVIATIONS	1.4823	1.4119	1.3412	0.6977	0.6833	0.3142
	0.4789	0.7268	1.1352	0.8949	1.1019	1.5004

PERCOLATION/LEAKAGE THROUGH LAYER 4

TOTALS	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001
	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002
STD. DEVIATIONS	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000
	0.0001	0.0001	0.0002	0.0001	0.0001	0.0003

PERCOLATION/LEAKAGE THROUGH LAYER 6

TOTALS	0.0015	0.0014	0.0020	0.0025	0.0022	0.0017
	0.0016	0.0016	0.0008	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0154	0.0141	0.0204	0.0246	0.0220	0.0174
	0.0159	0.0158	0.0080	0.0000	0.0000	0.0000

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)

DAILY AVERAGE HEAD ON TOP OF LAYER 4

AVERAGES	0.0042	0.0048	0.0041	0.0018	0.0011	0.0006
	0.0005	0.0009	0.0030	0.0017	0.0018	0.0055
STD. DEVIATIONS	0.0035	0.0047	0.0044	0.0016	0.0015	0.0007
	0.0011	0.0020	0.0112	0.0020	0.0034	0.0231

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

	INCHES		CU. FEET	PERCENT
PRECIPITATION	42.67	(6.674)	4244024.0	100.00
RUNOFF	0.454	(0.5547)	45175.31	1.064
EVAPOTRANSPIRATION	31.074	(3.1755)	3090693.00	72.825
LATERAL DRAINAGE COLLECTED FROM LAYER 3	11.12627	(4.36804)	1106641.120	26.07528
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.00159	(0.00055)	158.183	0.00373
AVERAGE HEAD ON TOP OF LAYER 4	0.003	(0.002)		
PERCOLATION/LEAKAGE THROUGH LAYER 6	0.01536	(0.15360)	1527.736	0.03600
CHANGE IN WATER STORAGE	-0.001	(1.2507)	-87.68	-0.002

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PEAK DAILY VALUES FOR YEARS 1 THROUGH 100

	(INCHES)	(CU. FT.)
PRECIPITATION	5.93	589809.625
RUNOFF	1.773	176350.5000
DRAINAGE COLLECTED FROM LAYER 3	1.99466	198393.10900
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.001985	197.42455
AVERAGE HEAD ON TOP OF LAYER 4	5.580	
MAXIMUM HEAD ON TOP OF LAYER 4	76.775	
PERCOLATION/LEAKAGE THROUGH LAYER 6	0.010563	1050.57178
SNOW WATER	4.59	456636.6560

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.3935
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0980

*** MAXIMUM HEADS ARE COMPUTED USING THE MOUND EQUATION. ***

****

****

FINAL WATER STORAGE AT END OF YEAR 100

LAYER	(INCHES)	(VOL/VOL)
1	1.7945	0.1994
2	3.6203	0.2414
3	0.0020	0.0100
4	0.0000	0.0000
5	162.1910	0.1642
6	9.4080	0.1960
SNOW WATER	0.000	

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**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.04    (10 APRIL 1995)                **
**                  DEVELOPED BY ENVIRONMENTAL LABORATORY                   **
**                    USAE WATERWAYS EXPERIMENT STATION                     **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
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******************************************************************************


PRECIPITATION DATA FILE:     C:\HELP3\P100.D4
TEMPERATURE DATA FILE:       C:\HELP3\T100.D7
SOLAR RADIATION DATA FILE:   C:\HELP3\S100.D13
EVAPOTRANSPIRATION DATA:     C:\HELP3\ET100.D11
SOIL AND DESIGN DATA FILE:   C:\HELP3\AREA3PO.D10
OUTPUT DATA FILE:            C:\HELP3\AREA3PO.OUT


TIME:   9:32     DATE:  12/10/2001


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     TITLE:  BCS Landfill - Area 3 - Post Operational Period

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     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.


                                  LAYER  1
                                  --------

                     TYPE 1 - VERTICAL PERCOLATION LAYER
                         MATERIAL TEXTURE NUMBER  96
          THICKNESS                    =      9.00   INCHES
          POROSITY                     =      0.4300 VOL/VOL
          FIELD CAPACITY               =      0.2060 VOL/VOL
          WILTING POINT                =      0.0980 VOL/VOL
          INITIAL SOIL WATER CONTENT   =      0.1720 VOL/VOL
          EFFECTIVE SAT. HYD. COND.    =  0.345999986000E-03 CM/SEC
```

LAYER 2

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 98

THICKNESS	=	15.00	INCHES
POROSITY	=	0.4300	VOL/VOL
FIELD CAPACITY	=	0.2060	VOL/VOL
WILTING POINT	=	0.0980	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.1720	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.115000003000E-03	CM/SEC

LAYER 3

TYPE 2 - LATERAL DRAINAGE LAYER
MATERIAL TEXTURE NUMBER 20

THICKNESS	=	0.20	INCHES
POROSITY	=	0.8500	VOL/VOL
FIELD CAPACITY	=	0.0100	VOL/VOL
WILTING POINT	=	0.0050	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	10.0000000000	CM/SEC
SLOPE	=	29.00	PERCENT
DRAINAGE LENGTH	=	350.0	FEET

LAYER 4

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 35

THICKNESS	=	0.04	INCHES
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.	=	0.199999996000E-12	CM/SEC
FML PINHOLE DENSITY	=	1.00	HOLES/ACRE
FML INSTALLATION DEFECTS	=	4.00	HOLES/ACRE
FML PLACEMENT QUALITY	=	3 - GOOD	

LAYER 5

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 99

```
THICKNESS                    =    431.00   INCHES
POROSITY                     =      0.4500 VOL/VOL
FIELD CAPACITY               =      0.2150 VOL/VOL
WILTING POINT                =      0.0570 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1640 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.104999999000E-03 CM/SEC
```

LAYER 6

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 97

```
THICKNESS                    =     48.00   INCHES
POROSITY                     =      0.5200 VOL/VOL
FIELD CAPACITY               =      0.1960 VOL/VOL
WILTING POINT                =      0.0610 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.2280 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.153000001000E-03 CM/SEC
```

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS USER-SPECIFIED.

```
SCS RUNOFF CURVE NUMBER              =     72.00
FRACTION OF AREA ALLOWING RUNOFF     =    100.0     PERCENT
AREA PROJECTED ON HORIZONTAL PLANE   =      5.300   ACRES
EVAPORATIVE ZONE DEPTH               =     18.0     INCHES
INITIAL WATER IN EVAPORATIVE ZONE    =      3.096   INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE   =      7.740   INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE   =      1.764   INCHES
INITIAL SNOW WATER                   =      0.000   INCHES
INITIAL WATER IN LAYER MATERIALS     =     85.756   INCHES
TOTAL INITIAL WATER                  =     85.756   INCHES
TOTAL SUBSURFACE INFLOW              =      0.00    INCHES/YEAR
```

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
GREENSBORO NORTH CAROLINA

```
STATION LATITUDE                          =  35.13 DEGREES
MAXIMUM LEAF AREA INDEX                   =   2.00
START OF GROWING SEASON (JULIAN DATE)     =     90
END OF GROWING SEASON (JULIAN DATE)       =    305
EVAPORATIVE ZONE DEPTH                    =  18.0  INCHES
```

AVERAGE ANNUAL WIND SPEED = 7.60 MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 66.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 68.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 74.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 70.00 %

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY PRECIPITATION (INCHES)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
3.51	3.37	3.88	3.16	3.37	3.93
4.27	4.19	3.64	3.18	2.59	3.38

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
37.50	39.90	48.00	58.30	66.50	73.50
77.20	76.30	69.90	58.40	48.50	40.20

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR GREENSBORO NORTH CAROLINA
AND STATION LATITUDE = 35.13 DEGREES

****

AVERAGE MONTHLY VALUES IN INCHES FOR YEARS 1 THROUGH 100

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	3.47	3.45	4.14	3.02	3.20	3.83
	4.43	4.33	3.83	3.11	2.68	3.18
STD. DEVIATIONS	1.75	1.75	1.93	1.43	1.66	2.04
	2.01	2.19	2.50	2.02	1.61	1.98
RUNOFF						

```
------
  TOTALS                  0.044    0.129    0.043    0.002    0.017    0.021
                          0.009    0.027    0.077    0.034    0.011    0.056

  STD. DEVIATIONS         0.198    0.443    0.146    0.008    0.066    0.095
                          0.043    0.086    0.215    0.097    0.048    0.186

EVAPOTRANSPIRATION
------------------
  TOTALS                  1.204    1.561    2.683    3.034    3.650    3.605
                          3.736    2.919    2.481    2.438    1.112    0.987

  STD. DEVIATIONS         0.269    0.309    0.461    0.734    0.923    1.466
                          1.396    1.054    0.845    0.881    0.349    0.256

LATERAL DRAINAGE COLLECTED FROM LAYER  3
----------------------------------------
  TOTALS                  1.8806   1.8310   1.7730   0.7917   0.5039   0.4100
                          0.5735   0.7273   1.0861   0.9018   0.7866   1.5130

  STD. DEVIATIONS         1.4249   1.4030   1.3368   0.7264   0.6811   0.3606
                          0.4978   0.6984   1.0128   0.8416   1.0413   1.3728

PERCOLATION/LEAKAGE THROUGH LAYER  4
-------------------------------------
  TOTALS                  0.0001   0.0001   0.0001   0.0001   0.0000   0.0000
                          0.0000   0.0001   0.0001   0.0001   0.0000   0.0001

  STD. DEVIATIONS         0.0001   0.0001   0.0001   0.0000   0.0000   0.0000
                          0.0000   0.0000   0.0000   0.0000   0.0000   0.0001

PERCOLATION/LEAKAGE THROUGH LAYER  6
-------------------------------------
  TOTALS                  0.0015   0.0014   0.0020   0.0025   0.0022   0.0017
                          0.0016   0.0016   0.0008   0.0000   0.0000   0.0000

  STD. DEVIATIONS         0.0154   0.0141   0.0204   0.0246   0.0220   0.0174
                          0.0159   0.0158   0.0080   0.0000   0.0000   0.0000


-------------------------------------------------------------------------------
              AVERAGES OF MONTHLY AVERAGED DAILY HEADS (INCHES)
-------------------------------------------------------------------------------


DAILY AVERAGE HEAD ON TOP OF LAYER  4
-------------------------------------
  AVERAGES                0.0014   0.0015   0.0013   0.0006   0.0004   0.0003
                          0.0004   0.0005   0.0008   0.0007   0.0006   0.0011

  STD. DEVIATIONS         0.0011   0.0012   0.0010   0.0006   0.0005   0.0003
                          0.0004   0.0005   0.0008   0.0006   0.0008   0.0010

*******************************************************************************
```

****

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

	INCHES		CU. FEET	PERCENT
PRECIPITATION	42.67	(6.674)	820924.4	100.00
RUNOFF	0.468	(0.5683)	9003.40	1.097
EVAPOTRANSPIRATION	29.409	(3.2370)	565802.19	68.923
LATERAL DRAINAGE COLLECTED FROM LAYER 3	12.77836	(4.20868)	245842.812	29.94707
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.00078	(0.00019)	15.039	0.00183
AVERAGE HEAD ON TOP OF LAYER 4	0.001	(0.000)		
PERCOLATION/LEAKAGE THROUGH LAYER 6	0.01536	(0.15360)	295.511	0.03600
CHANGE IN WATER STORAGE	-0.002	(1.2688)	-33.92	-0.004

****

****

PEAK DAILY VALUES FOR YEARS 1 THROUGH 100

	(INCHES)	(CU. FT.)
PRECIPITATION	5.93	114087.273
RUNOFF	1.780	34250.3047
DRAINAGE COLLECTED FROM LAYER 3	1.97949	38083.32810
PERCOLATION/LEAKAGE THROUGH LAYER 4	0.000053	1.02113
AVERAGE HEAD ON TOP OF LAYER 4	0.046	
MAXIMUM HEAD ON TOP OF LAYER 4	5.058	
PERCOLATION/LEAKAGE THROUGH LAYER 6	0.010563	203.21281
SNOW WATER	4.59	88327.5312

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.4180
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0980

*** MAXIMUM HEADS ARE COMPUTED USING THE MOUND EQUATION. ***

****

****

FINAL WATER STORAGE AT END OF YEAR 100

LAYER	(INCHES)	(VOL/VOL)
1	1.9774	0.2197
2	3.4295	0.2286
3	0.0026	0.0131
4	0.0000	0.0000
5	70.7622	0.1642
6	9.4080	0.1960
SNOW WATER	0.000	

****
****

Appendix 5

Appendix 5

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
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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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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

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

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.

	Installation Instructions
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 *Run* screen will be displayed; type: A:\Setup (CD: Use CD drive designator, example: E:\Setup)
Step 6.	With the *Run* 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 *Welcome* screen is displayed.	Press OK to continue with installation.	Press Cancel to stop installation.
Step 8	The *Read Me* screen is displayed.	Press OK to continue with installation.	Press Cancel to stop installation.
Step 9	The *Select Destination Directory* 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 *Make Backups* screen is displayed.	Press Yes to create backup copies of all files replaced during the installation. Next, the *Select Backup Directory* screen will be displayed. Use the browse list to select a backup directory (Example: C:\Mygrt3\Backup). Press OK to close the *Select Backup Directory* screen.	Press No if you do not want backup copies created or press Cancel to stop installation.
Step 11	The *Group Name* screen is displayed.	Enter a group name to appear in the Start Menu when you press the Start button. Press OK to close the *Group Name* 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 *Installation is Complete* screen is displayed.	Press OK to close the screen.	

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 *Add/Remove Programs* from the Control Panel window.
Step 6.	Select MYGRT and press Add/Remove from the *Add/Remove Programs Properties* screen.
Step 7.	Respond to the displayed uninstall prompts.
Step 8.	Press OK from the *Add/Remove Programs Properties* 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

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 *About* 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).

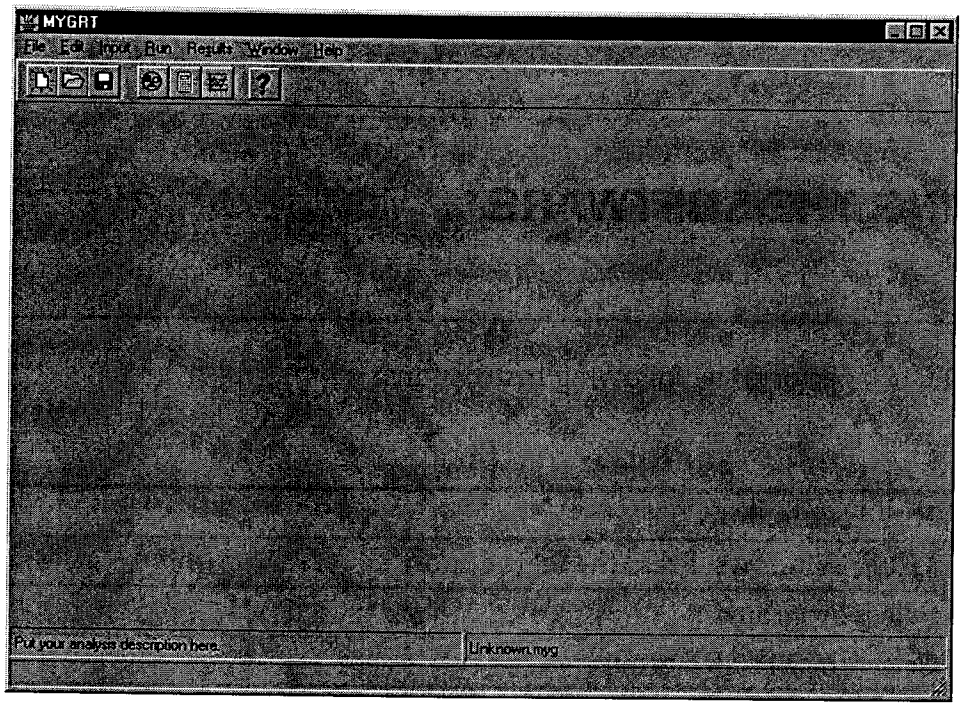

Figure 5-1
Main Screen

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

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

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 1st 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.

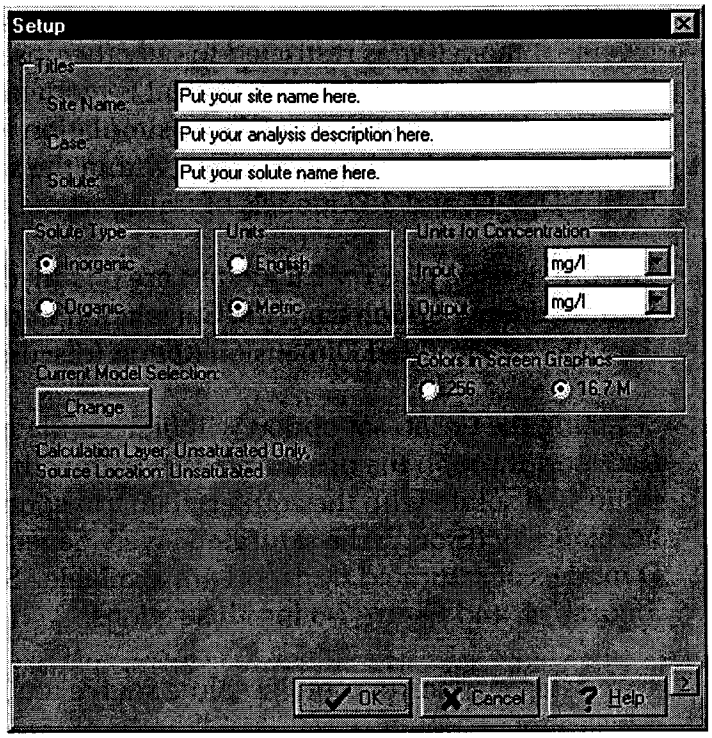

Figure 7-1
Setup Screen

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..

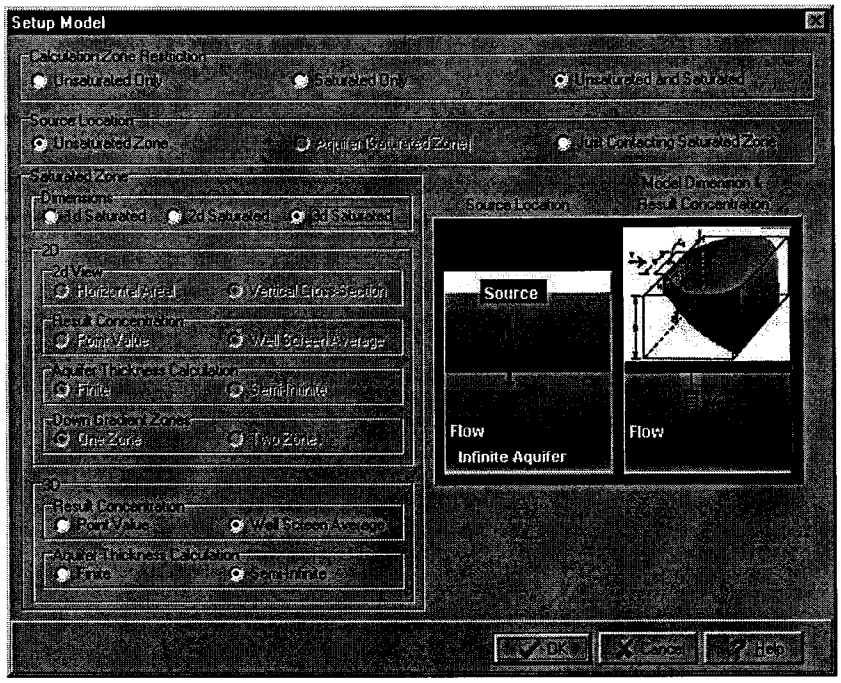

Figure 7-2
Setup Model Screen

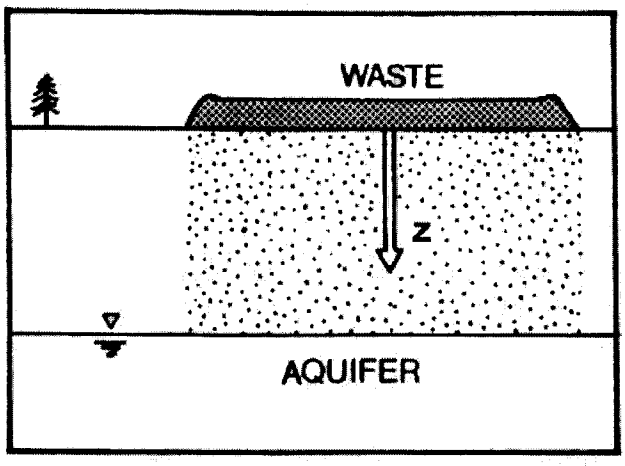

Figure 7-3
Selection of a 1-D, unsaturated calculation zone restriction.

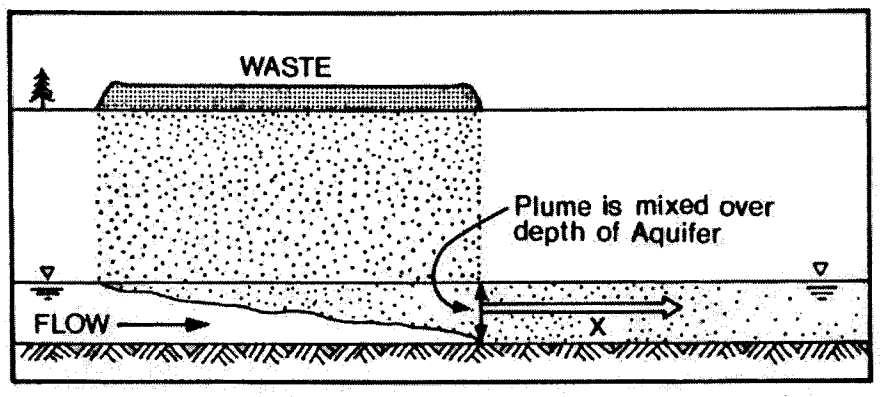

Figure 7-4
Selection of a 1-D saturated calculation zone restriction.

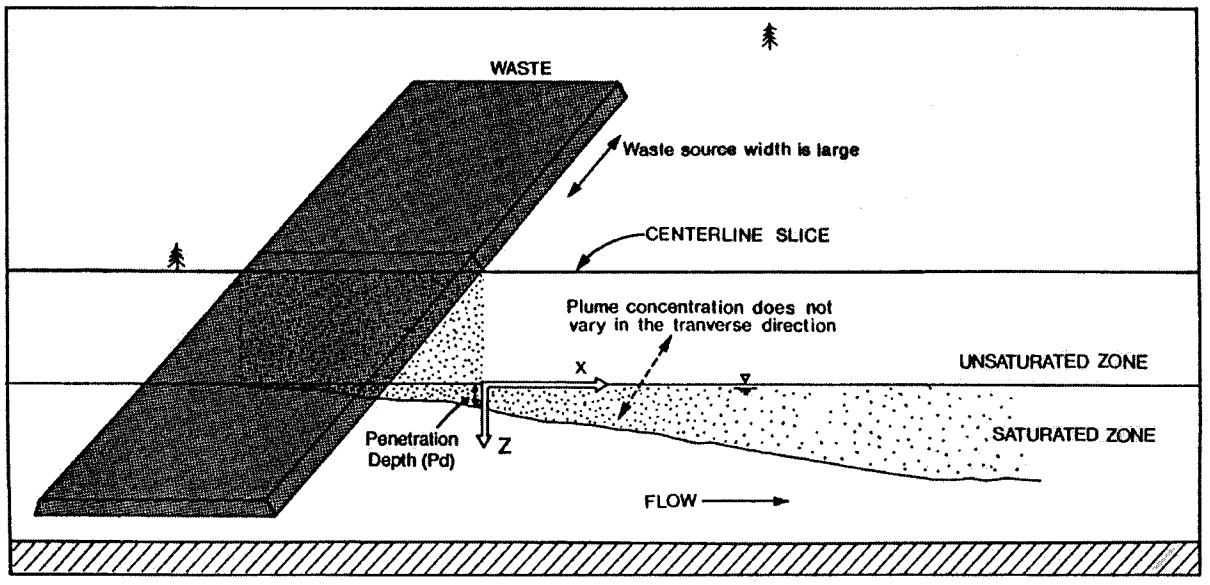

Figure 7-5
Selection of a 2-D, cross-sectional view for saturated or unsaturated/saturated calculation zone restriction.

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) <u>Both Unsaturated And Saturated Layer Modeling</u>

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.

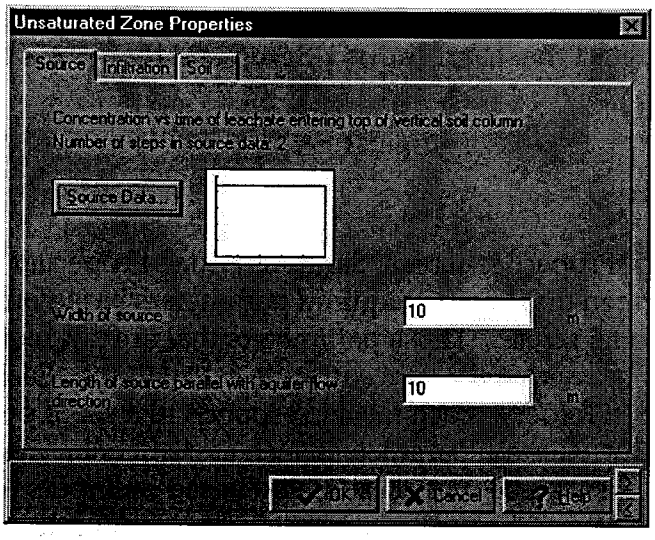

Figure 7-6
Unsaturated Zone Properties Screen

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	cm3/cm3	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	m2/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 $1/10^{th}$ 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.

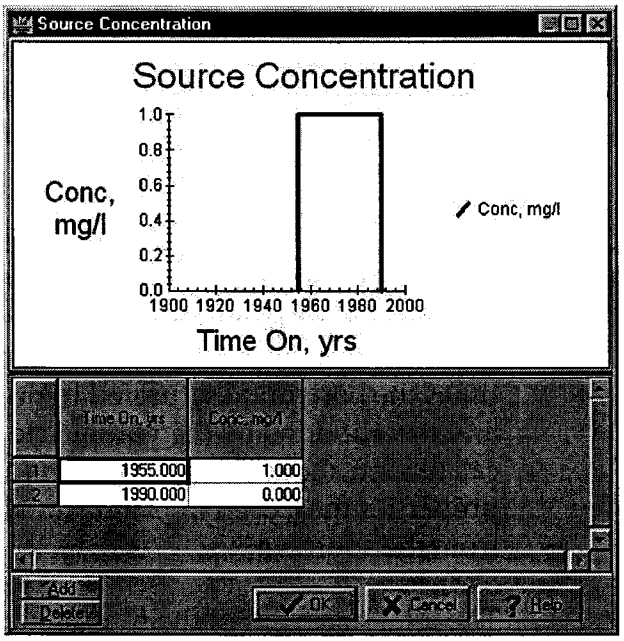

Figure 7-7
Source Concentration Screen

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	cm3/cm 3	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, Vx	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.

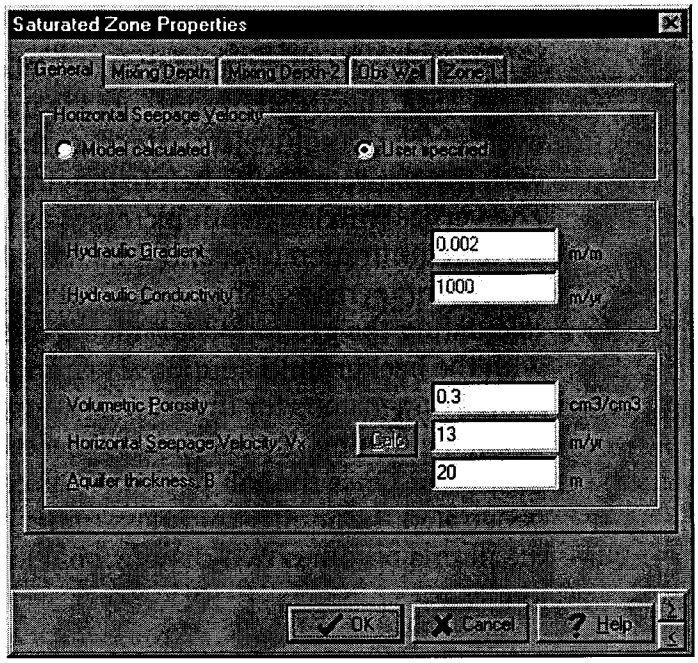

Figure 7-8
Saturated Zone Properties Screen

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 then 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	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 (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 1/10th 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	m2/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 1/10th the specified scale distance.
Transverse Dispersion Coefficient, Dy	m2/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 1/10th the horizontal dispersion coefficient is used.
Vertical Dispersion Coefficient, Dz	m2/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 1/100th 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, Z2	m	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.

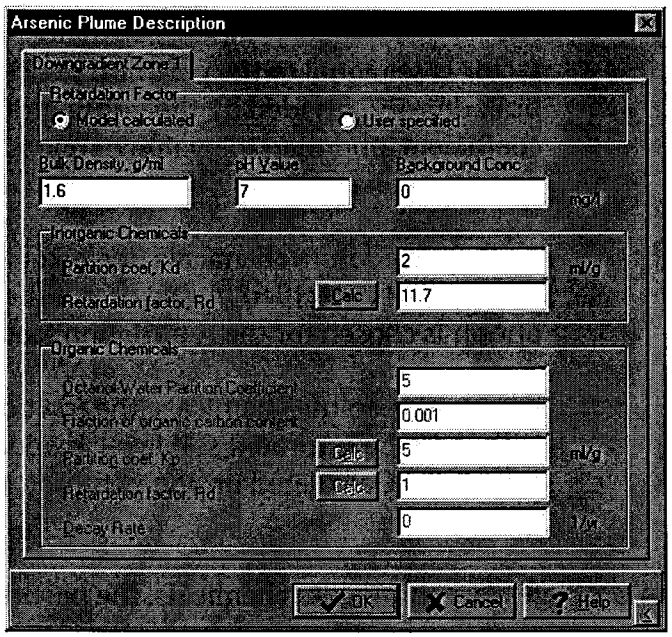

Figure 7-9
Solute Plume Description Screen

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.

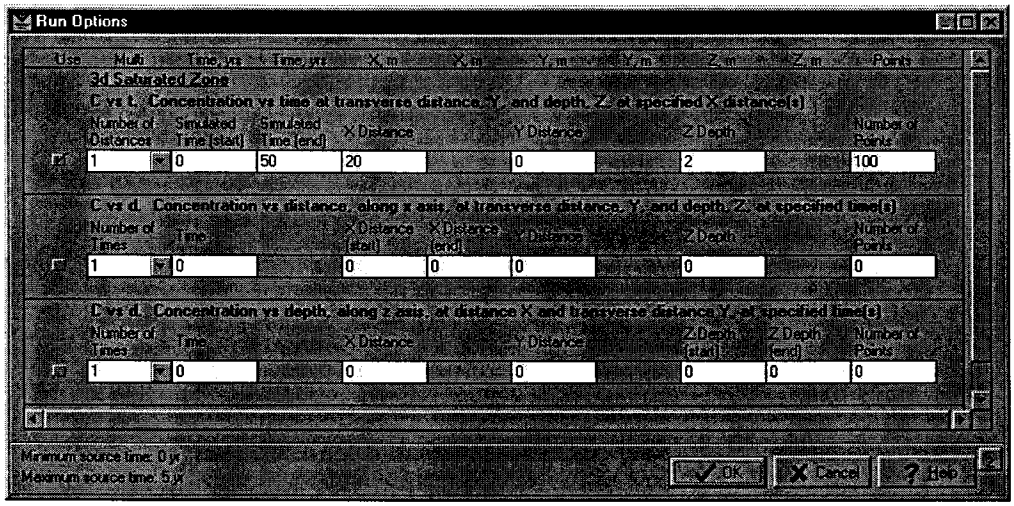

Figure 7-10
Run Options Screen

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.

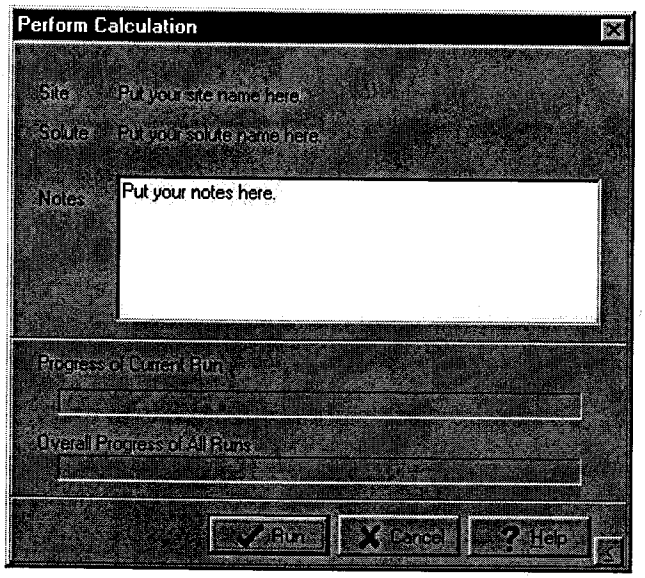

Figure 7-11
Run Screen

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.

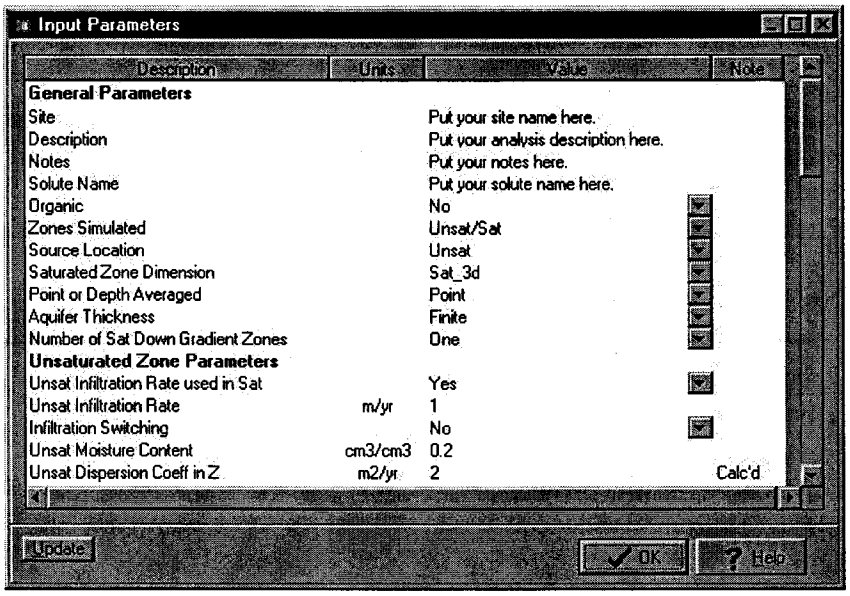

Figure 7-12
Input Parameters Screen

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 **File | New**
	Opens an existing project **File | Open**
	Saves current project **File | Save**
	Displays *Setup* screen **Input | Setup**
	Display the Run screen **Run | Run Model**
	Generates plots for each selected run option **Results | Generate Plots**
	Displays the help table of contents **Help | Contents**

8

LIMITATIONS

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

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 cm^3/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 m/yr from (11.81 in/yr) 0.3 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 cm^3/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.

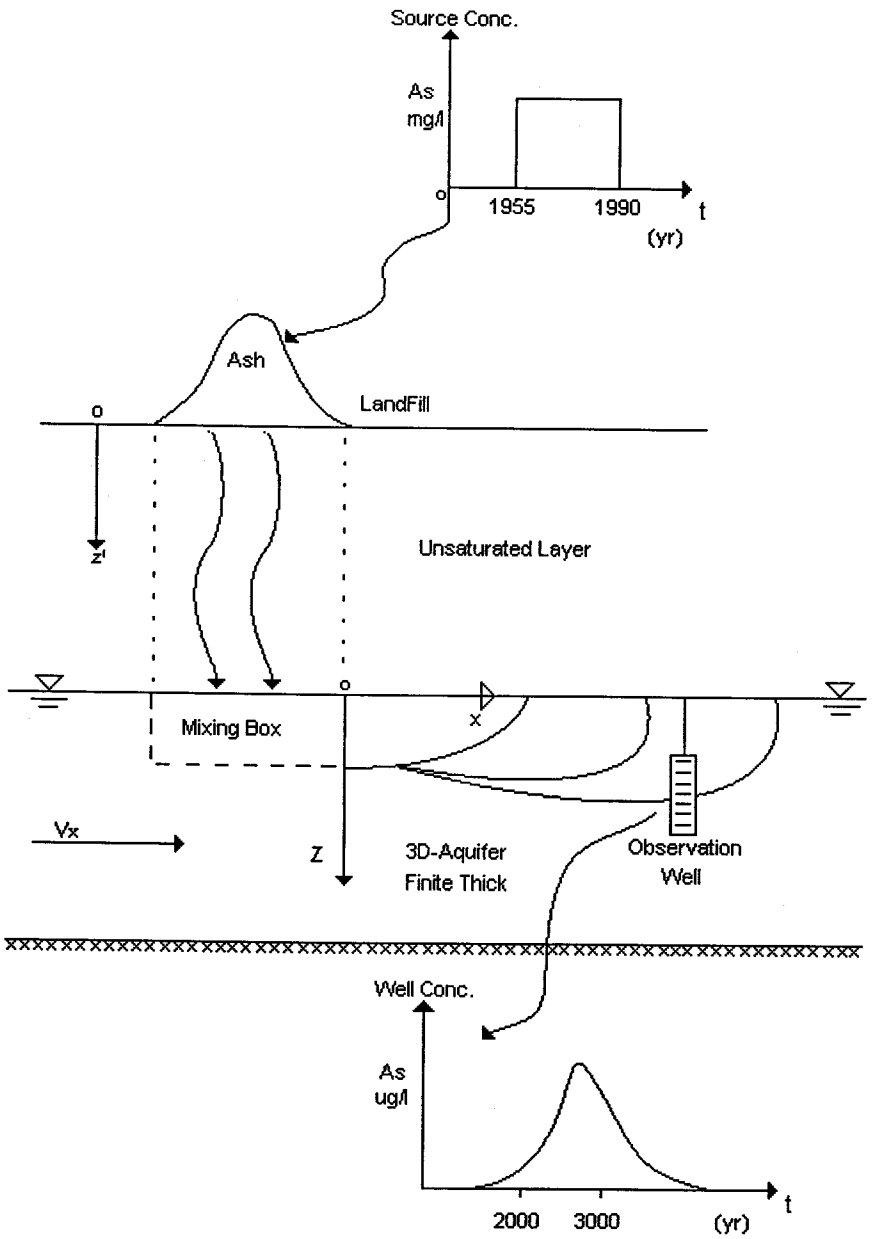

Figure 9-1
Example 1, Schematic

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 cm3/cm3
Depth to water table below source	4 m

Vertical Dispersion Coefficient (model calculated)	0.6 m2/yr
Retardation factor, Rd	100
Porosity	0.3 cm3/cm3
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 m2/yr
Transverse Dispersion Coefficient, Dy (model calculated)	19.5 m2/yr
Vertical Dispersion Coefficient, Dz (model calculated)	1.95 m2/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.

Step	Using Screen	Instruction
1	Main	Double-click the title bar to maximize the *Main* screen.
2	Main	Select **Input | Setup** to display the *Setup* 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

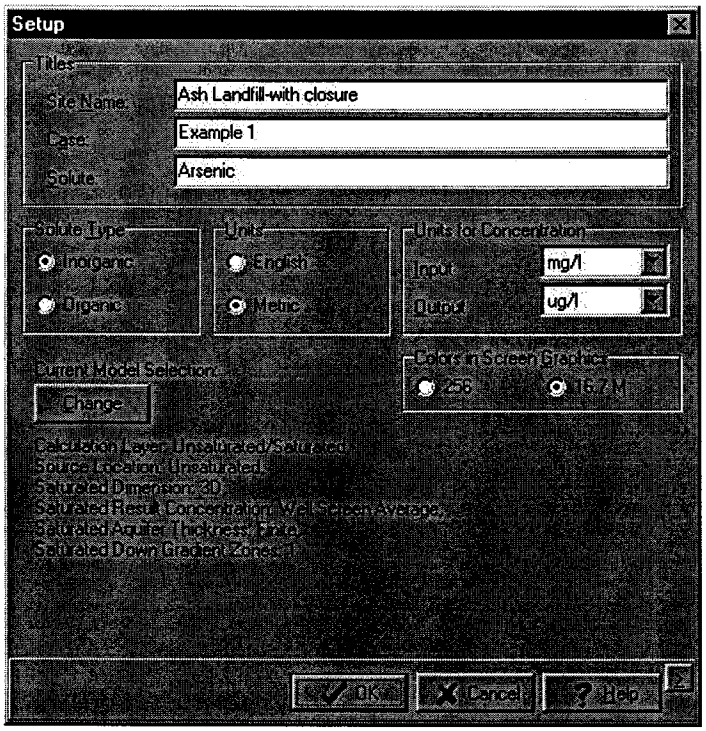

Figure 9-2
Setup screen as seen when step 6 is completed.

Step	Using Screen	Instruction
4	Setup	Press the Change button to display the *Setup Model* screen.
5	Setup Model	Edit values and make selections as indicated below. This is illustrated in 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

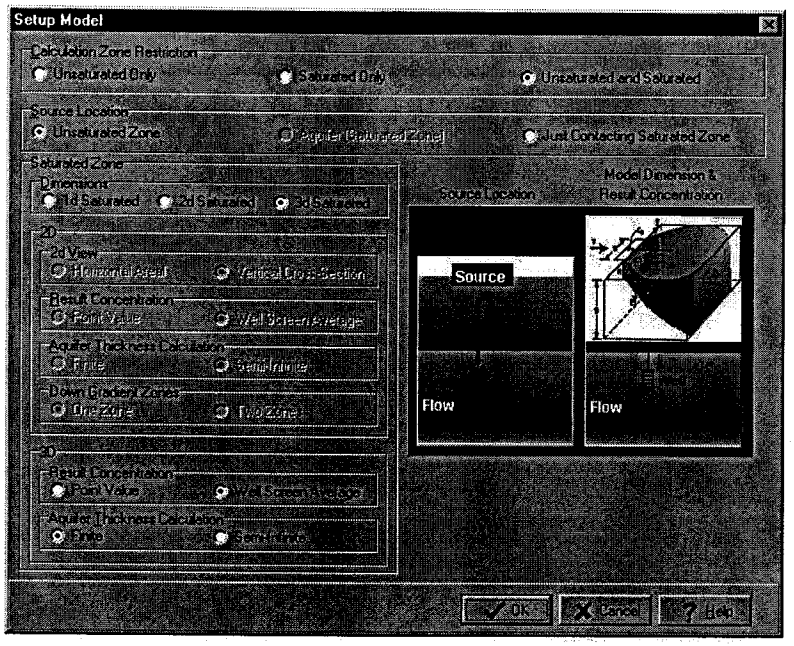

Figure 9-3
Setup Model screen

Step	Using Screen	Instruction
6	Setup Model	Press the OK button to return close the *Setup Model* screen and return to the *Setup* screen.
7	Setup	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the *Unsaturated Zone Properties* screen.
8	Unsaturated Zone Prop. (Source)	The *Source* page is displayed.
9	Unsaturated Zone Prop. (Source)	Press the Source Data button to display the *Source Concentration* 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

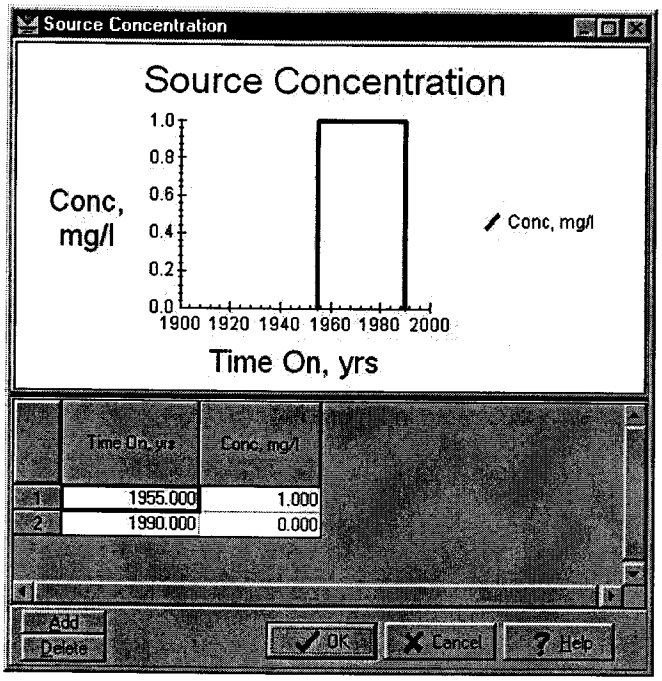

Figure 9-4
Example 1, Source Concentrations

Step	Using Screen	Instruction
11	Source Concentration	Press the OK button to return to the *Unsaturated Zone Properties* 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

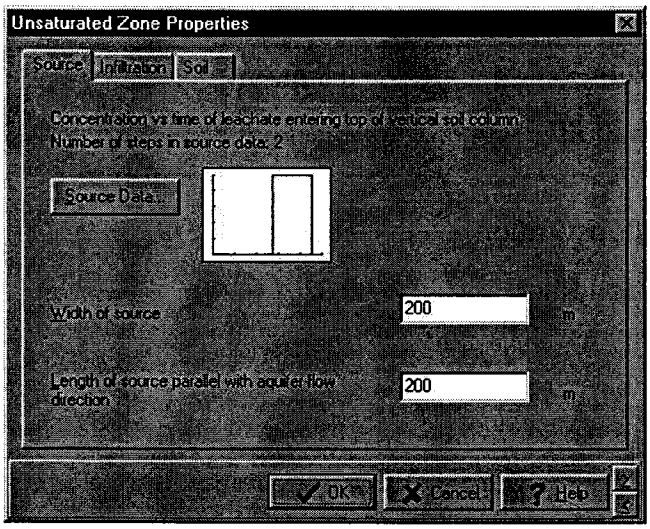

Figure 9-5
Unsaturated Zone Properties (Source Page) screen

Step	Using Screen	Instruction
13	Unsaturated Zone Prop. (Source)	Press the Infiltration tab to display the *Infiltration* 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.

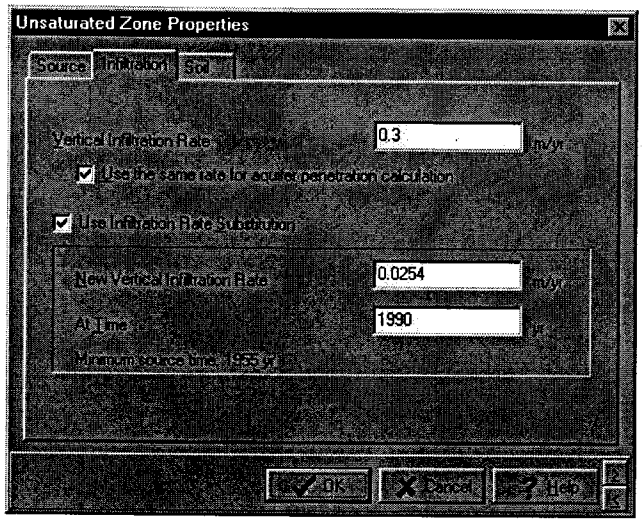

Figure 9-6
Unsaturated Zone Properties (Infiltration Page)

Step	Using Screen	Instruction
15	Unsaturated Zone Prop. (Infiltration)	Press the Soil tab to display the *Soil* 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 cm3/cm3
Depth to water table below source	4 m
Vertical Dispersion Coefficient (model calculated)	0.6 m2/yr
Retardation factor, Rd	100

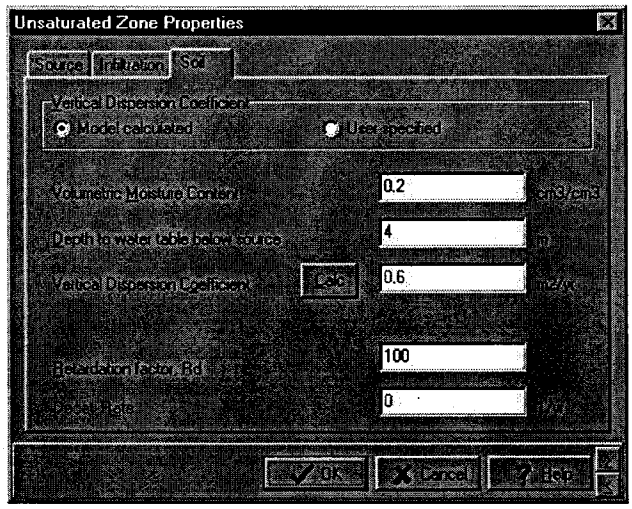

Figure 9-7
Unsaturated Zone Properties (Soil Page)

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 *Saturated Zone Properties* Screen.
18	Saturated Zone Prop. (General)	The *General* 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 cm3/cm3
Horizontal Seepage Velocity, Vx	13 m/yr
Aquifer thickness, B	20m

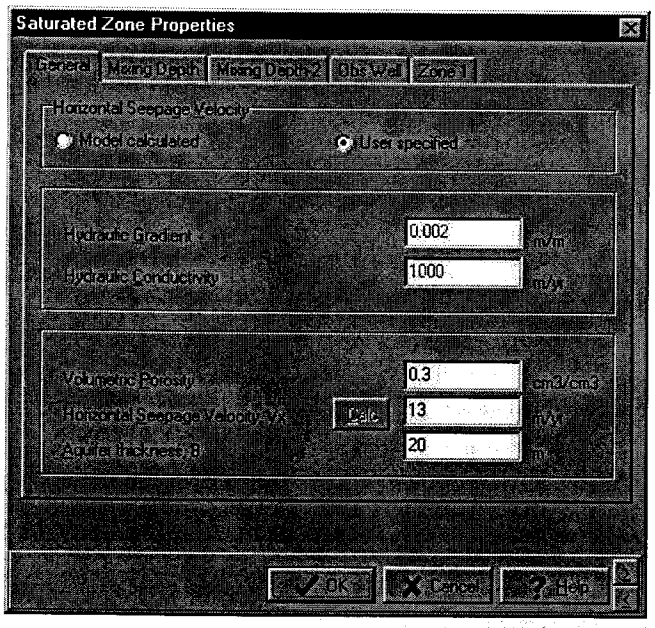

Figure 9-8
Saturated Zone Properties (General Page)

Step	Using Screen	Instruction
20	Saturated Zone Prop. (General)	Press the Mixing Depth tab to display the *Mixing Depth* 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

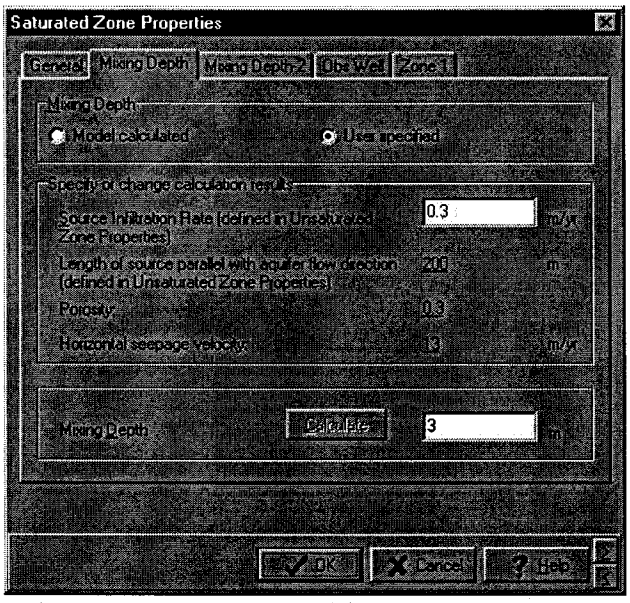

Figure 9-9
Saturated Zone Properties (Mixing Depth Page)

Step	Using Screen	Instruction
22	Saturated Zone Prop. (Mixing Depth)	Press the Mixing Depth-2 tab to display the *Mixing Depth-2* 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

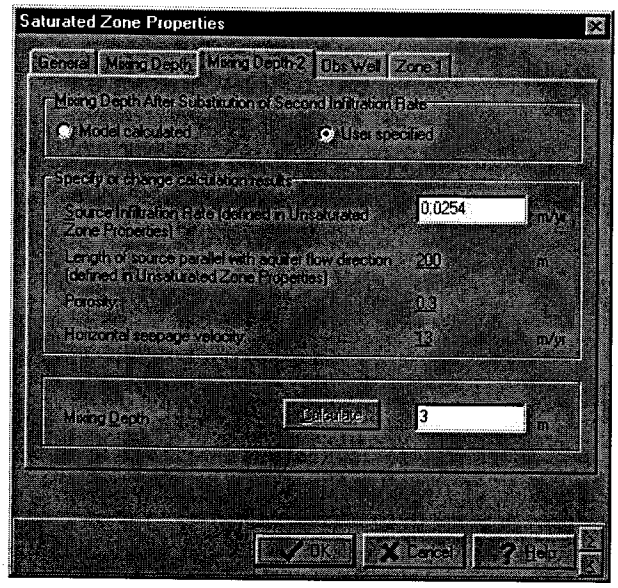

Figure 9-10
Saturated Zone Properties (Mixing Depth-2 Page)

Step	Using Screen	Instruction
24	Saturated Zone Prop. (Mixing Depth-2)	Press the Obs Well tab to display the *Obs Well* 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

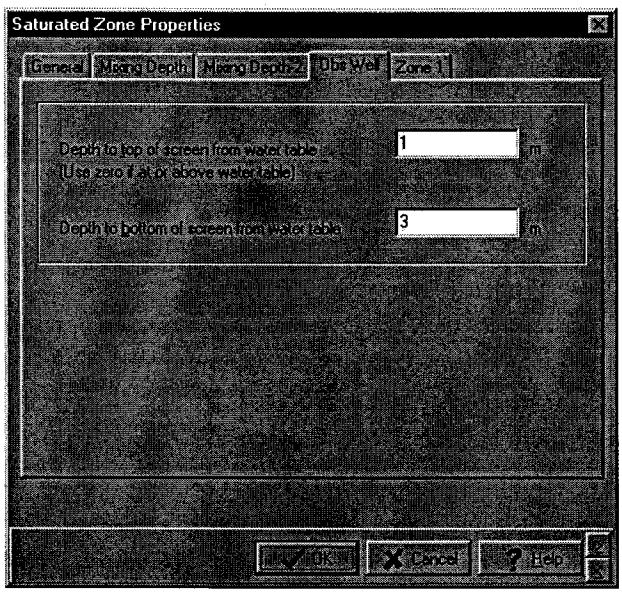

Figure 9-11
Saturated Zone Properties (Obs Well Page)

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

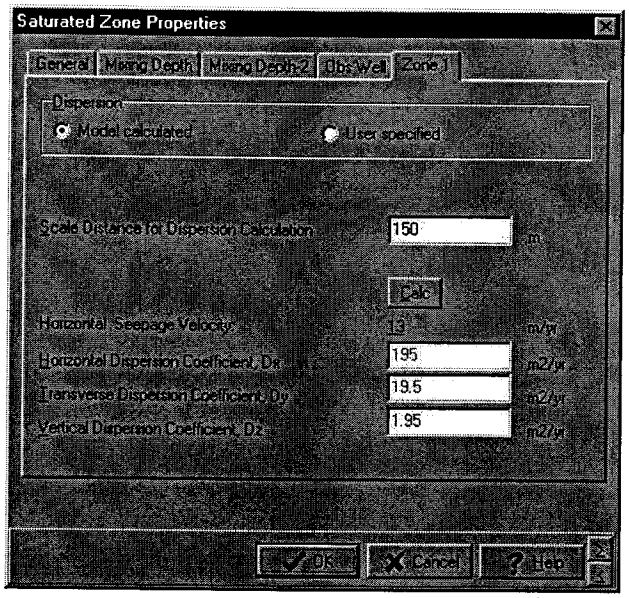

Figure 9-12
Saturated Zone Properties (Zone 1 Page) screen

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 *Plume Description* Screen.
29	Plume Description (Down Gradient Zone 1)	The *Down Gradient Zone 1* 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

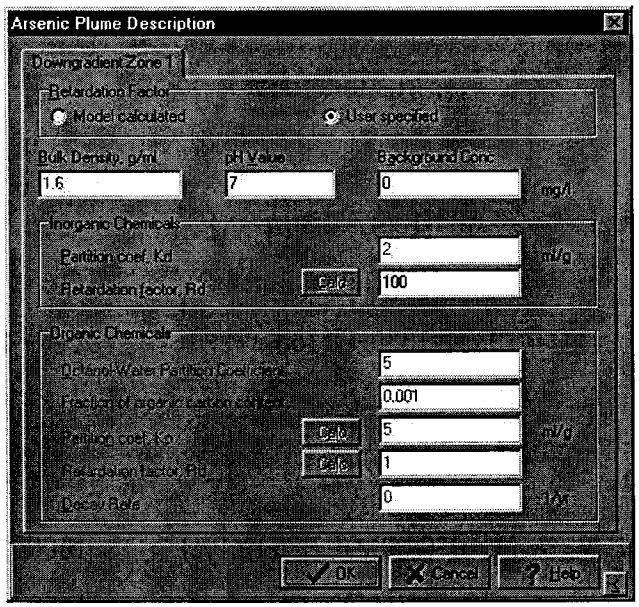

Figure 9-13
Solute Plume Properties (Down Gradient Zone 1)

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 **Run | Options** to display the *Run Options* 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

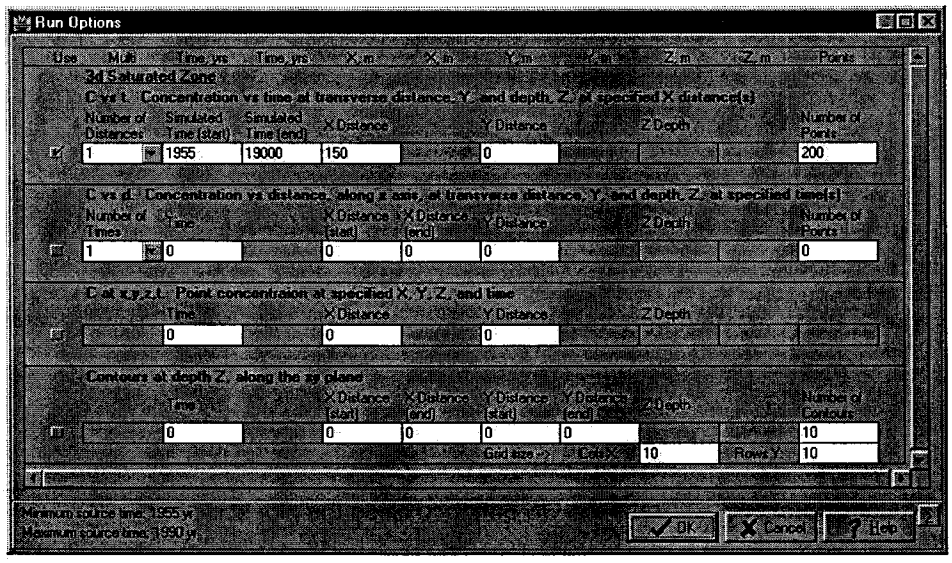

Figure 9-14
Run Options screen

Step	Using Screen	Instruction
34	Run Options	Press OK to close the screen.
35	Main	Select **Run | Run Model** to display the *Perform Calculation* screen.
36	Perform Calculation	Press the RunI 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 *Main Screen.*
37	Main	Select **Results | Generate Plots** to display the plots for the run options selected earlier. See generated plot in Figure 9-15.

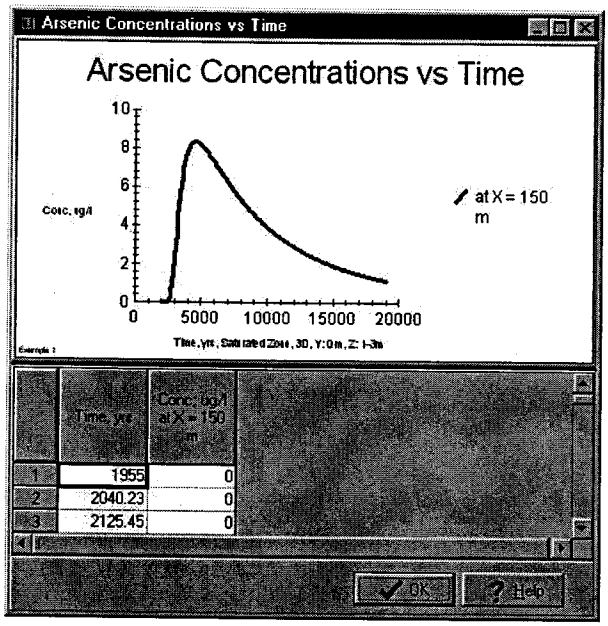

Figure 9-15
Example 1, Plot of Calculated Results

Step	Using Screen	Instruction
38	Arsenic Concentrations vs Time	Press the OK button to close the plot screen.
39	Main Screen	Select **File | Save As** to display the *Save As* 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 *Main* screen.
2	Main	Select **Run | Options** to display the *Run Options* 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

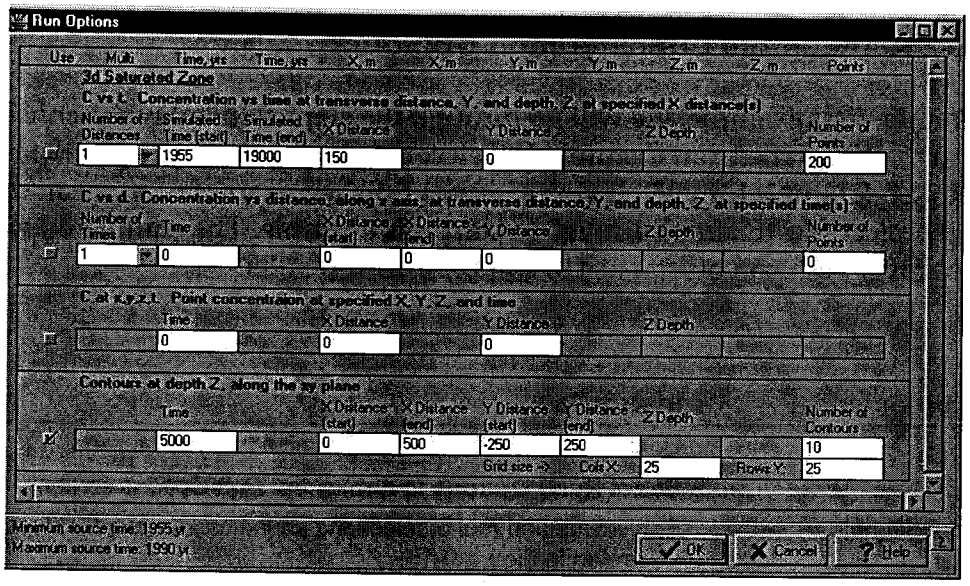

Figure 9-16
Run Options Screen

Step	Using Screen	Instruction
4	Run Options	Press OK to close the screen.
5	Main	Select **Run | Run Model** to display the *Perform Calculation* 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 *Main Screen.*
7	Main	Select **Results | Generate Plots** 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.

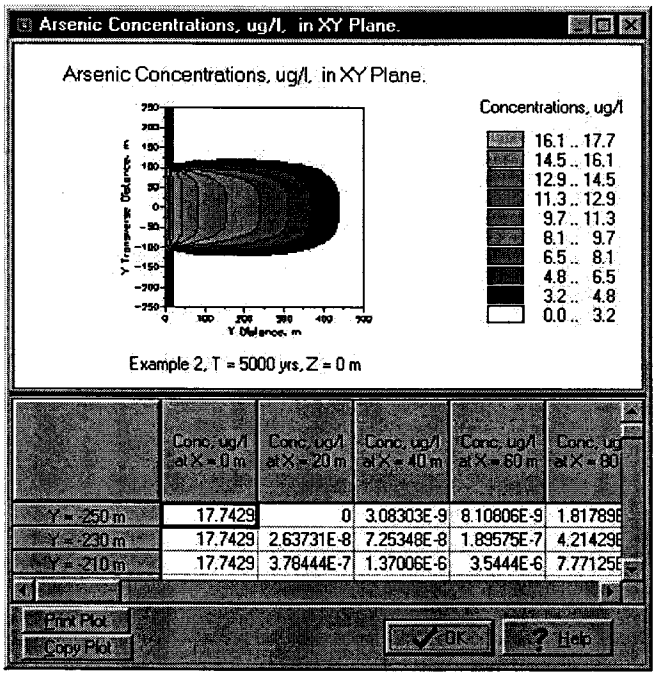

Figure 9-17
Example 2, Concentration Contours

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.

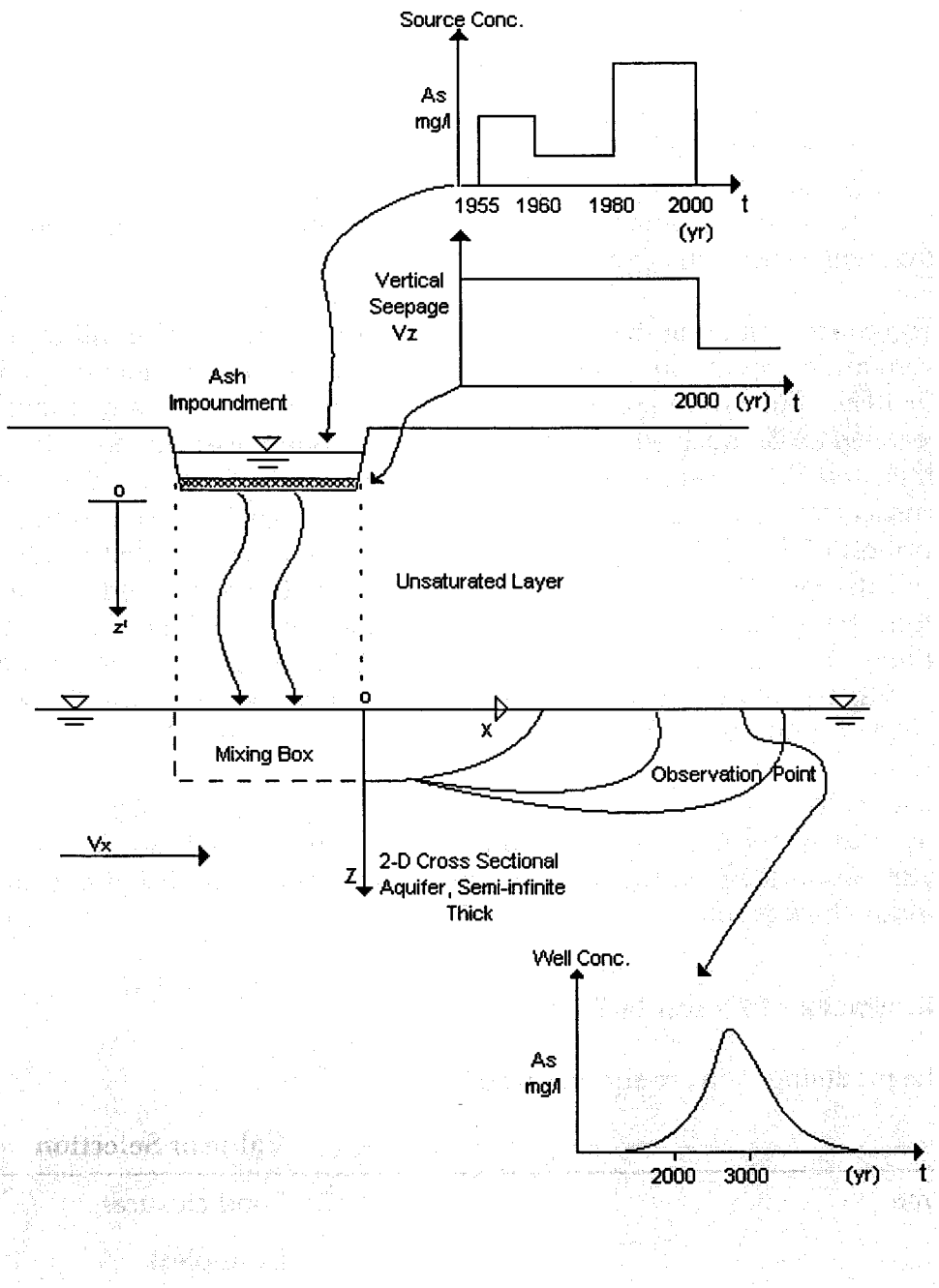

Figure 9-18
Example 3, Schematic

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

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 cm^3/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 cm^3/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 ½ 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 cm3/cm3
Depth to water table below source	4m
Retardation factor, Rd	11
Volumetric Porosity	0.3 cm3/cm3
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 m2/yr (User specified)

Transverse Dispersion Coefficient, Dy (model calculated)	16 m2/yr (User specified)
Vertical Dispersion Coefficient, Dz (model calculated)	2 m2/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 *Main* screen.
2	Main	Select **Input | Setup** to display the *Setup* 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

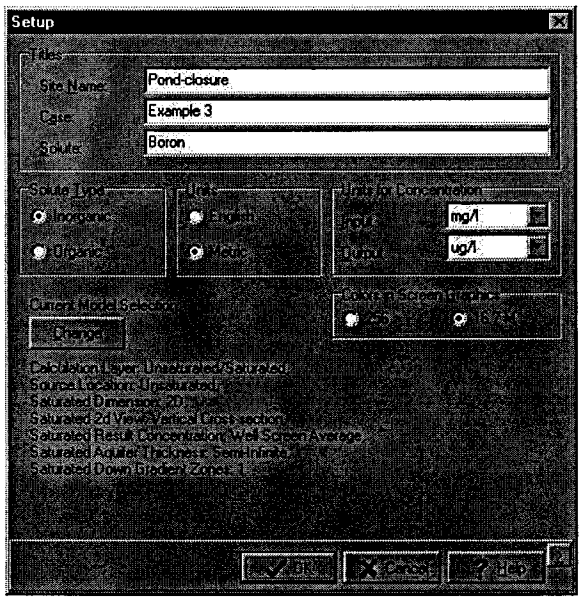

Figure 9-19
Setup screen as seen when step 6 is completed.

Step	Using Screen	Instruction
4	Setup	Press the Change button to display the *Setup Model* 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

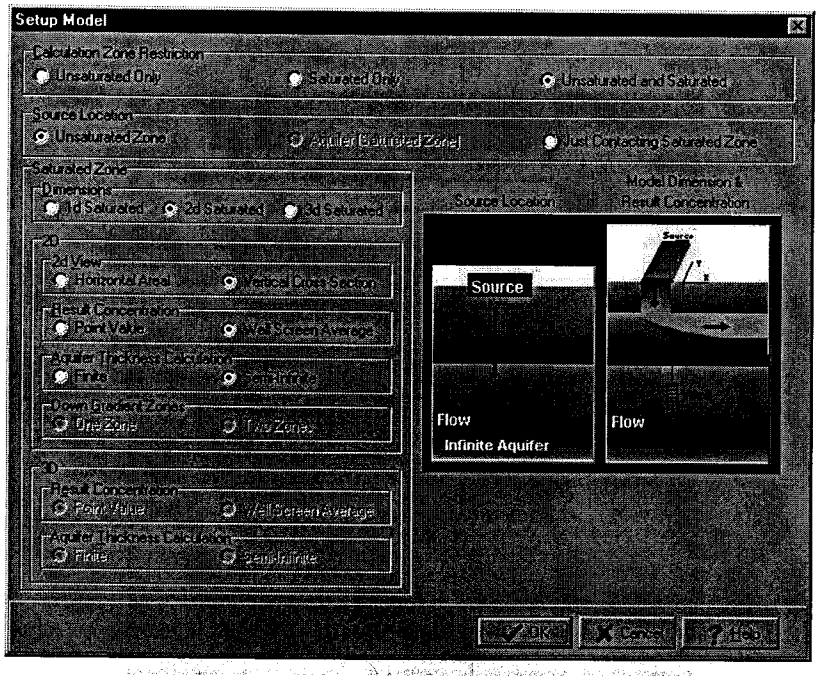

Figure 9-20
Setup Model Screen

Step	Using Screen	Instruction
6	Setup Model	Press the OK button to return close the *Setup Model* screen and return to the *Setup* screen.
7	Setup	Press the Next Screen button (or press the keys [Alt] [Shift] [Greater Than]) to display the *Unsaturated Zone Properties* Screen.
8	Unsaturated Zone Prop. (Source)	The *Source* page is displayed.
9	Unsaturated Zone Prop. (Source)	Press the Source Data button to display the *Source Concentration* 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

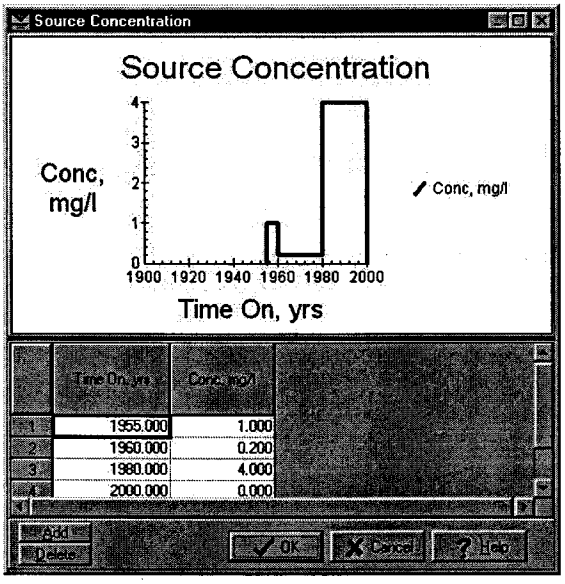

Figure 9-21
Example 3, Source Concentrations

Step	Using Screen	Instruction
11	Source Concentration	Press the OK button to return to the *Unsaturated Zone Properties* 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

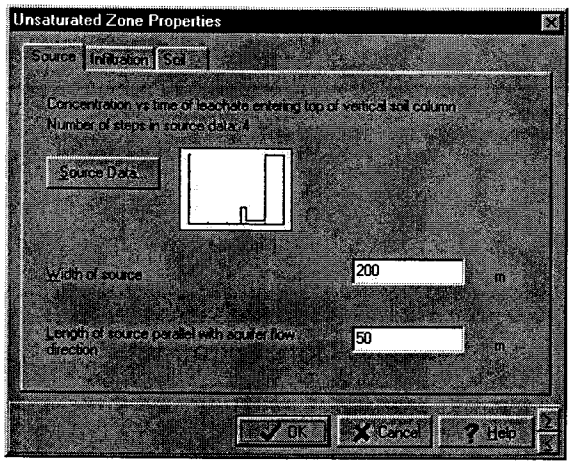

Figure 9-22
Unsaturated Zone Properties (Source Page)

Step	Using Screen	Instruction
13	Unsaturated Zone Prop. (Source)	Press the Infiltration tab to display the *Infiltration* 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.

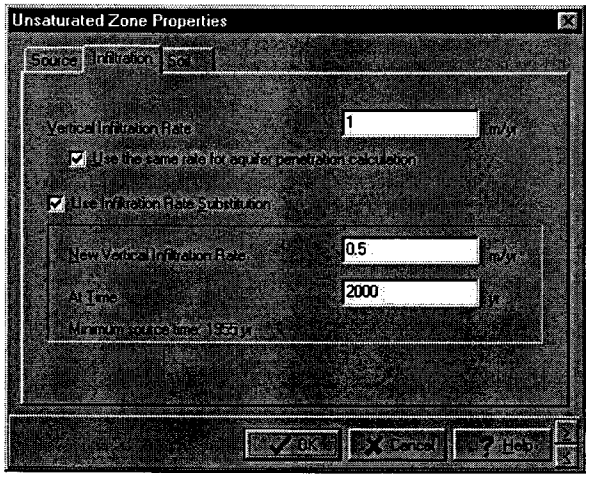

Figure 9-23
Unsaturated Zone Properties (Infiltration Page)

Step	Using Screen	Instruction
15	Unsaturated Zone Prop. (Infiltration)	Press the Soil tab to display the *Soil* 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 cm3/cm3
Depth to water table below source	4 m
Vertical Dispersion Coefficient (model calculated)	2 m2/yr
Retardation factor, Rd	11

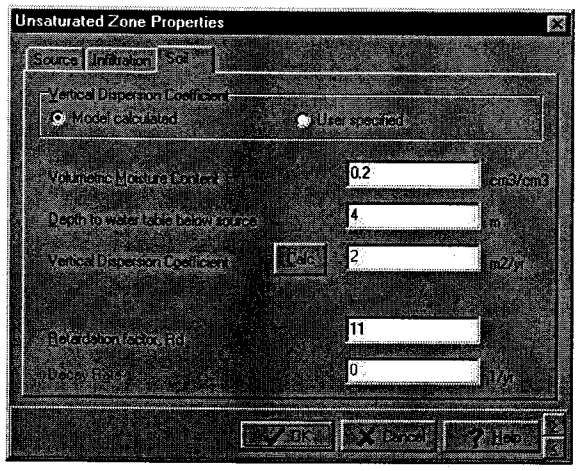

Figure 9-24
Unsaturated Zone Properties (Soil Page)

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 *Saturated Zone Properties* Screen.
18	Saturated Zone Prop. (General)	The *General* 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 cm3/cm3
Horizontal Seepage Velocity, Vx	20 m/yr
Aquifer thickness, B	300 m

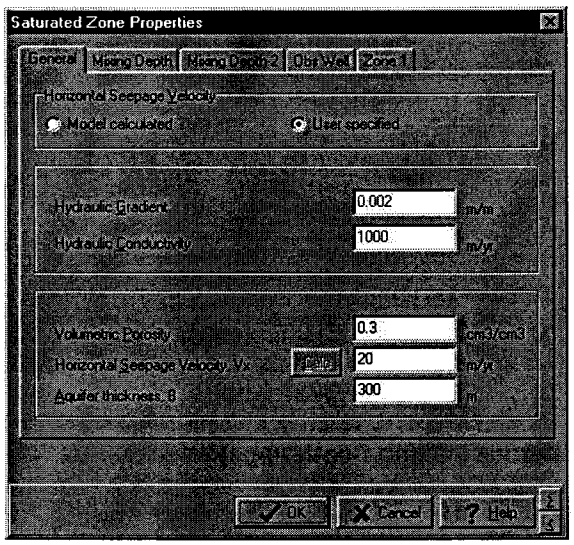

Figure 9-25
Saturated Zone Properties (General Page)

Step	Using Screen	Instruction
20	Saturated Zone Prop. (General)	Press the Mixing Depth tab to display the *Mixing Depth* 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

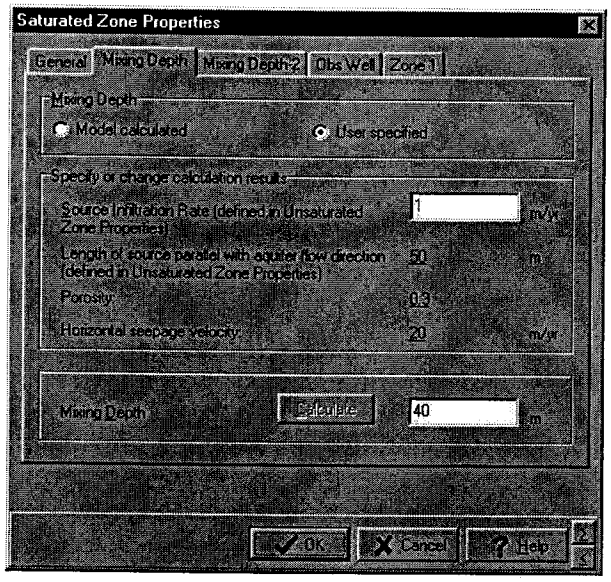

Figure 9-26
Saturated Zone Properties (Mixing Depth Page)

Step	Using Screen	Instruction
22	Saturated Zone Prop. (Mixing Depth)	Press the Mixing Depth-2 tab to display the *Mixing Depth-2* 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

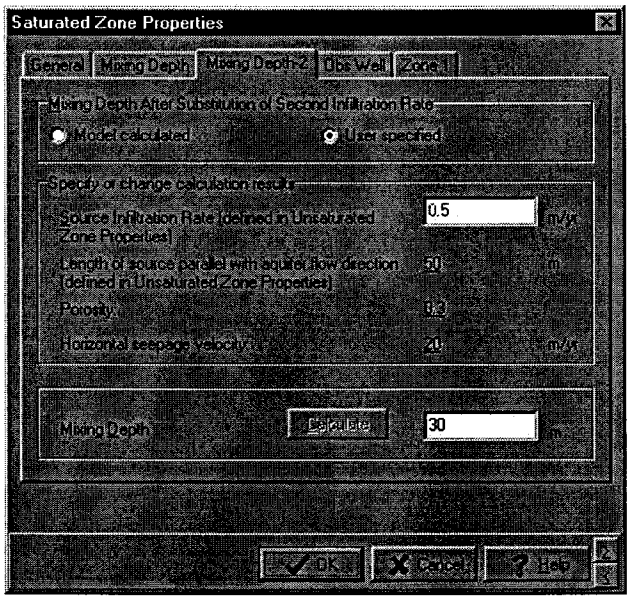

Figure 9-27
Saturated Zone Properties (Mixing Depth-2 Page)

Step	Using Screen	Instruction
24	Saturated Zone Prop. (Mixing Depth-2)	Press the Obs Well tab to display the *Obs Well* 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

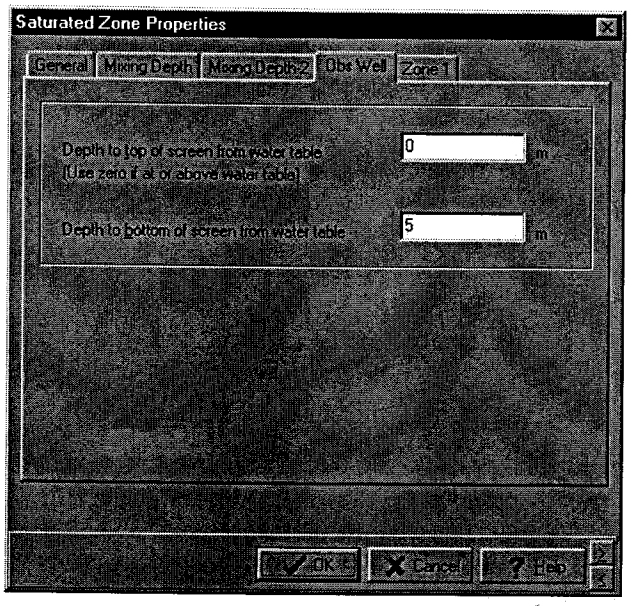

Figure 9-28
Saturated Zone Properties (Obs Well Page)

Step	Using Screen	Instruction
26	Saturated Zone Prop. (Obs Well)	Press the Zone 1 tab to display the *Zone 1* 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 m2/yr
Vertical Dispersion Coefficient, Dz	2 m2/yr

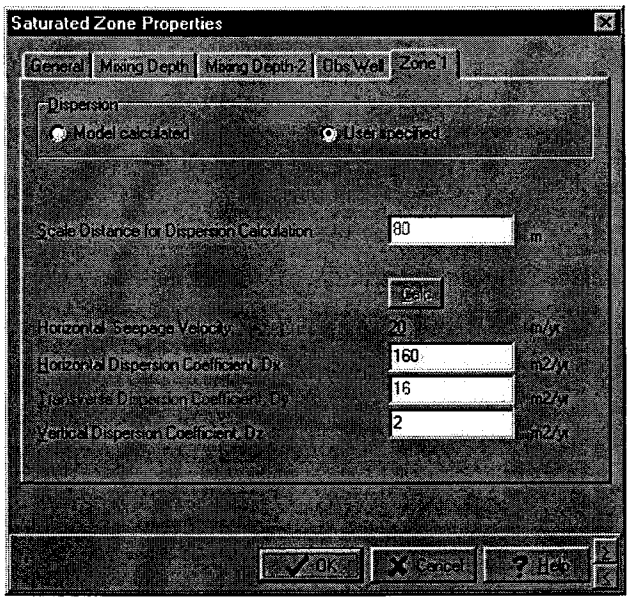

Figure 9-29
Saturated Zone Properties (Zone 1 Page)

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 *Plume Description* Screen.
29	Plume Description (Down Gradient Zone 1)	The *Down Gradient Zone 1* 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

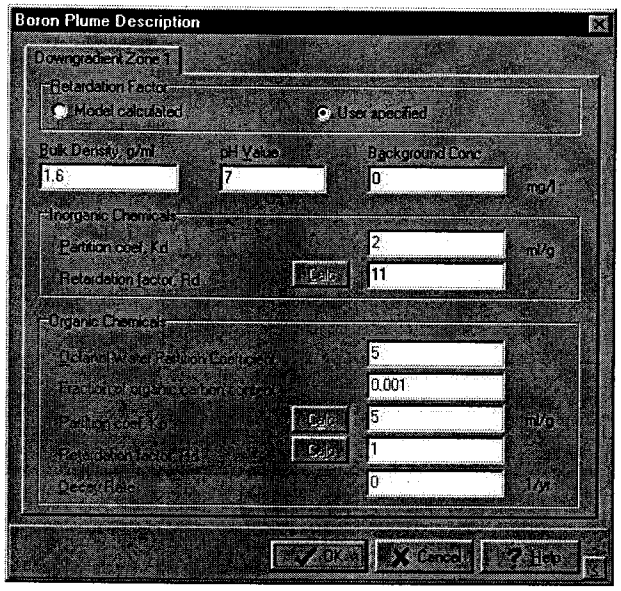

Figure 9-30
Solute Plume Properties (Down Gradient Zone 1)

Step	Using Screen	Instruction
31	Plume Description (Down Gradient Zone 1)	Press the OK button to close the screen.
32	Main	Select **Run | Options** to display the *Run Options* 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

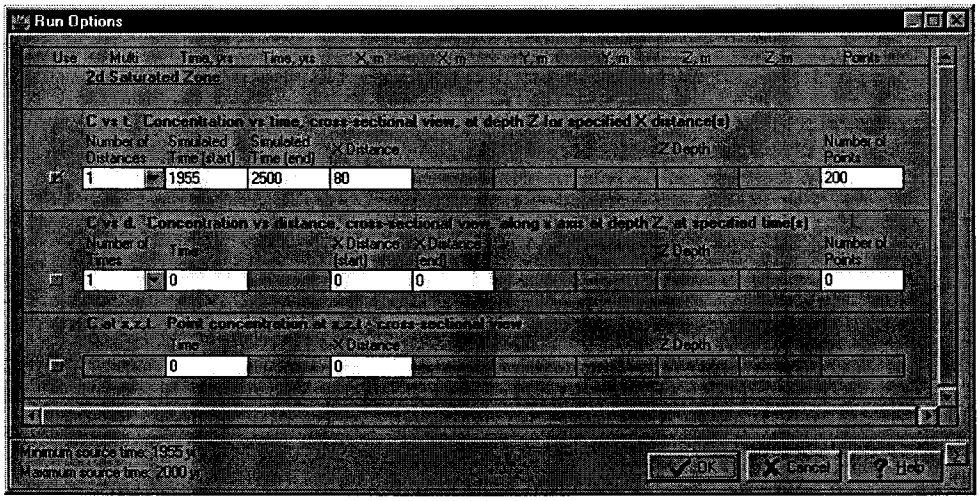

Figure 9-31
Run Options

Step	Using Screen	Instruction
34	Run Options	Press OK to close the screen.
35	Main	Select **Run | Run Model** to display the *Perform Calculation* 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 *Main Screen.*

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 **Results | Generate Plots** to display the plots for the run options selected earlier. See generated plot in Figure 9-32.

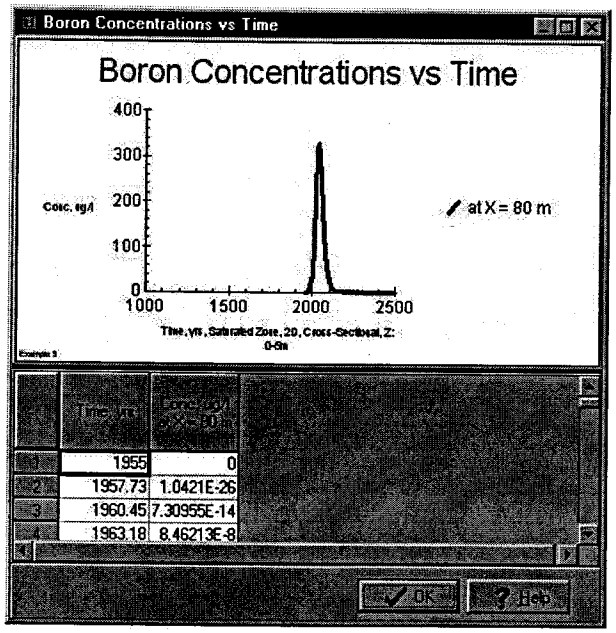

Figure 9-32
Example 3, Plot of Calculated Results

Step	Using Screen	Instruction
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 velociy 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, θ:

$$V_x = \frac{K_x I_x}{\theta} \tag{A-1}$$

where

K_x = saturated, horizontal hydraulic conductivity of the aquifer, m/yr

I_x = hydraulic gradient of aquifer, m/m

θ = 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.

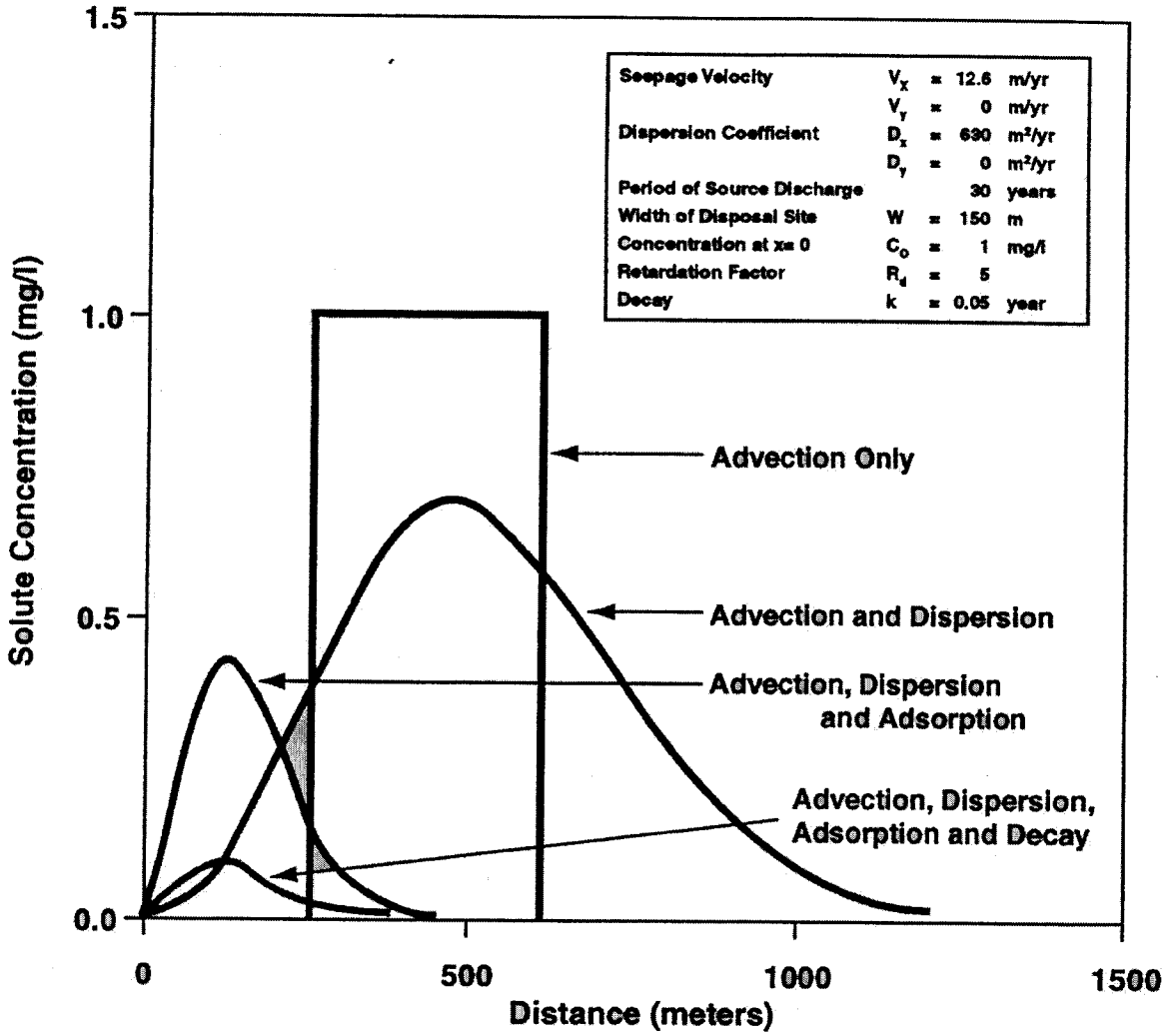

Figure A-1
A one-dimensional example showing the individual effects of advection, dispersion, adsorption (retardation), and first-order decay.

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).

$$D_x = \alpha_L V_x \tag{A-2}$$

where

D_x = longitudinal dispersion, m^2/yr

α_L = longitudinal dispersivity coefficient, m

V_x = average seepage velocity in primary direction of flow, m/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 (α_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 $1/10^{th}$ to $1/100^{th}$ 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:

$$R_d = 1 + \frac{K_p \rho_b}{\theta} \tag{A-3}$$

where

R_d = retardation factor (unitless)

K_p = soluton: solid phase linear partition coefficient (ml/g)

ρ_b = dry bulk density of permeable material (g/ml)

θ = 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 condiions). K_p can be measured in the laboratory as:

$$K_p = \frac{X}{c} \qquad \text{(A-4)}$$

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):

$$K_p = 0.63 X_{oc} K_{ow} \tag{A-5}$$

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):

$$K_p = 0.63 K_{ow} \left[0.2(1-f) X_{oc}^{s} + f X_{oc}^{f} \right] \tag{A-6}$$

where

K_{ow} = octanol-water partition coefficient, dimensionless

f = decimal fraction of fine soil (≤50 μm 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:

$$\frac{\partial c}{\partial t} = k_v c + k_h c + k_p c + k_b c + k_o c, \quad \text{or}$$

$$= k_v + k_h + k_p + k_b + k_o \quad \text{or} \qquad \text{(A-7)}$$

$$= \left(\sum_i k_i\right) c$$

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 "$-R_d kC$" 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_{liquid}, and the first-order decay rate of the solid phase, k_{solid}, are different, then the following algorithm can be used to find the equivalent first-order decay rate "k":

$$k = \frac{\left(k_{liquid} + \frac{k_{solid}\,\rho_b K_d}{\theta} \right)}{R_d} \qquad \text{(A-8)}$$

Where

ρ_b = dry bulk density of permeable material (g/ml)

θ = 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 $C_{unsat\text{-}bc}$ 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 (θ), 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).

$$C_{bc} = \frac{\left(C_{ic}Q_{gw} + C_{lcht}Q_{lcht}\right)}{\left(Q_{gw} + Q_{lcht}\right)} \tag{A-9}$$

where the volumetric flow rates Q_{gw} and Q_{lcht} are defined as:

$$Q_{gw} = V_x \theta W_{source} P_d$$

$$Q_{lcht} = I_{\inf l} A_{source} \tag{A-10}$$

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 GW1S 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)

θ = 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_{infl} = infiltration flux rate through unsaturated layer (m/yr)

A_{source} = area of source (m^2), where $A_{source} = L_{source}W_{source}$.

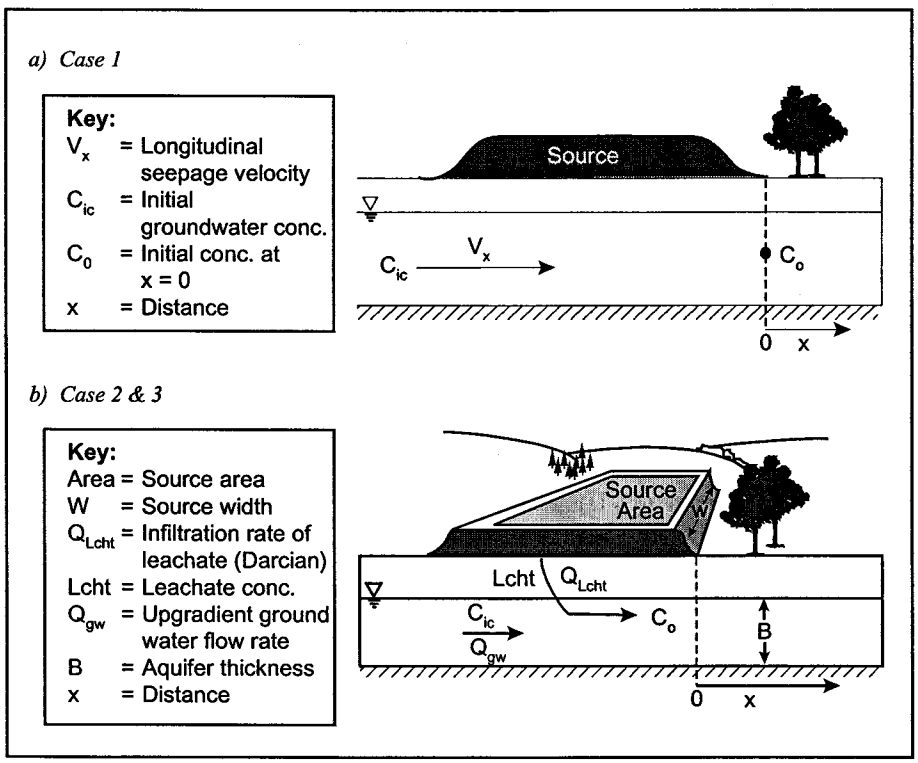

Figure A-2
Schematic showing source location options: a) Case 1 - source located in aquifer (saturated zone); b) Case 2 - source located in unsaturated zone, Case 3 - source just contacting saturated zone.

Penetration Depth

The penetration depth is the thickness of the solute plume that developes beneath the source (e.g., disposal site) at the down gradient edge. The solutes are carried downward by infilitration 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):

$$P_d = \sqrt{2\alpha_v L_{source}} + B\left\{1 - e^{-\frac{L_{source} I_{infl}}{B V_x \theta}}\right\} \qquad \text{(A-11)}$$

where

P_d = penetration depth (m)

α_v = vertical dispersivity coefficient in the saturated layer (m)

$L_{sourcce}$ = 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_{infl} = vertical infiltration velocity (Darcy) through the unsaturated layer (m/yr)

θ = 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; page121). The general form of solution is as follows:

$$\int_{t'=a}^{b} G(t')dt' = \sum_{i=1}^{N_{pts}} W_i G(Z_i) \qquad \text{(A-12)}$$

where the function G(t') is integrated between the limits of t' = a and b. The term W_i is the ith Gauss weight, Z_i is the ith Gauss evaluation point, and N_{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_{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 GW1S 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 GW1S 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 jth subdivision, which represents the linear variation in the boundary condition between the time t_{ONj} and t_{OFFj}:

$$C_{bc}(t) = \{C_{bcj} + (t - t_{ONj})Slope_j\}\{H(t - t_{ONj}) - H(t - t_{OFFj})\} \qquad \text{(A-13)}$$

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 GW1S 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 jth 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:

$$C_{ic}(z) = \{C_{icj} + (z - z_{ONj})Slope_j\}\{H(z - z_{ONj}) - H(z - z_{OFFj})\} \qquad \text{(A-14)}$$

Where H(.) 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
∞	Infinity	
Ψ_m	M^{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 jth 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 jth initial condition, as a function of depth in the unsaturated layer	(mg/l)
D_x	Longitudinal dispersion coefficient	(m^2/yr)
D_y	Transverse-horizontal dispersion coefficient	(m^2/yr)
D_z	Vertical dispersion coefficient	(m^2/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^{-1})
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)

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 jth boundary condition, Max[0,t-t_{OFFj}]	(yr)
t_{2j}	Time relative to the start of the jth boundary condition, Max[0,t-t_{ONj}]	(yr)
t_{OFFj}	The time at which the jth boundary condition is to end	(yr)
t_{ONj}	The time at which the jth 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 jth boundary condition starts	(m)
y_{2j}	Transverse-horizontal distance along the Y axis at which the jth boundary condition ends	(m)
z	Depth	(m)
z_{1j}	Depth at which either the jth initial condition in the unsaturated layer or the jth boundary condition in the saturated layer starts	(m)
z_{2j}	Depth at which either the jth initial condition in the unsaturated layer or the jth boundary condition in the saturated layer ends	(m)

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B

MODELS GW1S & GW1SBIC

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

$$0 \le x \le \infty$$

$$t \ge 0$$

Initial Condition (only used in GW1SBIC)

$$c(x,0) = C_{ico} + \sum_{j=1}^{N_{ic}} \left(C_{icj} - C_{ico}\right)\left\{H\left(x - x_{ONj}\right) - H\left(x - x_{OFFj}\right)\right\}$$

where H(.) is the Heaviside unit step function

Boundary Conditions (used in both GW1S & GW1SBIC)

$$c(0,t) = C_{ico} + \sum_{j=1}^{N_{bc}} \left(C_{bcj} - C_{ico}\right)\left\{H\left(t - t_{ONj}\right) - H\left(t - t_{OFFj}\right)\right\}$$

$$\frac{\partial c}{\partial x}(\infty, t) = 0$$

Solution (D > 0)

$$c(x,t) = C_{ico} + \frac{x}{2}\sqrt{\frac{R_d}{\pi D}}\, e^{\frac{Ux}{2D}} \sum_{j=1}^{N_{bc}} \left(C_{bc_j} - C_{ico}\right) \int_{\tau = Max\left[0, t - t_{OFF\,j}\right]}^{Max\left[0, t - t_{ON_j}\right]} \frac{e^{-\left(\frac{U^2}{4DR_d} + k\right)\tau - \frac{x^2 R_d}{4D\tau}}}{\tau^{3/2}}\, d\tau$$

$$-\frac{k}{2} C_{ico}\, e^{\frac{Ux}{2D}} \int_{\tau=o}^{t^*} e^{-k\tau} \left\{ e^{\frac{-xU}{2D}}\, erfc\left(-x\sqrt{\frac{R_d}{4D\tau}} + U\sqrt{\frac{\tau}{4DR_d}}\right) - e^{\frac{xU}{2D}}\, erfc\left(x\sqrt{\frac{R_d}{4D\tau}} + U\sqrt{\frac{\tau}{4DR_d}}\right)\right\} d\tau$$

$$+\frac{e^{-kt^*}}{2} \sum_{j=1}^{N_{ic}} \left(C_{ic_j} - C_{ico}\right) \left[e^{\frac{Ux}{D}}\, erfc\left(\frac{\left(x + x_{OFF_j}\right)}{2}\sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2}\sqrt{\frac{t^*}{DR_d}}\right) - erfc\left(\frac{-\left(x - x_{OFF_j}\right)}{2}\sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2}\sqrt{\frac{t^*}{DR_d}}\right)\right]$$

$$-\frac{e^{-kt^*}}{2} \sum_{j=1}^{N_{ic}} \left(C_{ic_j} - C_{ico}\right) \left[e^{\frac{Ux}{D}}\, erfc\left(\frac{\left(x + x_{ON_j}\right)}{2}\sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2}\sqrt{\frac{t^*}{DR_d}}\right) - erfc\left(\frac{-\left(x - x_{ON_j}\right)}{2}\sqrt{\frac{R_d}{Dt^*}} + \frac{U}{2}\sqrt{\frac{t^*}{DR_d}}\right)\right]$$

$x \geq 0$

$t \geq t_{ON1}$

where

$t^* = t - t_{ON1}$

Solution (D = 0)

$$c(x,t) = C_{ico} + C_{ico}\left\{e^{-k\,Min[t - t_{ON1}, \tau_o]} - 1\right\} + e^{-k(t - t_{ON1})} \sum_{j=1}^{N_{ic}} \left(C_{icj} - C_{ico}\right)\left[H\left\{x - x_{1j}\right\} - H\left\{x - x_{2j}\right\}\right]$$

$$+ e^{-k\tau_o} \sum_{j=1}^{N_{bc}} \left\{C_{bcj}\left(t - t_{ON1} - \tau_o\right) - C_{ico}\right\}\left[H\left\{\tau_o - t_{1j}\right\} - H\left\{\tau_o - t_{2j}\right\}\right]$$

where

$\tau_o = x R_d/U$

$t_{1j} = Max\ [0, t - t_{OFFj}$

$t_{2j} = \text{Max}\,[0, t - t_{ONj}]$

$X_{1j} = (t - t_{ON1})U/R_d + X_{ONj}$

$X_{2j} = (t - t_{ON1})U/R_d + X_{OFFj}$

Note the following indefinite integrals

$$\int \frac{e^{-a^2\tau - \frac{b^2}{\tau}}}{\tau^{3/2}} d\tau = \frac{\sqrt{\pi}}{2b}\left\{e^{-2ab} erf\left(a\sqrt{\tau} - \frac{b}{\sqrt{\tau}}\right) - e^{2ab} erf\left(a\sqrt{\tau} + \frac{b}{\sqrt{\tau}}\right)\right\}$$

$$\int \frac{e^{-a^2\tau - \frac{b^2}{\tau}}}{\tau^{1/2}} d\tau = \frac{\sqrt{\pi}}{2a}\left\{e^{-2ab} erf\left(a\sqrt{\tau} - \frac{b}{\sqrt{\tau}}\right) + e^{2ab} erf\left(a\sqrt{\tau} + \frac{b}{\sqrt{\tau}}\right)\right\}$$

C

MODEL GW2DSF

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

$$0 \le x \le \infty$$

$$0 \le z \le \infty$$

$$t \ge 0$$

Initial Condition

$$c(x,z,0) = C_{ic}$$

Boundary Conditions

$$c(0,z,t) = C_{ic} + \sum_{j=1}^{N_{bc}} \left(C_{bcj} - C_{ic}\right)\left\{H\left(t - t_{ONj}\right) - H\left(t - t_{OFFj}\right)\right\}\left\{H\left(z - z_{1j}\right) - H\left(z - z_{2j}\right)\right\}$$

$$\frac{\partial c}{\partial x}(\infty, z, t) = 0$$

$$\frac{\partial c}{\partial z}(x, 0, t) = 0$$

$$\frac{\partial c}{\partial z}(x, B, t) = 0$$

where H(.) is the Heaviside unit step function.

Solution ($D_x > 0$, $D_z > 0$)

$$c(x,z,t) = C_{ic}$$

$$+x\sqrt{\frac{R_d}{\pi D_x}}\,e^{\frac{V_x x}{2D_x}}\sum_{j=1}^{N_{bc}}\int_{\tau=0}^{t^*}\frac{e^{-\left(\frac{V_x^2}{4R_dD_x}+k\right)\tau-\frac{X^2R_d}{4D_x\tau}}}{\tau^{3/2}}\left\{C_{bcj}\left(t^*-\tau\right)-C_{ic}\right\}\sum_{m=0}^{\infty}L_mO_{mj}\cos\left(\psi_m z\right)e^{-\frac{\psi_m^2D_z\tau}{R_d}}\,d\tau$$

$$-\frac{k}{2}C_{ic}\int_{\tau=0}^{t^*}e^{-k\tau}\left[erfc\left(-x\sqrt{\frac{R_d}{4D_x\tau}}+V_x\sqrt{\frac{\tau}{4D_xR_d}}\right)-e^{\frac{xV_x}{D_x}}erfc\left(x\sqrt{\frac{R_d}{4D_x\tau}}+V_x\sqrt{\frac{\tau}{4D_xR_d}}\right)\right]d\tau$$

where $t^* = t - t_{ON1}$ $\qquad t \geq t_{ON1}$

Define the following dimensionless coefficients

$$O_{mj} = \begin{cases} \dfrac{\left(z_{2j}-z_{1j}\right)}{B} & \text{if } m=0 \\ \left\{\dfrac{\sin\left(\psi_m z_{2j}\right)-\sin\left(\psi_m z_{1j}\right)}{\psi_m B}\right\} & \text{if } m=1,2,\ldots \end{cases}$$

$$P_m = \begin{cases} 1 & \text{if } m=0 \\ \left\{\dfrac{\sin(\psi_m B)}{\psi_m B}\right. & \text{if } m=1,2,\ldots \end{cases}$$

$$L_m = \begin{cases} 1/2 & \text{if } m=0 \\ 1 & \text{if } m=1,2,\ldots \end{cases}$$

$$\psi_m = \frac{\pi m}{B} \qquad m=0,1,2,\ldots$$

Solution ($D_x = 0$, $D_z > 0$)

$$
\begin{aligned}
c(x,z,t) &= C_{ic} \\
&+ 2\sum_{m=o}^{\infty} L_m \cos(\psi_m z)\, e^{-\left(\frac{\psi_m^2 D_z}{R_d}+k\right)\tau_o} \sum_{j=1}^{N_{bc}} O_{mj}\left\{C_{bcj}\left(t^* - \tau_o\right) - C_{ic}\right\}\left\{H\left(\tau_o - t_{1j}\right) - H\left(\tau_o - t_{2j}\right)\right\} \\
&+ C_{ic}\left\{e^{-kMin[t^*,\tau_o]} - 1\right\}
\end{aligned}
$$

$t \geq t_{ON1}$

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

$$0 \le x \le \infty$$

$$0 \le z \le \infty$$

$$t \ge 0$$

Initial Condition

$$c(x,z,0) = C_{ic}$$

Boundary Conditions

$$c(0,z,t) = C_{ic} + \sum_{j=1}^{N_{bc}} \left(C_{bcj} - C_{ic}\right)\left\{H\left(t - t_{ONj}\right) - H\left(t - t_{OFFj}\right)\right\}\left\{H\left(z - z_{1j}\right) - H\left(z - z_{2j}\right)\right\}$$

where H(.) 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 ($D_x > 0$, $D_z > 0$)

$$c(x,z,t) = C_{ic} + \frac{x}{4}\sqrt{\frac{R_d}{\pi D_x}}\, e^{\frac{V_x x}{2D_x}} \sum_{j=1}^{N_{bc}} \int_{\tau=o}^{t^*} \frac{e^{-\left(\frac{V_x^2}{4R_d D_x}+k\right)\tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{\frac{3}{2}}} \bullet$$

$$\left\{C_{bcj}(t-\tau) - C_{ic}\right\}\left[erfc\left\{(z_{1j}+z)\sqrt{\frac{R_d}{4D_z\tau}}\right\} - erfc\left\{(z_{2j}+z)\sqrt{\frac{R_d}{4D_z\tau}}\right\}\right.$$

$$\left. + erfc\left\{(z_{1j}-z)\sqrt{\frac{R_d}{4D_z\tau}}\right\} - erfc\left\{(z_{2j}-z)\sqrt{\frac{R_d}{4D_z\tau}}\right\}\right] d\tau$$

$$-\frac{k}{2} C_{ic} \int_{\tau=o}^{t^*} e^{-k\tau}\left[erfc\left\{-x\sqrt{\frac{R_d}{4D_x\tau}} + V_x\sqrt{\frac{\tau}{4D_x R_d}}\right\} - e^{\frac{xV_x}{D_x}}\, erfc\left\{x\sqrt{\frac{R_d}{4D_x\tau}} + V_x\sqrt{\frac{\tau}{4D_x R_d}}\right\}\right] d\tau$$

where $t \geq t_{ON1}$

$t^* = t - t_{ON1}$

Solution ($D_x = 0$, $D_z > 0$)

$$c(x,z,t) = C_{ic} - C_{ic} \sum_{j=1}^{N_{bc}} \left\{ e^{-k\,Max[t_{1j},\tau_o]} - e^{-k\,Max[t_{2j},\tau_o]} \right\}$$

$$+ \frac{e^{-k\tau_o}}{2} \sum_{j=1}^{N_{bc}} \left\{ C_{bcj}\left(t^* - \tau_o\right) - C_{ic} \right\} \left\{ H\left(\tau_o - t_{1j}\right) - H\left(\tau_o - t_{2j}\right) \right\} \bullet$$

$$\left[erfc\left(\left(z_{1j} + z\right) \sqrt{\frac{R_d}{4D_z\tau}} \right) - erfc\left(\left(z_{2j} + z\right) \sqrt{\frac{R_d}{4D_z\tau}} \right) \right.$$

$$\left. + erfc\left(\left(z_{1j} - z\right) \sqrt{\frac{R_d}{4D_z\tau}} \right) - erfc\left(\left(z_{2j} - z\right) \sqrt{\frac{R_d}{4D_z\tau}} \right) \right]$$

where $t \geq t_{ON1}$

$\tau_o = xR_d/V_x$

$t_{1j} = \text{Max}\ [0, t - t_{OFFj}]$

$t_{2j} = \text{Max}\ [0, t - t_{ONj}]$

E

MODEL GW2SI

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

$$0 \le x \le \infty$$

$$-\infty \le y \le \infty$$

$$t \ge 0$$

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(.) 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 ($D_x > 0$, $D_y > 0$)

$$c(x,y,t) = c_{ic} + \frac{x}{4}\sqrt{\frac{R_d}{\pi D_x}}\, e^{\frac{V_x x}{2D_x}} \int_{\tau=o}^{t^*} \frac{e^{-\frac{x^2 R_d}{4D_x\tau} - \left(\frac{V_x^2}{4R_d D_x} + k\right)\tau}}{\tau^{3/2}} \quad U_{Tj} \bullet$$

$$\sum_{j=1}^{N_{bc}} \left\{C_{bcj}\left(t^* - \tau\right) - C_{ic}\right\}\left\{-erfc\left(\left(y_{2j} - y\right)\sqrt{\frac{R_d}{4D_y\tau}}\right) + erfc\left(\left(y_{1j} - y\right)\sqrt{\frac{R_d}{4D_y\tau}}\right)\right\} d\tau$$

$$-\frac{c_{ic}}{4}\left[-2e^{-kt^*} erfc\left(\sqrt{(a^2+k)t^*} - \frac{b}{\sqrt{t^*}}\right) \quad + \quad 4\right.$$

$$-e^{2b\sqrt{a^2+k}-2ba}\, erfc\left(-a\sqrt{t^*} + \frac{b}{\sqrt{t^*}}\right)\left\{\frac{\sqrt{a^2+k}}{a} + 1\right\}$$

$$\left. + e^{2b\sqrt{a^2+k}+2ba}\, erfc\left(a\sqrt{t^*} + \frac{b}{\sqrt{t^*}}\right)\left\{\frac{\sqrt{a^2+k}}{a} - 1\right\}\right]$$

$$+\frac{C_{ic}}{4} e^{\frac{xV_x}{D_x}}\left[-2e^{-kt^*} erfc\left(\sqrt{(a^2+k)t^*} + \frac{b}{\sqrt{t^*}}\right)\right.$$

$$+ e^{-2b\sqrt{a^2+k}+2ba}\, erfc\left(a\sqrt{t^*} + \frac{b}{\sqrt{t^*}}\right)\left\{\frac{\sqrt{a^2+k}}{a} + 1\right\}$$

$$\left. - e^{-2b\sqrt{a^2+k}-2ba}\, erfc\left(-a\sqrt{t^*} + \frac{b}{\sqrt{t^*}}\right)\left\{\frac{\sqrt{a^2+k}}{a} - 1\right\}\right]$$

where $t \geq t_{ON1}$

$t^* = t - t_{ON1}$

$$a^2 = \left(\frac{V_x^2}{4R_d D_x} + k \right)$$

$$b^2 = \left(\frac{x^2 R_d}{4D_x} \right)$$

$$U_{Tj} = \left\{ H\left(t - \tau - t_{ONj}\right) - H\left(t - \tau - t_{OFFj}\right) \right\}$$

Solution ($D_x = 0$, $D_y > 0$)

$$c(x,y,t) = C_{ic} + C_{ic} \sum_{j=1}^{N_{bc}} \left\{ e^{-kMax[t_{2j},\tau_o]} - e^{-kMax[t_{1j},\tau_o]} \right\}$$

$$+ \frac{1}{2} \sum_{j=1}^{N_{bc}} e^{-k\tau_o} \left\{ C_{bcj}\left(t^* - \tau_o\right) - C_{ic} \right\} \left\{ H\left(\tau_o - t_{1j}\right) - H\left(\tau_o - t_{2j}\right) \right\} \bullet$$

$$\left\{ erfc\left(\left(y_{1j} - y\right) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) - erfc\left(\left(y_{2j} - y\right) \sqrt{\frac{R_d}{4D_y \tau_o}} \right) \right\}$$

where $t \geq t_{ON1}$

$\tau_o = xR_d/V_x$

$t_{1j} = Max[0, t - t_{OFFj}]$

$t_{2j} = Max\ [0, t - t_{ONj}]$

F

MODEL GW3SIF

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

$$0 \le x \le \infty$$

$$-\infty \le y \le \infty$$

$$0 \le z \le B$$

$$t \ge 0$$

Initial Condition

$$c(x, y, z, 0) = C_{ic}$$

Boundary Conditions

$$c(0, y, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic})\{H(t - t_{ONj}) - H(t - t_{OFFj})\} \bullet$$
$$\{H(y - y_{1j}) - H(y - y_{2j})\}\{H(z - z_{1j}) - H(z - z_{2j})\}$$

where H(.) 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 ($D_x > 0$, $D_y > 0$)

$$c(x,y,z,t) = C_{ic} + \frac{x}{2}\sqrt{\frac{R_d}{\pi D_x}}\, e^{\frac{V_x x}{2D_x}} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \bullet$$

$$\int_{\tau=o}^{t^*} \frac{e^{-\left(\frac{\psi_m^2 D_z}{R_d} + k + \frac{V_x^2}{4D_x R_d}\right)\tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{3/2}} \left\{ erfc\left((y_{1j} - y)\sqrt{\frac{R_d}{4D_y \tau}} \right) - erfc\left((y_{2j} - y)\sqrt{\frac{R_d}{4D_y \tau}} \right) \right\} \bullet$$

$$\left\{ C_{bcj}(t^* - \tau) - C_{ic} \right\} \left\{ H(t - \tau - t_{ONj}) - H(t - \tau - t_{OFFj}) \right\} d\tau$$

$$- kC_{ic} \sum_{m=0}^{\infty} L_m P_m \cos(\psi_m z) \int_{\tau=o}^{t^*} e^{-\left(k + \frac{\psi_m^2 D_z}{R_d}\right)\tau} \left\{ erfc\left(-x\sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) \right.$$

$$\left. - e^{\frac{xV_x}{D_x}} erfc\left(x\sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4D_x R_d}} \right) \right\} d\tau$$

where $t \geq t_{ON1}$

$t^* = t - t_{ON1}$

Define the following coefficients

$$O_{mj} = \begin{cases} \dfrac{(z_{2j} - z_{1j})}{B} & if \quad m = 0 \\ \left\{ \dfrac{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})}{\psi_m B} \right\} & if \quad m = 1,2,3,\ldots \end{cases}$$

$$P_m = \begin{cases} 1 & if \quad m = 0 \\ \left\{ \dfrac{\sin(\psi_m B)}{\psi_m B} \right\} & if \quad m = 1,2,3,\ldots \end{cases}$$

$$\psi_m = \frac{\pi m}{B} \qquad m = 0,1,2,\ldots$$

Solution (D_x = 0)

$$c(x,y,z,t) = C_{ic} + \sum_{m=0}^{\infty} L_m \cos(\psi_m z)\, e^{-\left(\frac{\psi_m^2 D_z}{R_d} + k\right)\tau_o} \bullet$$

$$\sum_{j=1}^{N_{bc}} O_{mj} \{C_{bcj}(t^* - \tau_o) - C_{ic}\}\{H(\tau_o - t_{1j}) - H(\tau_o - t_{2j})\} \bullet$$

$$\left\{ erfc\left((y_{1j} - y)\sqrt{\frac{R_d}{4D_y \tau_o}} \right) - erfc\left((y_{2j} - y)\sqrt{\frac{R_d}{4D_y \tau_o}} \right) \right\} + C_{ic}\left\{ e^{-k\, Min[t^*, \tau_o]} - 1 \right\}$$

where $t \geq t_{ON1}$

$\tau_o = xR_d/V_x$

G

MODEL GW3SIS

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

$$0 \le x \le \infty$$

$$-\infty \le y \le \infty$$

$$0 \le z \le \infty$$

$$t \ge 0$$

Initial Condition

$$c(x, y, z, 0) = C_{ic}$$

Boundary Conditions

$$c(0, y, z, t) = C_{ic} + \sum_{j=1}^{N_{bc}} (C_{bcj} - C_{ic})\{H(t - t_{ONj}) - H(t - t_{OFFj})\} \bullet$$
$$\{H(y - y_{1j}) - H(y - y_{2j})\}\{H(z - z_{1j}) - H(z - z_{2j})\}$$

where H(.) 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 ($D_x > 0$, $D_y > 0$, $D_z > 0$)

$$c(x,y,z,t) = C_{ic} + \frac{x}{8}\sqrt{\frac{R_d}{\pi D_x}}\, e^{\frac{V_x x}{2D_x}} \sum_{j=1}^{N_{bc}} \int_{\tau=o}^{t^*} \left\{ C_{bcj}\left(t^* - \tau\right) - C_{ic} \right\} \bullet$$

$$\frac{e^{-\left(\frac{V_x^2}{4D_x R_d} + k\right)\tau - \frac{x^2 R_d}{4D_x \tau}}}{\tau^{3/2}} \left\{ erfc\left(\left(y_{1j} - y\right)\sqrt{\frac{R_d}{4D_y \tau}}\right) - erfc\left(\left(y_{2j} - y\right)\sqrt{\frac{R_d}{4D_y \tau}}\right) \right\} \bullet$$

$$\left[erfc\left\{\left(z + z_{1j}\right)\sqrt{\frac{R_d}{4D_z \tau}}\right\} - erfc\left\{\left(z + z_{2j}\right)\sqrt{\frac{R_d}{4D_z \tau}}\right\} \right]$$

$$+ erfc\left\{\left(z_{1j} - z\right)\sqrt{\frac{R_d}{4D_z \tau}}\right\} - erfc\left\{\left(z_{2j} - z\right)\sqrt{\frac{R_d}{4D_z \tau}}\right\} \Bigg] d\tau$$

$$-\frac{kC_{ic}}{2} \int_{\tau=o}^{t^*} e^{-k\tau} \left[erfc\left\{ -x\sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4R_d D_x}} \right\} - e^{\frac{V_x x}{D_x}}\, erfc\left\{ x\sqrt{\frac{R_d}{4D_x \tau}} + V_x \sqrt{\frac{\tau}{4R_d D_x}} \right\} \right] d\tau$$

$t \geq t_{ON1}$

Solution ($D_x = 0$, $D_y > 0$, $D_z > 0$)

$$c(x,y,z,t) = C_{ic} - C_{ic}\left\{1 - e^{-k\,Min[t^*,\tau_o]}\right\}$$

$$+\frac{e^{-k\tau_o}}{4}\sum_{j=1}^{N_{bc}}\left\{C_{bcj}\left(t^* - \tau_o\right) - C_{ic}\right\}\left\{H\left(\tau_o - t_{1j}\right) - H\left(\tau_o - t_{2j}\right)\right\}\bullet$$

$$\left\{erfc\left(\left(y_{1j} - y\right)\sqrt{\frac{R_d}{4D_y\tau_o}}\right) - erfc\left(\left(y_{2j} - y\right)\sqrt{\frac{R_d}{4D_y\tau_o}}\right)\right\}\bullet$$

$$\left[erfc\left(\left(z_{1j} + z\right)\sqrt{\frac{R_d}{4D_z\tau_o}}\right) - erfc\left(\left(z_{2j} + z\right)\sqrt{\frac{R_d}{4D_z\tau_o}}\right)\right.$$

$$\left. + erfc\left(\left(z_{1j} - z\right)\sqrt{\frac{R_d}{4D_z\tau_o}}\right) - erfc\left(\left(z_{2j} - z\right)\sqrt{\frac{R_d}{4D_z\tau_o}}\right)\right]$$

where $t \geq t_{ON1}$

$\tau_o = xR_d/V_x$

$t_{1j} = \text{Max}\,[0, t - t_{OFFj}]$ $\quad j = 1,2,3,\ldots.$

$t_{2j} = \text{Max}\,[0, t - t_{ONj}]$

$t^* = t - t_{ON1}$

H

VERTICAL AVERAGING

The vertical averaged concentration between depths z_a and z_b is determined as follows:

$$\int_{z'=z_a}^{z_b} \frac{c(x,y,z',t)}{(z_b - z_a)}\, dz' = \textit{screen averaged conc.}$$

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:

$$\int erfc(Az+B)\, dz = \left(z + \frac{B}{A}\right) erfc(Az+B) - \frac{B}{A} - \frac{e^{-(Az+B)^2}}{A\sqrt{\pi}}$$

$$\int erfc(-Az+B)\, dz = \left(z - \frac{B}{A}\right) erfc(-Az+B) + \frac{B}{A} + \frac{e^{-(-Az+B)^2}}{A\sqrt{\pi}}$$

$$\int_{z'=z_a}^{z_b} \frac{\cos(\psi_m z')}{(z_b - z_a)}\, dz' = \frac{[\sin(\psi_m z_b) - \sin(\psi_m z_a)]}{\psi_m (z_b - z_a)}$$

$$= \frac{(z_b - z_a)}{(z_b - z_a)} = 1 \qquad \textit{if } \psi_m = o$$

I

DETAILED DERIVATION OF MODEL GW3SIF

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) $$R_d \frac{\partial C}{\partial t} + V \frac{\partial C}{\partial x} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - kcR_d$$

$$0 \le x \le \infty$$

$$-\infty \le y \le \infty$$

$$0 \le z \le B$$

$$t \ge 0$$

with the initial condition

2) $C(x,y,z,0) = C_{ic}$ at $t = 0$

and boundary conditions

$$
3)\quad \begin{cases}
C, \dfrac{\partial C}{\partial y} = 0 & \text{at } y = \pm\infty \\
\dfrac{\partial C}{\partial z} = 0 & \text{at } z = 0 \\
\dfrac{\partial C}{\partial z} = 0 & \text{at } z = B \\
\dfrac{\partial C}{\partial x} = 0 & \text{at } x = +\infty \\
C(0,y,z,t) = C_{ic} + \sum_{j=1}^{N_{bc}} \{C_{bcj}(t) - C_{ic}\}\{H(y-y_{1j}) - H(y-y_{2j})\}\bullet & \text{at } x = 0 \\
\{H(z-z_{1j}) - H(z-z_{2j})\}\{H(t-t_{ONj}) - H(t-t_{OFFj})\} &
\end{cases}
$$

where H() are Heaviside unit step functions. The boundary condition at x=0 is subdivided into N_{bc} boundary "patches". As given above, the jth 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:

$$
4)\quad H(x-a) = \begin{cases} 0 & \text{if } x < a \\ \frac{1}{2} & \text{if } x = a \\ 1 & \text{if } x > a \end{cases}
$$

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:

$$
5)\quad C = \hat{C}\exp\left\{\frac{V_x x}{2D_x} - \left(\frac{V_x^2}{4D_x R_d} + k\right)t\right\} + C_{ic}
$$

Differentiate Eq. (5) to get the following expressions:

6)
$$\begin{cases} \dfrac{\partial C}{\partial x} = \dfrac{\partial \hat{C}}{\partial x} e^{A} + \dfrac{V_x}{2D_x} \hat{C} e^{A} \\ \dfrac{\partial^2 C}{\partial x^2} = \dfrac{\partial^2 \hat{C}}{\partial x^2} e^{A} + \dfrac{V_x}{D_x} \dfrac{\partial \hat{C}}{\partial x} e^{A} + \left(\dfrac{V_x}{2D_x} \right)^2 \hat{C} e^{A} \\ \dfrac{\partial C}{\partial t} = -\left(\dfrac{V_x^2}{4D_x R_d} + k \right) \hat{C} e^{A} + \dfrac{\partial \hat{C}}{\partial t} e^{A} \end{cases}$$

where the symbol "A" is defined as:

7)
$$A = \left\{ \frac{V_x x}{2D_x} - \left(\frac{V_x^2}{4D_x R_d} + k \right) t \right\}$$

Upon substitution of the derivatives of Eq. (6) into Eqs. (1), (2), (3), the mass transport equation reduces to the diffusion equation.

8)
$$R_d \frac{\partial \hat{C}}{\partial t} = D_x \frac{\partial^2 \hat{C}}{\partial x^2} + D_y \frac{\partial^2 \hat{C}}{\partial y^2} + D_z \frac{\partial^2 \hat{C}}{\partial z^2} - k R_d C_{ic} e^{\left\{ -\frac{V_x x}{2D_x} + \left(\frac{V_x^2}{4D_x R_d} + k \right) t \right\}}$$

subject to the initial condition:

9) $\hat{C}(x,y,z,0) = 0 \quad \text{at } t = 0$

and boundary conditions

$$
10)\quad \begin{cases}
\dfrac{\partial \hat{C}}{\partial y} = 0 & \text{at } y = \pm\infty \\
\dfrac{\partial \hat{C}}{\partial z} = 0 & \text{at } z = 0 \\
\dfrac{\partial \hat{C}}{\partial z} = 0 & \text{at } z = B \\
C, \dfrac{\partial \hat{C}}{\partial x} = 0 & \text{at } x = +\infty \\
\hat{C}(0,y,z,t) = e^{\left(\frac{V_x^2}{4D_xR_d}+k\right)t} \sum_{j=1}^{N_{bc}} \{C_{bcj}(t) - C_{ic}\} \bullet & \text{at } x = 0 \\
\quad \{H(y-y_{1j}) - H(y-y_{2j})\}\{H(z-z_{1j}) - H(z-z_{2j})\} \bullet & \\
\quad \{H(t-t_{ONj}) - H(t-t_{OFFj})\} &
\end{cases}
$$

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:

$$
11)\quad \begin{cases}
K_z(\Psi_m, z) = \left(\dfrac{2}{B}\right)^{\frac{1}{2}} \cos(\Psi_m z) & \text{for } \Psi_m = \dfrac{\pi m}{B} \quad m = 1,2\ldots \\
K_z(0,z) = \left(\dfrac{1}{B}\right)^{\frac{1}{2}} & \text{for } m = 0
\end{cases}
$$

where Ψ_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

$$
13)\quad K_y(\nu, y) = e^{i\nu y}
$$

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) $$\overline{C}(\beta,y,z,t)=\int_{x'=0}^{\infty}K_x(\beta,x')\hat{C}(x',y,z,t)dx'$$

In order to eliminate the y and z variation from the partial differential equation, we will apply the following two integral transformations:

15) $$\overline{\overline{C}}(\beta,\nu,z,t)=\int_{y'=\infty}^{\infty}K_y(\nu,y')\overline{C}(\beta,y',z,t)dy'$$

16) $$\overline{\overline{\overline{C}}}(\beta,\nu,\psi_m,t)=\int_{z'=0}^{B}K_z(\psi_m,z')\overline{\overline{C}}(\beta,\nu,z',t)dz'$$

where $K_y(\nu,y')$ 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) $$\int_{x'=0}^{\infty}K_x(\beta,x')\frac{\partial^2\hat{C}}{\partial x^2}dx'=\left\{K_x(\beta,x)\frac{\partial\hat{C}}{\partial x}-\hat{C}\frac{\partial K_x}{\partial x}\right\}\Bigg|_{x=0}^{\infty}+\int_{x'=0}^{\infty}\hat{C}\frac{\partial^2K_x}{\partial x^2}dx'$$

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) $$\int_{x'=0}^{\infty}K_x(\beta,x')\frac{\partial^2\hat{C}}{\partial x^2}dx'=\left\{\frac{\partial K_x}{\partial x}(\beta,0)\hat{C}(0,y,z,t)\right\}_{\text{at } x=0}-\beta^2\overline{C}(\beta,y,z,t)$$

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 $K_y(\nu,y')$ and then $K_z(\Psi_m,z')$ and then integrate-by-parts to get the following:

19) $$\int_{y'=\infty}^{\infty}K_y(\nu,y')\frac{\partial^2\overline{C}}{\partial y^2}dy'=-\nu^2\overline{\overline{C}}(\beta,\nu,z,t)$$

20) $$\int_{z'=0}^{B}K_z(\psi_m,z')\frac{\partial^2\overline{\overline{C}}}{\partial z^2}dz'=-\psi_m^2\overline{\overline{\overline{C}}}(\beta,\nu,\psi_m,t)$$

where the boundary condition of Eq. (10) where used.

The final triple transformed solution of Eq. (8) is:

$$R_d \frac{d\overline{\overline{\overline{C}}}}{dt} = -\beta^2 D_x \overline{\overline{\overline{C}}} - \nu^2 D_y \overline{\overline{\overline{C}}} - \psi_m^2 D_z \overline{\overline{\overline{C}}}$$
$$+ \int_{y'=-\infty}^{\infty} \int_{z'=0}^{B} D_x \left\{ \frac{\partial K_x}{\partial x} \hat{C}(0, y', z', t) \right\}_{\text{at } x=0} K_y K_z dy' dz'$$
$$- kR_d C_{ic} e^{\left(\frac{V_x^2}{4D_x R_d} + k\right)t} \int_{x'=0}^{\infty} K_x e^{\frac{-V_x x'}{2D_x}} \int_{y'=-\infty}^{\infty} K_y \int_{z'=0}^{B} K_z dx' dy' dz'$$

21)

with the initial condition:

22) $\overline{\overline{\overline{C}}}(\beta, \nu, \psi_m, 0) = 0$ at t=0

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:

$$\overline{\overline{\overline{C}}}(\beta, \nu, \psi_m, t) = \frac{D_x}{R_d} \beta \sqrt{\frac{2}{\pi}}\, e^{-\left(\beta^2 D_x + \nu^2 D_y + \psi_m^2 D_z\right)\frac{t}{R_d}} \bullet$$
$$\sum_{j=1}^{N_{bc}} \int_{t'=0}^{t} e^{\left(\beta^2 D_x + \nu^2 D_y + \psi_m^2 D_z\right)\frac{t'}{R_d} + \left(k + \frac{V_x^2}{4D_x R_d}\right)t'} \int_{z'=z_{1j}}^{z_{2j}} \int_{y'=y_{1j}}^{y_{2j}} K_z(\psi_m, z') K_y(\nu, y') \bullet$$
$$(C_{bcj} - C_{ic}) dy' dz' dt'$$
$$- kC_{ic} \int_{t'=0}^{t} e^{-\left(\beta^2 D_x + \nu^2 D_y + \psi_m^2 D_z\right)\frac{(t-t')}{R_d} + \left(k + \frac{V_x^2}{4D_x R_d}\right)t'} \bullet$$
$$\int_{x'=0}^{\infty} K_x e^{\frac{-V_x x'}{2D_x}} \int_{y'=-\infty}^{\infty} K_y \int_{z'=0}^{B} K_z dx' dy' dz' dt'$$

23)

where the x = 0 boundary condition of Eq. (10) was used to get

$$\left\{\frac{\partial K_x}{\partial x}\hat{C}\right\} = \beta\sqrt{\frac{2}{\pi}}\,e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}\sum_{j=1}^{N_{bc}}\left\{C_{bcj}(t')-C_{ic}\right\}\left\{H(y-y_{1j})-H(y-y_{2j})\right\}\bullet$$
$$\left\{H(z-z_{1j})-H(z-z_{2j})\right\}\left\{H(t'-t_{ONj})-H(t'-t_{OFFj})\right\}$$

24)

The three inverse transforms are defined as follows:

$$\overline{\overline{C}}(\beta,\nu,z,t)=\sum_{m=0}^{\infty}K_z(\psi_m,z)\overline{\overline{\overline{C}}}(\beta,\nu,\psi_m,t)$$

25)

$$\overline{C}(\beta,y,z,t)=\frac{1}{2\pi}\int_{\nu=-\infty}^{\infty}K_y(-\nu,y)\overline{\overline{C}}(\beta,\nu,z,t)d\nu$$

26)

$$\hat{C}(x,y,z,t)=\int_{\beta=0}^{\infty}K_x(\beta,x)\overline{C}(\beta,y,z,t)d\beta$$

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 $K_y(-\nu,y)$ and finally multiplying by $K_x(\beta,x)$.

The end result of applying the three inverse transforms to Eq. (23) is as follows:

$$\hat{C}(x,y,z,t)=\frac{D_x e^{\left(\frac{V_x^2}{4D_xR_d}+k\right)t}}{\pi R_d\sqrt{2\pi}}\sum_{m=0}^{\infty}K_z(\psi_m,z)\int_{\nu=-\infty}^{\infty}K_y(-\nu,y)\int_{\beta=0}^{\infty}K_x(\beta,x)\beta\bullet$$
$$\sum_{j=1}^{N_{bc}}\int_{t'=0}^{t}e^{-\left(\frac{\beta^2D_x}{R_d}+\frac{\nu^2D_y}{R_d}+\frac{\psi_m^2D_z}{R_d}\right)(t-t')-\left(k+\frac{V_x^2}{4D_xR_d}\right)(t-t')}\bullet$$
$$\int_{z'=z_{1j}}^{z_{2j}}\int_{y'=y_{1j}}^{y_{2j}}K_z(\psi_m,z')K_y(\nu,y')\left\{C_{bcj}(t')-C_{ic}\right\}dy'dz'dt'd\beta d\nu$$

28)

$$-\frac{kC_{ic}e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}}{2\pi}\sum_{m=0}^{\infty}K_z(\psi_m,z)\int_{\nu=-\infty}^{\infty}K_y(-\nu,y)\int_{\beta=0}^{\infty}K_x(\beta,x)\bullet$$
$$\int_{t'=0}^{t}e^{-\left(\beta^2D_x+\nu^2D_y+\psi_m^2D_z\right)\frac{(t-t')}{R_d}-\left(k+\frac{V_x^2}{4D_xR_d}\right)(t-t')}\int_{x'=0}^{\infty}K_xe^{\frac{-V_xx'}{2D_x}}\int_{y'=-\infty}^{\infty}K_y\int_{z'=0}^{B}K_zdy'dx'dz'dt'd\beta d\nu$$

Define the following coefficient

29)
$$L_m = \begin{cases} \frac{1}{2} & \text{if } m = 0 \\ 1 & \text{if } m = 1,2,3\ldots \end{cases}$$

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:

30)
$$\hat{C}(x,y,z,t) = \frac{2D_x e^{\left(\frac{V_x^2}{4D_xR_d}+k\right)t}}{B\pi^2 R_d} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \bullet$$
$$\sum_{j=1}^{N_{bc}} \int_{t'=0}^{t} e^{-\left(\frac{\psi_m^2 D_z}{R_d}+k+\frac{V_x^2}{4D_xR_d}\right)(t-t')} \int_{\beta=0}^{\infty} \beta \sin(\beta x) e^{-\frac{\beta^2 D_x}{R_d}(t-t')} \bullet$$
$$\int_{z'=z_{1j}}^{z_{2j}} \cos(\psi_m z') \int_{y'=y_{1j}}^{y_{2j}} \int_{v=-\infty}^{\infty} e^{-iv(y-y')-\frac{v^2 D_y}{R_d}(t-t')} \left(C_{bcj}(t') - C_{ic}\right) dt'\,dv\,dy'\,dz'\,d\beta$$
$$-\frac{2kC_{ic} e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}}{B\pi^2} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \int_{y'=-\infty}^{\infty} \int_{z'=0}^{B} \cos(\psi_m z') \bullet$$
$$\int_{t'=0}^{t} e^{-\left(\frac{\psi_m^2 D_z}{R_d}+k+\frac{V_x^2}{4D_xR_d}\right)(t-t')} \int_{v=-\infty}^{\infty} e^{-\frac{v^2 D_y}{R_d}(t-t')-iv(y-y')} \, dv \bullet$$
$$\int_{\beta=0}^{\infty} \sin(\beta x) e^{-\frac{\beta^2 D_x}{R_d}(t-t')} \int_{x'=0}^{\infty} \sin(\beta x') e^{\frac{-V_x x'}{2D_x}} dx'\,d\beta\,dt'\,dz'\,dy'$$

However, we can evaluate the following five integrals

31)
$$\int_{z'=z_{1j}}^{z_{2j}} \cos(\psi_m z') dz' = \begin{cases} (z_{2j} - z_{1j}) & \text{if } m = 0 \\ \left\{\dfrac{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})}{\psi_m}\right\} & \text{if } m > 0 \end{cases}$$

32)
$$\int_{\beta=0}^{\infty} \beta \sin(\beta x) e^{-\left(\frac{\beta^2 D_x}{R_d}\right)(t-t')} d\beta = \frac{x\sqrt{\pi}\, e^{\frac{-x^2 R_d}{4D_x(t-t')}}}{4\left(D_x \frac{(t-t')}{R_d}\right)^{\frac{3}{2}}}$$

33)
$$\int_{v=-\infty}^{\infty} e^{-iv(y-y')-\frac{v^2 D_y}{R_d}(t-t')} dv = \sqrt{\frac{\pi R_d}{D_y(t-t')}}\; e^{\frac{-(y-y')^2 R_d}{4D_y(t-t')}}$$

34)
$$\int_{z'=0}^{H} \cos(\psi_m z') dz' = \begin{cases} B & \text{if m} = 0 \\ \dfrac{\sin(\psi_m B)}{\psi_m} & \text{if m} = 1, 2, 3, \ldots \end{cases}$$

35)
$$\int_{x'=0}^{\infty} \sin(\beta x') e^{\frac{-V_x x'}{2D_x}} dx' = \frac{\beta}{\left(\dfrac{V_x^2}{4D_x^2} + \beta^2\right)}$$

Define the following dimensionless coefficients

36)
$$O_{mj} = \begin{cases} \dfrac{(z_{2j} - z_{1j})}{B} & \text{if m} = 0 \\ \left\{\dfrac{\sin(\psi_m z_{2j}) - \sin(\psi_m z_{1j})}{\psi_m B}\right\} & \text{if m} > 0 \end{cases}$$

37)
$$P_m = \begin{cases} 1 & \text{if m} = 0 \\ \dfrac{\sin(\psi_m B)}{\psi_m B} & \text{if m} = 1, 2, \ldots \end{cases}$$

Substitute the integrals of Eqs. (31-35) into Eq. (30) and use Eqs. (36) and 37) to get:

$$\hat{C}(x,y,z,t)=\frac{xR_d e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}}{2\pi\sqrt{D_xD_y}}\sum_{m=0}^{\infty}L_m\cos(\psi_m z)\sum_{j=1}^{N_{bc}}O_{mj}\bullet$$

$$\int_{t'=0}^{t}\frac{e^{-\left(\frac{\psi_m^2D_z}{R_d}+k+\frac{V_x^2}{4D_xR_d}\right)(t-t')-\frac{x^2R_d}{4D_x(t-t')}}}{(t-t')^2}\int_{y'=y_{1j}}^{y_{2j}}e^{-\frac{(y-y')^2R_d}{4D_y(t-t')}}dy'\bullet$$

$$\left(C_{bcj}(t')-C_{ic}\right)dt'$$

$$-\frac{2kC_{ic}}{\pi^2}\sqrt{\frac{\pi R_d}{D_y}}e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}\sum_{m=0}^{\infty}L_mP_m\cos(\psi_m z)\bullet$$

$$\int_{t'=0}^{t}\frac{e^{-\left(\frac{V_x^2}{4D_xR_d}+k+\frac{\psi_m^2D_z}{R_d}\right)(t-t')}}{\sqrt{t-t'}}\int_{y'=-\infty}^{\infty}e^{-\frac{(y-y')^2R_d}{4D_y(t-t')}}\bullet$$

$$\int_{\beta=0}^{\infty}\frac{\beta\sin(\beta x)e^{-\frac{\beta^2D_x(t-t')}{R_d}}}{\left(\beta^2+\frac{V_x^2}{4D_x^2}\right)}d\beta dy'dt'$$

38)

Note the following three integrals:

$$\int_{y'=y_{1j}}^{y_{2j}}e^{-\frac{(y-y')^2R_d}{4D_y(t-t')}}dy'=\sqrt{\frac{\pi D_y(t-t')}{R_d}}\left\{erfc\left(\frac{(y_{1j}-y)}{\sqrt{4D_y\frac{(t-t')}{R_d}}}\right)-erfc\left(\frac{(y_{2j}-y)}{\sqrt{4D_y\frac{(t-t')}{R_d}}}\right)\right\}$$

39)

$$\int_{y'=-\infty}^{\infty}e^{-\frac{(y-y')^2R_d}{4D_y(t-t')}}dy'=2\sqrt{\frac{\pi D_y(t-t')}{R_d}}$$

40)

$$\int_{\beta=0}^{\infty}\frac{\beta\sin(\beta x)e^{-\frac{\beta^2D_x(t-t')}{R_d}}}{\left(\beta^2+\frac{V_x^2}{4D_x^2}\right)}d\beta=\frac{\pi e^{\frac{V_x^2(t-t')}{4D_xR_d}}}{4}\left\{e^{-\frac{xV_x}{2D_x}}erfc\left(-\frac{x}{2}\sqrt{\frac{R_d}{D_x(t-t')}}+\frac{V_x}{2}\sqrt{\frac{t-t'}{D_xR_d}}\right)\right.$$

$$\left.-e^{\frac{xV_x}{2D_x}}erfc\left(\frac{x}{2}\sqrt{\frac{R_d}{D_x(t-t')}}+\frac{V_x}{2}\sqrt{\frac{t-t'}{D_xR_d}}\right)\right\}$$

41)

Substitute the integrals of Eqs. (39-41) into Eq. (38) and rearrange to get:

$$\hat{C}(x,y,z,t)=\frac{x}{2}\sqrt{\frac{R_d}{\pi D_x}}e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}\sum_{m=0}^{\infty}L_m\cos(\psi_m z)\sum_{j=1}^{N_{bc}}O_{mj}\bullet$$

$$\int_{t'=0}^{t}\frac{e^{-\left(\frac{\psi_m^2D_z}{R_d}+k+\frac{V_x^2}{4D_xR_d}\right)(t-t')-\frac{x^2R_d}{4D_x(t-t')}}}{(t-t')^{\frac{3}{2}}}\left\{erfc\left(\frac{(y_{1j}-y)}{\sqrt{\frac{4D_y(t-t')}{R_d}}}\right)\right.$$

$$\left.-erfc\left(\frac{(y_{2j}-y)}{\sqrt{\frac{4D_y(t-t')}{R_d}}}\right)\right\}(C_{bcj}(t')-C_{ic})dt'$$

$$-kC_{ic}e^{\left(k+\frac{V_x^2}{4D_xR_d}\right)t}\sum_{m=0}^{\infty}L_mP_m\cos(\psi_m z)\int_{t'=0}^{t}e^{-\left(k+\frac{\psi_m^2D_z}{R_d}\right)(t-t')}\bullet$$

$$\left\{e^{-\frac{xV_x}{2D_x}}erfc\left(-\frac{x}{2}\sqrt{\frac{R_d}{D_x(t-t')}}+\frac{V_x}{2}\sqrt{\frac{t-t'}{D_xR_d}}\right)\right.$$

$$\left.-e^{\frac{xV_x}{2D_x}}\left(\frac{x}{2}\sqrt{\frac{R_d}{D_x(t-t')}}+\frac{V_x}{2}\sqrt{\frac{t-t'}{D_xR_d}}\right)\right\}dt'$$

42)

Note the following integral relationships:

43) $$\int_{\tau=0}^{t}f(\tau)H(t-\tau-t_{on})d\tau=\int_{\tau=0}^{\max[0,t-t_{on}]}f(\tau)d\tau$$

44) $$\int_{\tau=0}^{t}f(\tau)\{H(t-\tau-t_{on})-H(t-\tau-t_{off})\}d\tau=\int_{\tau=\max[0,t-t_{off}]}^{\max[0,t-t_{on}]}f(\tau)d\tau$$

45) $$\int_{\tau=0}^{t} f(\tau)H(t-\tau-t_{off})d\tau = \int_{\tau=0}^{\max[0,t-t_{off}]} f(\tau)d\tau$$

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) $$\begin{aligned} C(x,y,z,t) = C_{ic} &+ \frac{x}{2}\sqrt{\frac{R_d}{\pi D_x}}\, e^{\frac{V_x x}{2D_x}} \sum_{m=0}^{\infty} L_m \cos(\psi_m z) \sum_{j=1}^{N_{bc}} O_{mj} \bullet \\ &\int_{\tau=0}^{t^*} \frac{e^{-\left(k+\frac{V_x^2}{4D_xR_d}+\frac{\psi_m^2 D_z}{R_d}\right)\tau - \frac{x^2 R_d}{4D_x\tau}}}{\tau^{\frac{3}{2}}} \left\{ erfc\left((y_{1j}-y)\sqrt{\frac{R_d}{4D_y\tau}}\right) - erfc\left((y_{2j}-y)\sqrt{\frac{R_d}{4D_y\tau}}\right)\right\} \bullet \\ &\left\{C_{bcj}(t^*-\tau) - C_{ic}\right\}\left\{H(t-\tau-t_{ONj}) - H(t-\tau-t_{OFFj})\right\} d\tau \\ &- kC_{ic}\sum_{m=0}^{\infty} L_m P_m \cos(\psi_m z) \int_{\tau=0}^{t^*} e^{-\left(k+\frac{\psi_m^2 D_z}{R_d}\right)\tau} \left\{ erfc\left(-x\sqrt{\frac{R_d}{4D_x\tau}} + V_x\sqrt{\frac{\tau}{4D_xR_d}}\right)\right. \\ &\left. - e^{\frac{xV_x}{D_x}} erfc\left(x\sqrt{\frac{R_d}{4D_x\tau}} + V_x\sqrt{\frac{\tau}{4D_xR_d}}\right)\right\} d\tau \end{aligned}$$

where the eigenvalue $\Psi_m = \frac{\pi m}{B}$ and $t^* = t - t_{ON1}$. $t \geq t_{ON1}$

Note the following indefinite integral:

47) $$\begin{aligned} \int e^{(M\tau+N)} erfc\left(a\sqrt{\tau}+\frac{b}{\sqrt{\tau}}\right)d\tau &= \frac{e^{(m\tau+N)}}{M} erfc\left(a\sqrt{\tau}+\frac{b}{\sqrt{\tau}}\right) \\ &+ \frac{e^{-2ab+N+2b\sqrt{a^2-M}}}{2M} erf\left(\sqrt{\tau(a^2-M)}+\frac{b}{\sqrt{\tau}}\right)\left(\frac{a}{\sqrt{a^2-M}}+1\right) \\ &+ \frac{e^{-2ab+N-2b\sqrt{a^2-M}}}{2M} erf\left(\sqrt{\tau(a^2-M)}-\frac{b}{\sqrt{\tau}}\right)\left(\frac{a}{\sqrt{a^2-M}}-1\right) \end{aligned}$$

In addition, note that all of the P_m terms vanish except for the m=0 case. Upon substitution the Ψ_m eigenvalues from Eq. 11), we find that:

48) $\sin(\Psi_m B) = \sin(\pi m) = 0 \qquad m=0,1,\ldots$

Hence, the P_m coefficient reduces to:

49) $$P_m = \begin{cases} 1 & if\ m = 0 \\ 0 & if\ m = 1,2,\ldots \end{cases}$$

Our solution in Eq. 46) reduces to the following:

50)

$$C(x,y,z,t) = C_{ic} + \frac{x}{2}\sqrt{\frac{R_d}{\pi D_x}}e^{\frac{V_x x}{2D_x}}\sum_{m=0}^{\infty} L_m \cos(\psi_m z)\sum_{j=1}^{N_{bc}} O_{mj} \bullet$$

$$\int_{\tau=0}^{t^*} \frac{e^{-\frac{\frac{x^2 R_d}{4D_x\tau}}{\tau} - \left(k + \frac{V_x^2}{4D_x R_d} + \frac{\psi_m^2 D_z}{R_d}\right)\tau}}{\tau^{\frac{3}{2}}}\left\{erfc\left((y_{1j} - y)\sqrt{\frac{R_d}{4D_y\tau}}\right) - erfc\left((y_{2j} - y)\sqrt{\frac{R_d}{4D_y\tau}}\right)\right\} \bullet$$

$$\{C_{bcj}(t^* - \tau) - C_{ic}\}\{H(t - \tau - t_{ONj}) - H(t - \tau - t_{OFFj})\}d\tau$$

$$-kC_{ic}\int_{\tau=0}^{t} e^{-k\tau}\left\{erfc\left(-x\sqrt{\frac{R_d}{4D_x\tau}} + V_x\sqrt{\frac{\tau}{4D_x R_d}}\right) - e^{\frac{xV_x}{D_x}} erfc\left(x\sqrt{\frac{R_d}{4D_x\tau}} + V_x\sqrt{\frac{\tau}{4D_x R_d}}\right)\right\}d\tau$$

where $\Psi_m = \frac{\pi m}{B}$., $t^* = t - t_{ON1}$ $\qquad t \geq t_{ON1}$

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) $$\begin{cases} z_1 = 0 \\ z_2 = B \end{cases}$$

The solution of Eq. (50) now reduces to the 2-D solution (Cleary and Ungs, 1978; Javandel et al., 1984; EPRI, 1989):

52)
$$C(x,y,z,t)=\frac{C_{ic}x\sqrt{R_d}e^{\left(\frac{V_x x}{2D_x}-\gamma t\right)}}{4\sqrt{\pi D_x}}\int_{\tau=0}^{t}\frac{e^{-\left(k-\gamma+\frac{V_x^2}{4D_xR_d}\right)\tau-\frac{x^2R_d}{4D_x\tau}}}{\tau^{\frac{3}{2}}}\bullet$$
$$\left\{erfc\left(\frac{(y_1-y)}{\sqrt{\frac{4D_y\tau}{R_d}}}\right)-erfc\left(\frac{(y_2-y)}{\sqrt{\frac{4D_y\tau}{R_d}}}\right)\right\}d\tau$$

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)
$$\begin{cases} y_1 = -\infty \\ y_2 = +\infty \end{cases}$$

54)
$$C(x,y,z,t)=\frac{C_o x\sqrt{R_d}e^{\left(\frac{V_x x}{2D_x}\right)}}{\sqrt{\pi D_x}}\sum_{m=0}^{\infty}L_m O_m\cos(\psi_m z)$$
$$\bullet\int_{\tau=0}^{t^*}\frac{e^{-\left(\frac{\psi_m^2 D_z}{R_d}+k+\frac{V_x^2}{4D_xR_d}\right)\tau-\frac{x^2R_d}{4D_x\tau}}}{\tau^{\frac{3}{2}}}d\tau$$

which upon integration reduces to

55)
$$C(x,y,z,t)=C_o e^{\left(\frac{V_x x}{2D_x}\right)}\sum_{m=0}^{\infty}L_m O_m\cos(\psi_m z)$$
$$\bullet\left\{e^{\sqrt{\frac{\alpha R_d}{D_x}}}erfc\left(\frac{x}{\sqrt{\frac{4D_xt^*}{R_d}}}+\sqrt{\alpha t^*}\right)-e^{-\sqrt{\frac{\alpha R_d}{D_x}}}erfc\left(\frac{x}{\sqrt{\frac{4D_xt^*}{R_d}}}-\sqrt{\alpha t^*}\right)\right\}$$

where the coefficient α is defined as

56) $$\alpha = \left\{ \frac{\psi_m^2 D_z}{R_d} + k + \frac{V_x^2}{4 D_x R_d} \right\}$$

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) $$\dot{m}(x) = \theta V_x \int_{y'=-\infty}^{\infty} \int_{z'=0}^{B} C(x, y', z', \infty) dy' dz' - \theta D_x \int_{y'=-\infty}^{\infty} \int_{z'=0}^{B} \frac{\partial C}{\partial x}(x, y', z', \infty) dy' dz'$$

where θ is the porosity of the aquifer.

The steady-state concentration C(x,y,z,∞) is found by settling t = ∞ in Eq. (50).

In order to evaluate Eq. (57), we will need the following integral:

58) $$\int_{z'=0}^{B} \cos(\psi_m z') dz' = \left\{ \frac{\sin(\psi_m z')}{\psi_m} \right\} \Bigg|_O^B = \begin{cases} B & \text{if } m = 0 \\ 0 & \text{if } m > 0 \end{cases}$$

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) $$\int_{y'=-\infty}^{\infty} \left\{ erfc\left(\frac{(y_1 - y')}{\sqrt{\frac{4 D_y \tau}{R_d}}} \right) - erfc\left(\frac{(y_2 - y')}{\sqrt{\frac{4 D_y \tau}{R_d}}} \right) \right\} dy' = 2(y_2 - y_1)$$

Substitute the integrals of Eqs. (58) and (59) and the steady-state solution of Eq. (50) into the first integral of Eq. (57):

60)
$$\int_{y'=-\infty}^{\infty}\int_{z'=0}^{B} C(x,y',z',\infty)dy'dz' = C_{ic}\frac{x(z_2-z_1)(y_2-y_1)}{2\sqrt{\pi D_x}}e^{\frac{V_x x}{2D_x}}\sqrt{R_d}\bullet \int_{\tau=0}^{\infty}\frac{e^{-\left(k+\frac{V_x^2}{4D_xR_d}\right)\tau-\frac{x^2R_d}{4D_x\tau}}}{\tau^{\frac{3}{2}}}d\tau$$

The right-hand side integral of Eq. (60) can be evaluated as follows:

61)
$$b\int_{\tau=0}^{\infty}\frac{e^{-a^2\tau-\frac{b^2}{\tau}}}{\tau^{\frac{3}{2}}}d\tau = \sqrt{\pi}\,e^{-2ab}$$

Substitute Eq. (61) into Eq. (60) and let b = $x\sqrt{\frac{R_d}{4D_x}}$

62)
$$\int_{y'=-\infty}^{\infty}\int_{z'=0}^{B} C(x,y',z',\infty)dy'dz' = C_{ic}(z_2-z_1)(y_2-y_1)e^{x\left\{\frac{V_x}{2D_x}-\sqrt{\frac{kR_d}{D_x}+\frac{V_x^2}{4D_x^2}}\right\}}$$

Differentiate Eq. (62) with respect to x

63)
$$\int_{y'=-\infty}^{\infty}\int_{z'=0}^{B}\frac{\partial C}{\partial x}(x,y',z',\infty)dy'dz' = C_{ic}(z_2-z_1)(y_2-y_1)\bullet \left\{\frac{V_x}{2D_x}-\sqrt{\frac{kR_d}{D_x}+\frac{V_x^2}{4D_x^2}}\right\}e^{x\left\{\frac{V_x}{2D_x}-\sqrt{\frac{kR_d}{D_x}+\frac{V_x^2}{4D_x^2}}\right\}}$$

We will now evaluate Eq. (57) at x = 0.

64)
$$\dot{m}(x=0) = \theta V_x\int_{y'=-\infty}^{\infty}\int_{z'=0}^{B} C(0,y',z',\infty)dy'dz' - \theta D_x\int_{y'=-\infty}^{\infty}\int_{z'=0}^{B}\frac{\partial C}{\partial x}(0,y',z',\infty)dy'dz'$$

Substitute Eqs. (62) and (63) into Eq. (64) for x = 0 to give the total mass flux as:

65)
$$\dot{m}(x=0,t=\infty) = \theta C_o(z_2-z_1)(y_2-y_1)\frac{V_x}{2}\left\{1+\sqrt{1+\frac{k4R_dD_x}{V_x^2}}\right\}$$

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Appendix 6

Appendix 6

Calculations Used As Input for MYGRT Model Runs

Belews Creek Ash Landfill Expansion
Calculation for Time to Pass One Pore Volume of Water Through Ash Column
With an engineered cover

Assume one square foot of ash for calculations

Infiltration per year =	0.0154	in/year
	1.28E-03	feet/year

Calculate Area Weighted Depth of Ash

	Area (ac)	Mean Depth of Ash (ft)
Area 1	19.6	67.2
Area 2	22.9	82.3
Area 3	5.3	35.9
Total acres	47.8	

Area Weighted Depth of Ash	71.0	feet
Thickness of Unsaturated Ash	71.0	feet
Moisture Content of Unsaturated Ash	16.4%	(average)
Porosity of Ash (average), n =	0.45	volume/volume

The period of time required to exchange one pore volume in the column of ash is equal to the volume of water contained in the column of ash divided by the infiltration rate.

Calculate volume of water in ash column:

1) Calculate volume of water in 1 ft^3 of unsaturated ash

moisture content = 16%

$$\text{moisture content} = \frac{\text{weight of water}}{\text{weight of solids}}$$

volume of solids = 1 - n = 0.55 ft^3

Specific Gravity = 2.26 (average) (Source Appendix 1)

weight of solids = * 62.4 lb/ft^3 * Volume of solids
= 77.92 lb

weight of water = content * weight of solids
= 12.78 lb

$$\text{volume of water} = \frac{12.78 \text{ lb}}{62.40 \text{ lb/ft}^3}$$

volume of water = 0.20 ft^3

2) Calculate volume of water in unsaturated ash column

volume of water in 1 ft^3 =	0.20	ft^3
height of unsaturated ash =	71.0	feet
volume of water in unsaturated ash =	14.53	ft^3

3) Calculate time for 1 pore volume to pass through ash column

$$\text{Time for 1 pore volume} = \frac{14.53 \text{ ft}^3}{1.28\text{E-}03 \text{ ft}^3/\text{year}}$$

Time for 1 pore volume = 11,324 years

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 1

Source Dimensions

Dimensions of Area with respect to this flowpath

Source Width	=	620	feet
Source Length (parallel to groundwater flow)	=	1380	feet

Calculate Hydraulic Gradient

Uppermost groundwater elevation	809.56	ft	BC-1A
Lowermost groundwater elevation	754.08	ft	MW2-2
dH =	55.48	feet	
Length of Flow =	1380	feet	
Gradient, I = dH/Length of flow	0.040	ft/ft	

Hydraulic Conductivity

k =	1.40E-05	cm/sec	(Median K for Layer 1, in Volume 2, Reference 1)
k =	14.5	ft/yr	

Calculate Average Groundwater Velocity

ne = 0.15 NC Risk Analysis Framework, Draft December 1996, Table A6.1

$$V = \frac{k * I}{ne}$$

V = 3.88 ft/yr

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 1

Infiltration From HELP runs:
The maximum infiltration occurs during the Operational Period

Operational Period	2.72	inches/year
	0.23	ft/yr

Aquifer Thickness

The aquifer thickness is considered to be the distance from the groundwater surface to auger refusal.

The average of these values for the borings within the area will be used.

Groundwater readings taken 4/19/01.
Temporary wells at BC-2 and BC-3 abandoned.

Area 1	**Top of Casing (ft)**	**Depth to Groundwater (ft)**	**Groundwater Elevation (ft)**	**Layer 1 Thickness (ft)**	**Layer 2 Thickness (ft)**	**Total Depth Layer 1 + Layer 2 (ft)**	**Elevation of Lower End of Layer 2 (ft)**	**Thickness of Aquifer (ft)**
BC-1A	848.24	38.68	809.56	19.8	45.9	65.7	780.04	29.52
BC-4A	806.17	47.26	758.91	10.6	27.9	38.5	765.17	0
BC-5	822.34	25.64	796.7	12	18.2	30.2	789.64	7.06
MW2-1	789.32	36.69	752.63	17	30	47	739.82	12.81
MW2-2	787.23	32.9	754.33	37.95	18.25	56.2	728.53	25.8
							Average Thickness	**15.0**

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 1

MYGRT calculates an initial concentration at the source, based on the following equation:

Initial Concentration MYGRT Eqn.

$$Cbc = \frac{(Cic*Qgw + Clcht*Qlcht)}{(Qgw + Qlcht)}$$ (A-9)

This equation assumes that the landfill is located so that it receives groundwater flow from an upgradient area.

At Belews Creek, the landfill is located at the top of a groundwater divide. Therefore, the upgradient flow under the landfill is zero.

However, MYGRT will use the flow information to calculate a flow, Qgw.

The following calculations develop a factor that the input concentrations will be increased by.

Use of this factor will cause MYGRT to use the correct initial concentrations.

Groundwater Flow at Upgradient Edge of Source (Qgw)

Qgw = Vx * porosity * W source * Pd

k

Vx =	3.88	ft/yr	
porosity =	0.15	vol/vol	
W source =	620	ft	
Pd =	15.0	ft	mixing depth or aquifer thickness
Qgw =	5,429	ft^3/yr	
	153,746.79	L/yr	

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 1

Qlcht = Infiltration * Area of source

Infiltration =	0.227	ft/yr
Length =	1380	ft
Width =	620	ft
Area of source	855,600	ft^2
Qlcht =	5,491,686	L/yr

Initial Concentration

$$Cbc = \frac{(Cic*Qgw + Clcht*Qlcht)}{(Qgw + Qlcht)} \qquad \text{(A-9)}$$

UPSF Conc

Cic =	0	
Qgw =	153,747	L/yr

Equation (A-9) simplifies to:

$$Cbc = \frac{(0 + Clcht*Qlcht)}{(Qgw + Qlcht)}$$

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 1

The initial concentration that MYGRT will use can be calculated with this equation:
An assumed input concentration of 1 mg/L is used:

Clcht = 1 mg/L

Qlcht = 5,491,686 L/yr

Initial conc. @ down gradient side Cbc = 0.9728 mg/L

Since the initial concentration calculated by MYGRT should be: 1 mg/L

the input concentration, Clcht, should be increased by the factor: $\frac{1}{0.9728}$

Area 1
Adjustment Factor 1.03

This factor will be applied to the SPLP leach results to account for the dilution assumed by MYGRT

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: **Area 2**

Source Dimensions

Dimensions of Area with respect to this flowpath

Source Width	=	645	feet
Source Length (parallel to groundwater flow)	=	1550	feet

Calculate Hydraulic Gradient

Uppermost groundwater elevation	817.6	ft	C/L Haul Road
Lowermost groundwater elevation	750.8	ft	Ash Basin Pond Elev.
dH =	66.8	feet	
Length of Flow =	1550	feet	
Gradient, I = dH/Length of flow	0.043	ft/ft	

Hydraulic Conductivity

k =	1.40E-05	cm/sec	(Median K for Layer 1, in Volume 2, Reference 1)
k =	14.5	ft/yr	

Calculate Average Groundwater Velocity

ne = 0.15 NC Risk Analysis Framework, Draft December 1996, Table A6.1

$$V = \frac{k * I}{ne}$$

V = 4.16 ft/yr

Infiltration

From HELP runs:
The maximum infiltration occurs during the Operational Period

Operational Period	1.05	inches/year
	0.09	ft/yr

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 2

Aquifer Thickness

The aquifer thickness is considered to be the distance from the groundwater surface to auger refusal.

The average of these values for the borings within the area will be used.

Groundwater readings taken 4/19/01.

Area 2

	Top of Casing (ft)	Depth to Groundwater (ft)	Groundwater Elevation (ft)	Layer 1 Thickness (ft)	Layer 2 Thickness (ft)	Total Depth Layer 1 + Layer 2 (ft)	Elevation of Lower End of Laver 2 (ft)	Thickness of Aquifer (ft)
BC-1A	848.24	38.68	809.56	19.8	45.9	65.7	780.04	29.52
BC-4A	806.17	47.26	758.91	10.6	27.9	38.5	765.17	0
BC-5	822.34	25.64	796.7	12	18.2	30.2	789.64	7.06
BC-6A	843.94	28.73	815.21	19.2	5	24.2	817.24	0
MW2-5	849.32	41	808.32	24.5	18	42.5	804.32	4
MW2-3	796.69	39.58	757.11	13.7	27	40.7	753.49	3.62
							Average Thickness	**2.9**

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 2

MYGRT calculates an initial concentration at the source, based on the following equation:

Initial Concentration MYGRT Eqn.

$$Cbc = \frac{(Cic*Qgw + Clcht*Qlcht)}{(Qgw + Qlcht)}$$ (A-9)

This equation assumes that the landfill is located so that it receives groundwater flow from an upgradient area.

At Belews Creek, the landfill is located at the top of a groundwater divide. Therefore, the upgradient flow under the landfill is zero.

However, MYGRT will use the flow information to calculate a flow, Qgw.

The following calculations will develop a factor that the input concentrations will be increased by.

Use of this factor will cause MYGRT to use the correct initial concentrations.

Groundwater Flow at Upgradient Edge of Source (Qgw)

Qgw = Vx * porosity * W source * Pd

k			
Vx =	4.16	ft/yr	
porosity =	0.15	vol/vol	
W source =	620	ft	
Pd =	2.936	ft	mixing depth or aquifer thickness
Qgw =	1,136	ft^3/yr	
	32,178	L/yr	

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 2

Qlcht = Infiltration * Area of source

Infiltration =	0.088	ft/yr
Length =	1550	ft
Width =	645	ft
Area of source	999,750	ft^2
Qlcht =	2,477,118	L/yr

Initial Concentration

$$Cbc = \frac{(Cic*Qgw + Clcht*Qlcht)}{(Qgw + Qlcht)} \qquad \text{(A-9)}$$

Cic =	0	
Qgw =	32,178	L/yr

Equation (A-9) simplifies to:

$$Cbc = \frac{(0 + Clcht*Qlcht)}{(Qgw + Qlcht)}$$

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 2

The initial concentration that MYGRT will use can be calculated with this equation:
An assumed input concentration of 1 mg/L is used:

Clcht =	1	mg/L
Qlcht =	2,477,118	L/yr
Cbc =	0.9872	mg/L

Since the concentration used by MYGRT should be: 1 mg/L

the input concentration, Clcht, should be increased by the factor: $\frac{1}{0.9872}$

Area 2
Adjustment Factor **1.01**

This factor will be applied to the SPLP leach results to account for the dilution assumed by MYGRT

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: **Area 3**

Source Dimensions

Dimensions of Area with respect to this flowpath

Source Width	=	375	feet
Source Length (parallel to groundwater flow)	=	615	feet

Calculate Hydraulic Gradient

Uppermost groundwater elevation	810	ft	C/L Haul Road
Lowermost groundwater elevation	750.8	ft	Ash Basin Pond Elev.
dH =	59.2	feet	
Length of Flow =	615	feet	
Gradient, I = dH/Length of flow	0.096	ft/ft	

Hydraulic Conductivity

k =	1.40E-05	cm/sec	(Median K for Layer 1, in Volume 2, Reference 1)
k =	14.5	ft/yr	

Calculate Average Groundwater Velocity

ne =	0.15	NC Risk Analysis Framework, Draft December 1996, Table A6.1
V =	$\frac{k * I}{ne}$	
V =	9.30	ft/yr

Infiltration

From HELP runs:
The maximum infiltration occurs during the Operational Period

Operational Period	7.48	inches/year
	0.62	ft/yr

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 3

Aquifer Thickness

The aquifer thickness is considered to be the distance from the groundwater surface to auger refusal.

The average of these values for the borings within the area will be used.

Groundwater readings taken 4/19/01, except fro MW-3 reading taken 6/12/2001.

Area 3

	Top of Casing (ft)	Depth to Groundwater (ft)	Groundwater Elevation (ft)	Layer 1 Thickness (ft)	Layer 2 Thickness (ft)	Total DepthLayer 1 + Layer 2 (ft)	Elevation of Lower End of Layer 2 (ft)	Thickness of Aquifer (ft)
BC-6A	843.94	28.73	815.21	24.5	18.0	42.5	798.94	16.27
MW2-4	814.70	48.28	766.42	24.3	13.8	38.1	774.1	0
MW-3	843.19	41.81	801.38	23.01	24.8	47.81	792.88	8.5
							Average Thickness	**8.3**

Note: Borings MW-3 and BC-6A are used to represent Layer 1 and Layer 2 for this section.

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 3

MYGRT calculates an initial concentration at the source, based on the following equation:

Initial Concentration MYGRT Eqn.

$$Cbc = \frac{(Cic*Qgw + Clcht*Qlcht)}{(Qgw + Qlcht)}$$ (A-9)

This equation assumes that the landfill is located so that it receives groundwater flow from an upgradient area.

At Belews Creek, the landfill is located at the top of a groundwater divide. Therefore, the upgradient flow under the landfill is zero.

However, MYGRT will use the flow information to calculate a flow, Qgw.

The following calculations will develop a factor that the input concentrations will be increased by.

Use of this factor will cause MYGRT to use the correct initial concentrations.

Groundwater Flow at Upgradient Edge of Source (Qgw)

Qgw = Vx * porosity * W source * Pd

k			
Vx =	9.30	ft/yr	
porosity =	0.15	vol/vol	
W source =	375	ft	
Pd =	8.3	ft	mixing depth or aquifer thickness
Qgw =	4,317	ft^3/yr	
	122,250	L/yr	

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 3

Qlcht = Infiltration * Area of source

Infiltration =	0.623	ft/yr
Length =	615	ft
Width =	375	ft
Area of source	230,625	ft^2
Qlcht =	4,070,746	L/yr

Initial Concentration

$$Cbc = \frac{(Cic*Qgw + Clcht*Qlcht)}{(Qgw + Qlcht)} \qquad \text{(A-9)}$$

Cic =	0	
Qgw =	122,250	L/yr

Equation (A-9) simplifies to:

$$Cbc = \frac{(0 + Clcht*Qlcht)}{(Qgw + Qlcht)}$$

Belews Creek Ash Landfill Expansion
Correction Factor for Input Concentrations in MYGRT
Section Modeled: Area 3

The initial concentration that MYGRT will use can be calculated with this equation:
An assumed input concentration of 1 mg/L is used:

Clcht =	1	mg/L
Qlcht =	4,070,746	L/yr
Cbc =	0.9708	mg/L

Since the concentration used by MYGRT should be: 1 mg/L

the input concentration, Clcht, should be increased by the factor: $\frac{1}{0.9708}$

Area 3
Adjustment Factor **1.03**

This factor will be applied to the SPLP leach results to account for the dilution assumed by MYGRT

Belews Creek Ash Landfill Expansion
Model Inputs
Average Bulk Density and Mositure Content of Soil

SAMPLE ID	DEPTH (feet)		USCS Classif.	IN-SITU CONDITIONS			
	From	To		Unit Weight (pcf)	Natural Moist. (%)	Specific Gravity	Porosity
MW 2-1	9.5	11.5	CH	64.7	30.7	2.88	0.64
MW 2-4	19.0	21.0	ML	82.1	21.1	2.67	0.51
MW 2-2	24.1	25.5	ML	89.8	18.0	2.65	0.46
MW 2-3	29.0	30.6	ML	93.8	17.5	2.72	0.45
MW 2-2	34.1	36.1	ML	86.1	33.1	2.73	0.49
BC-4 UD-1	5.0	6.7	ML	79.4	16.1	2.73	0.53
BC-5 UD-1	9.5	11.5	ML	72.5	23.4	2.64	0.56
Average				**81.2**	**22.8**	**2.72**	**0.52**

Use 81.2 lbs/ft^3 as unit weight.
22.8% as natural moisture content.

Convert unit weight to dry bulk density (g/ml)

$$n = \frac{\text{1-Volume of Soilds}}{\text{Volume}}$$

Volume of Solids = 1-n
= 0.48 ft^3

Weight of Solids = Volume of Solids * Specifc Gravity of Solids * 62.4 lb/ft^3
= 81.4 lb/ft^3
Weight of Solids = 1.31 g/ml = Average bulk density

Belews Creek Ash Landfill Expansion
Model Inputs
Layer Thicknesses

Groundwater readings taken 4/19/01 except as noted.
Temporary wells at BC-2 and BC-3 abandoned.

Area 1	Top of Casing (ft)	Depth to Groundwater (ft)	Groundwater Elevation (ft)	Layer 1 Thickness (ft)	Layer 2 Thickness (ft)	Total DepthLayer 1 + Layer 2 (ft)	Elevation of Lower End of Layer 2 (ft)	Thickness of Aquifer (ft)
BC-1A	848.24	38.68	809.56	19.8	45.9	65.7	780.0	29.52
BC-4A	806.17	47.26	758.91	10.6	27.9	38.5	765.2	0
BC-5	822.34	25.64	796.7	12.0	18.2	30.2	789.6	7.06
MW2-1	789.32	36.69	752.63	17.0	30.0	47.0	739.8	12.81
MW2-2	787.23	32.90	754.33	37.9	18.3	56.2	728.5	25.8
							Average Thickness	**15.0**

Area 2	Top of Casing (ft)	Depth to Groundwater (ft)	Groundwater Elevation (ft)	Layer 1 Thickness (ft)	Layer 2 Thickness (ft)	Total DepthLayer 1 + Layer 2 (ft)	Elevation of Lower End of Layer 2 (ft)	Thickness of Aquifer (ft)
BC-1A	848.24	38.68	809.56	19.8	45.9	65.7	780.0	29.52
BC-4A	806.17	47.26	758.91	10.6	27.9	38.5	765.2	0
BC-5	822.34	25.64	796.70	12.0	18.2	30.2	789.6	7.06
BC-6A	843.94	28.73	815.21	19.2	5.0	24.2	817.2	0
MW2-5	849.32	41.00	808.32	24.5	18.0	42.5	804.3	4.0
MW2-3	796.69	39.58	757.11	13.7	27.0	40.7	753.5	3.62
							Average Thickness	**2.9**

Area 3	Top of Casing (ft)	Depth to Groundwater (ft)	Groundwater Elevation (ft)	Layer 1 Thickness (ft)	Layer 2 Thickness (ft)	Total DepthLayer 1 + Layer 2 (ft)	Elevation of Lower End of Layer 2 (ft)	Thickness of Aquifer (ft)
BC-6A	843.94	28.73	815.21	24.5	18.0	42.5	798.9	16.27
MW2-4	814.70	48.28	766.42	24.3	13.8	38.1	774.1	0
MW-3	843.19	41.81	801.38	23.0	24.8	47.8	792.9	8.5
Note MW-3 reading from 6/12/2001							**Average Thickness**	**8.3**

Note: Borings MW-3 and BC-6A are used to represent Layer 1 and Layer 2 for this section.

Belews Creek Ash Landfill Expansion
Model Inputs
Retardation Factors for Unsaturated Zone

The retardation factor is calculated as follows:

$$Rd = 1 + \frac{Kd * rb}{ne}$$

Rd = retardation factor
Kd = solid phase linear partition coefficient (ml/g)
rb = dry bulk density (g/ml)
ne = effective porosity

	Cadmium	Selenium	
Kd (mg/l)	5.5	8.3	
rb =	1.31	g/ml	
ne =	0.228	For unsaturated conditions, the moisture content is used.	
	Cadmium	**Selenium**	
Rd =	**32.6**	**48.7**	

Belews Creek Ash Landfill Expansion
Model Inputs
Retardation Factors for Saturated Zone

The retardation factor is calculated as follows:

$$Rd = 1 + \frac{Kd * rb}{ne}$$

Rd = retardation factor
Kd = solid phase linear partition coefficient (ml/g)
rb = dry bulk density (g/ml)
ne = effective porosity

	Cadmium	Selenium
Kd (mg/l)	5.5	8.3

rb = 1.31 g/ml

ne = 0.15 This is the suggested value for effective porosity found in North Carolina Risk Analysis Framework, DRAFT, December 1996. Table A.6.1 Aquifer Paremeters for Hydrologic Settings in NC

	Cadmium	**Selenium**
Rd =	**49.0**	**73.5**

Appendix 7

Appendix 7

MYGRT Model Results

MYGRT Results

Area 1

Cadmium, Selenium

Input Parameters

Description	Units	Value	Note
General Parameters			
Site		Duke Power Belews Creek Ash Landfill	
Description		Area 1	
Notes			
Solute Name		Cadmium	
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	0.227	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2008	
Unsat Infiltration After Switch	ft/yr	0.0013	
Unsat Moisture Content	ft3/ft3	0.228	
Unsat Dispersion Coeff in Z	ft2/yr	0.398	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		32.6	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	620	
Source Length	ft	1380	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	96.8	
Dispersion along Y	ft2/yr	9.68	
Dispersion along Z	ft2/yr	0.968	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	15	
Seepage Velocity	ft/yr	3.87	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.15	
Hydraulic Gradient	ft/ft	0.04	
Hydraulic Conductivity	ft/yr	14.5	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	15	Calc'd
Source Penetration Depth After	ft	15	Calc'd

This rate assumes 71' ash for all 5 years. 1.35 ft/yr @ yr 0

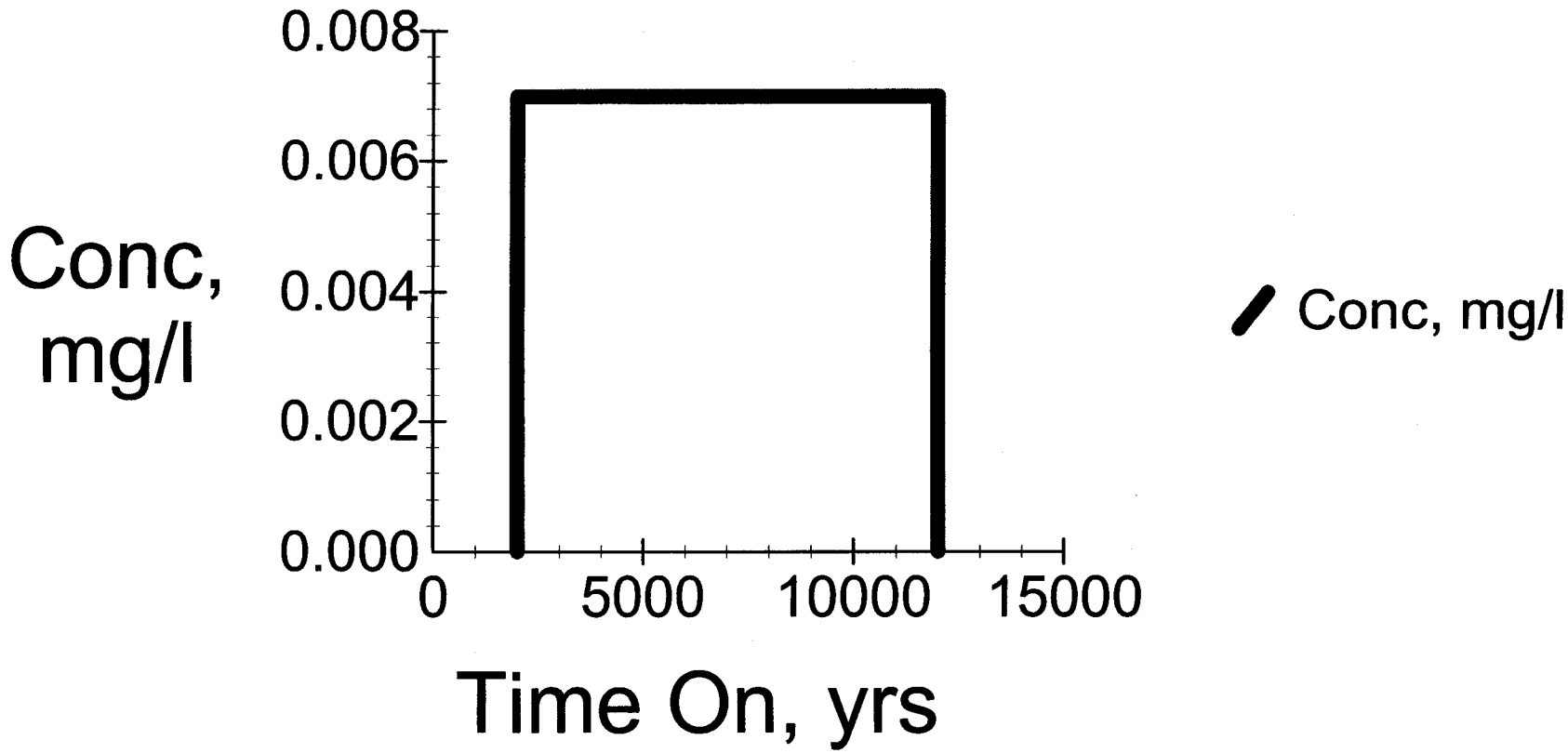
Input Parameters

Description	Units	Value	Note
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.31	
pH		5.5	
Rd (inorganic)		49	Calc'd
Partition Coeff, Kd	ml/g	5.5	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	0	

Source Concentration

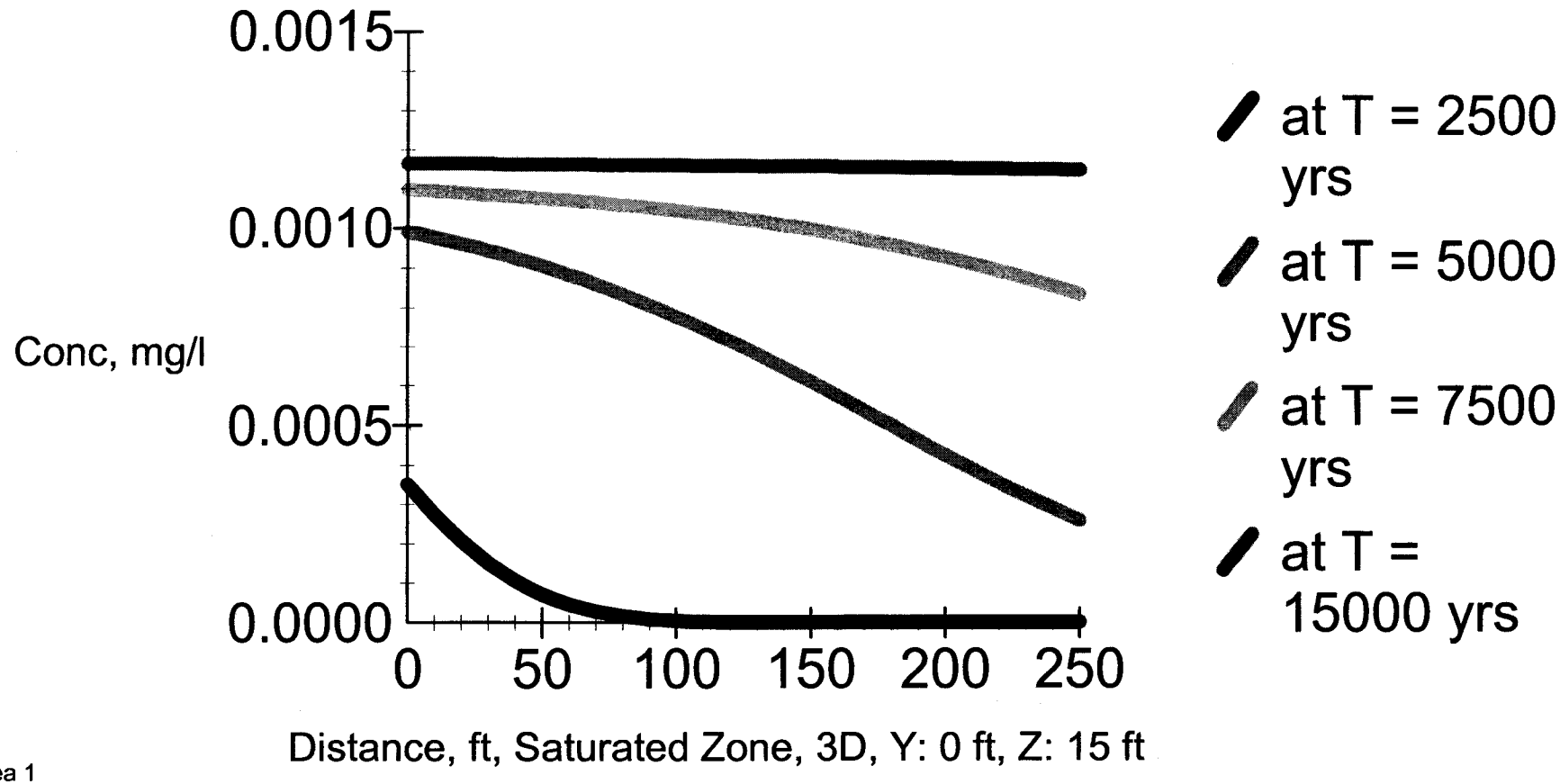
	Time On, yrs	Conc, mg/l
1	2003.000	0.007
2	12008.000	0.007
3	12008.000	0.000

Source Concentration



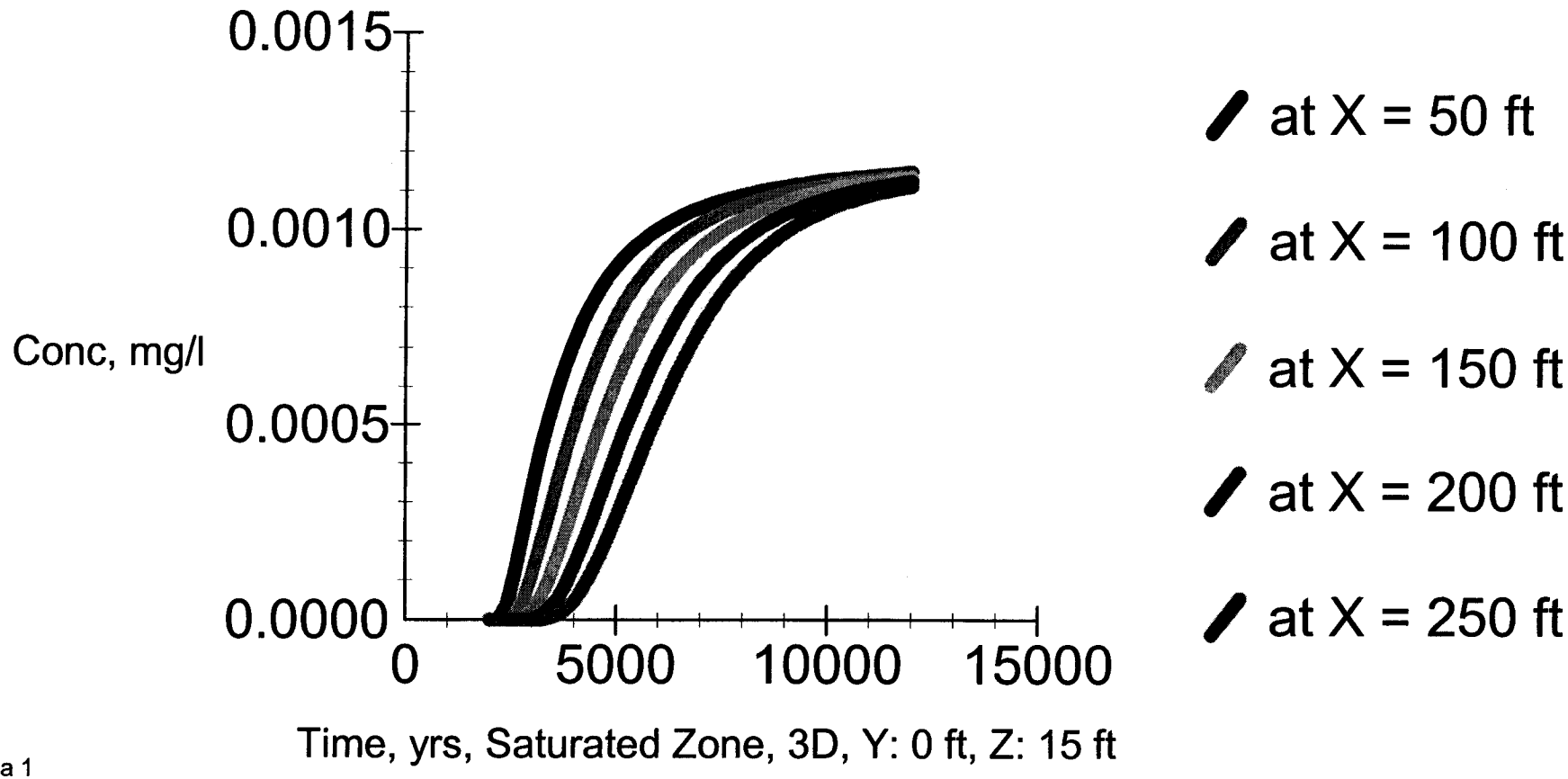
Cadmium Concentrations vs Distance

.005 = 2L



Area 1

Cadmium Concentrations vs Time



Area 1

Input Parameters

Description	Units	Value	Note
General Parameters			
Site		Duke Power Belews Creek Ash Landfill	
Description		Area 1	
Notes			
Solute Name		Selenium	
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	0.227	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2008	
Unsat Infiltration After Switch	ft/yr	0.0013	
Unsat Moisture Content	ft3/ft3	0.228	
Unsat Dispersion Coeff in Z	ft2/yr	0.398	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		48.7	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	620	
Source Length	ft	1380	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	96.8	
Dispersion along Y	ft2/yr	9.68	
Dispersion along Z	ft2/yr	0.968	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	15	
Seepage Velocity	ft/yr	3.87	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.15	
Hydraulic Gradient	ft/ft	0.04	
Hydraulic Conductivity	ft/yr	14.5	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	15	Calc'd
Source Penetration Depth After	ft	15	Calc'd

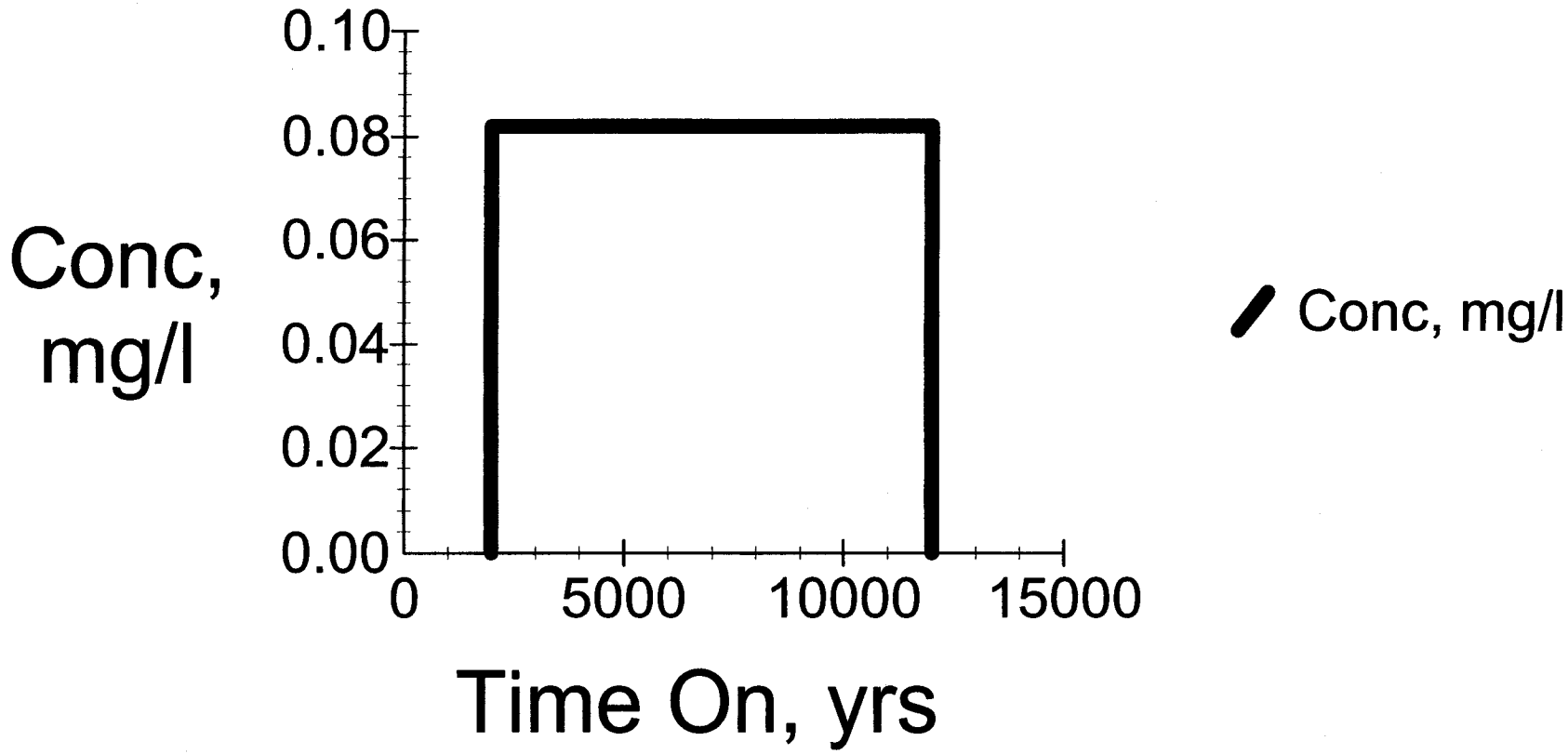
Input Parameters

Description	Units	Value	Note
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.31	
pH		5.5	
Rd (inorganic)		73.5	Calc'd
Partition Coeff, Kd	ml/g	8.3	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	0	

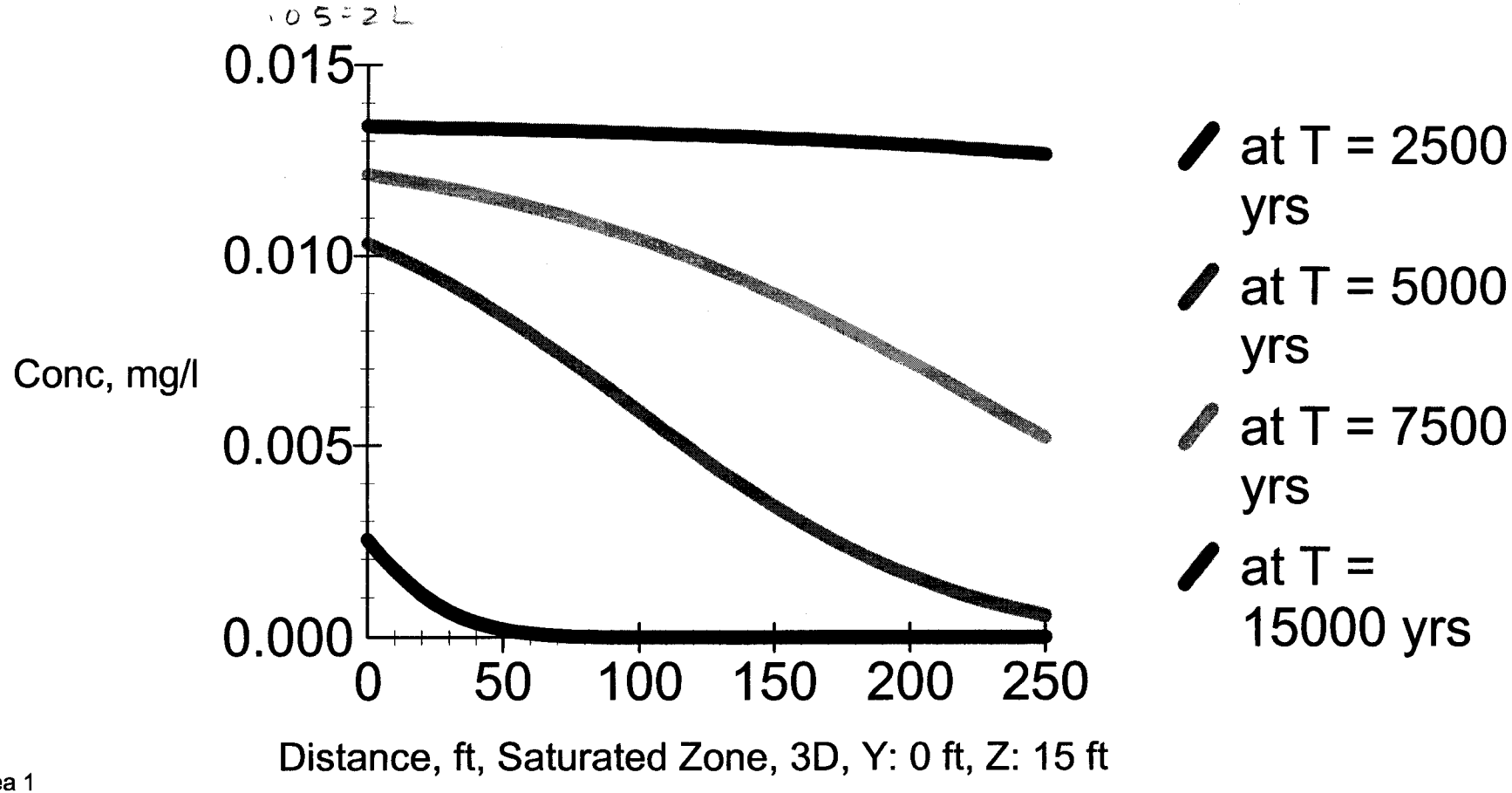
Source Concentration

	Time On, yrs	Conc, mg/l
1	2003.000	0.082
2	12008.000	0.082
3	12008.000	0.000

Source Concentration

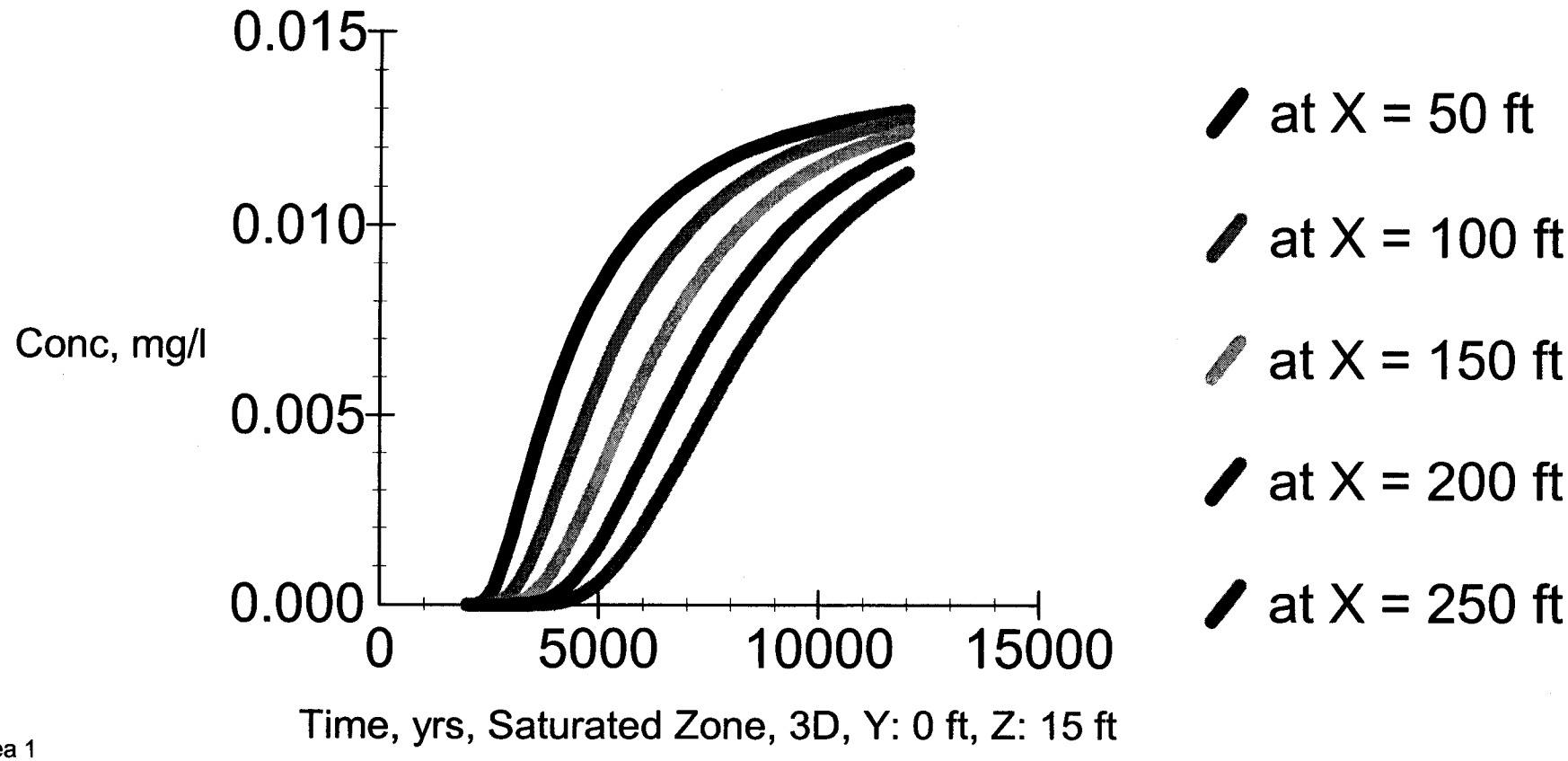


Selenium Concentrations vs Distance



Area 1

Selenium Concentrations vs Time



Area 1

MYGRT Results

Area 2

Cadmium, Selenium

Input Parameters

Description	Units	Value	Note
General Parameters			
Site		Duke Power Belews Creek Ash Landfill	
Description		Area 2	
Notes			
Solute Name		Cadmium	
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	0.088	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2008	
Unsat Infiltration After Switch	ft/yr	0.0013	
Unsat Moisture Content	ft3/ft3	0.228	
Unsat Dispersion Coeff in Z	ft2/yr	0.154	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		32.6	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	645	
Source Length	ft	1550	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	104	
Dispersion along Y	ft2/yr	10.4	
Dispersion along Z	ft2/yr	1.04	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	2.9	
Seepage Velocity	ft/yr	4.16	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.15	
Hydraulic Gradient	ft/ft	0.043	
Hydraulic Conductivity	ft/yr	14.5	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	2.9	Calc'd
Source Penetration Depth After	ft	2.9	Calc'd

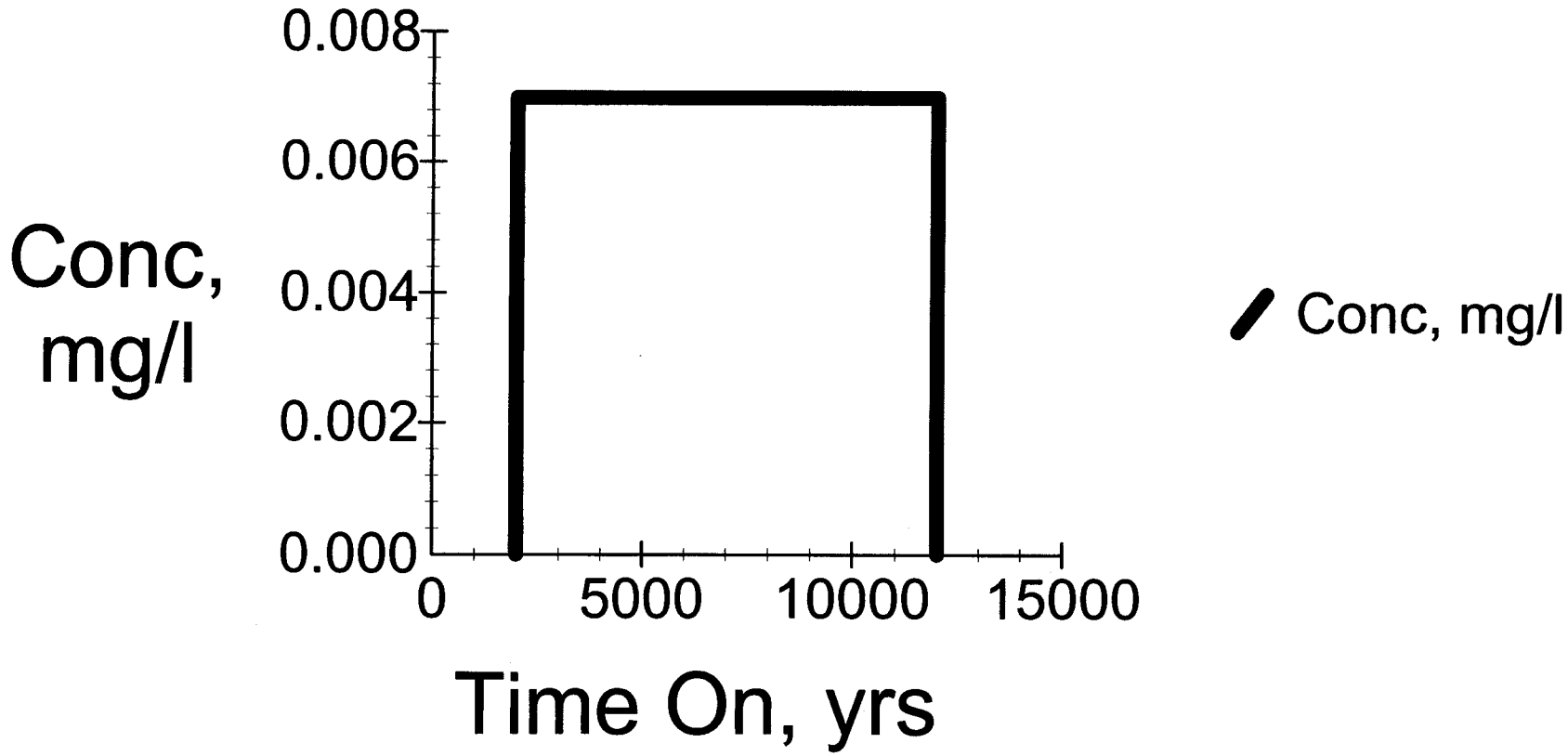
Input Parameters

Description	Units	Value	Note
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.31	
pH		5.5	
Rd (inorganic)		49	Calc'd
Partition Coeff, Kd	ml/g	5.5	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	0	

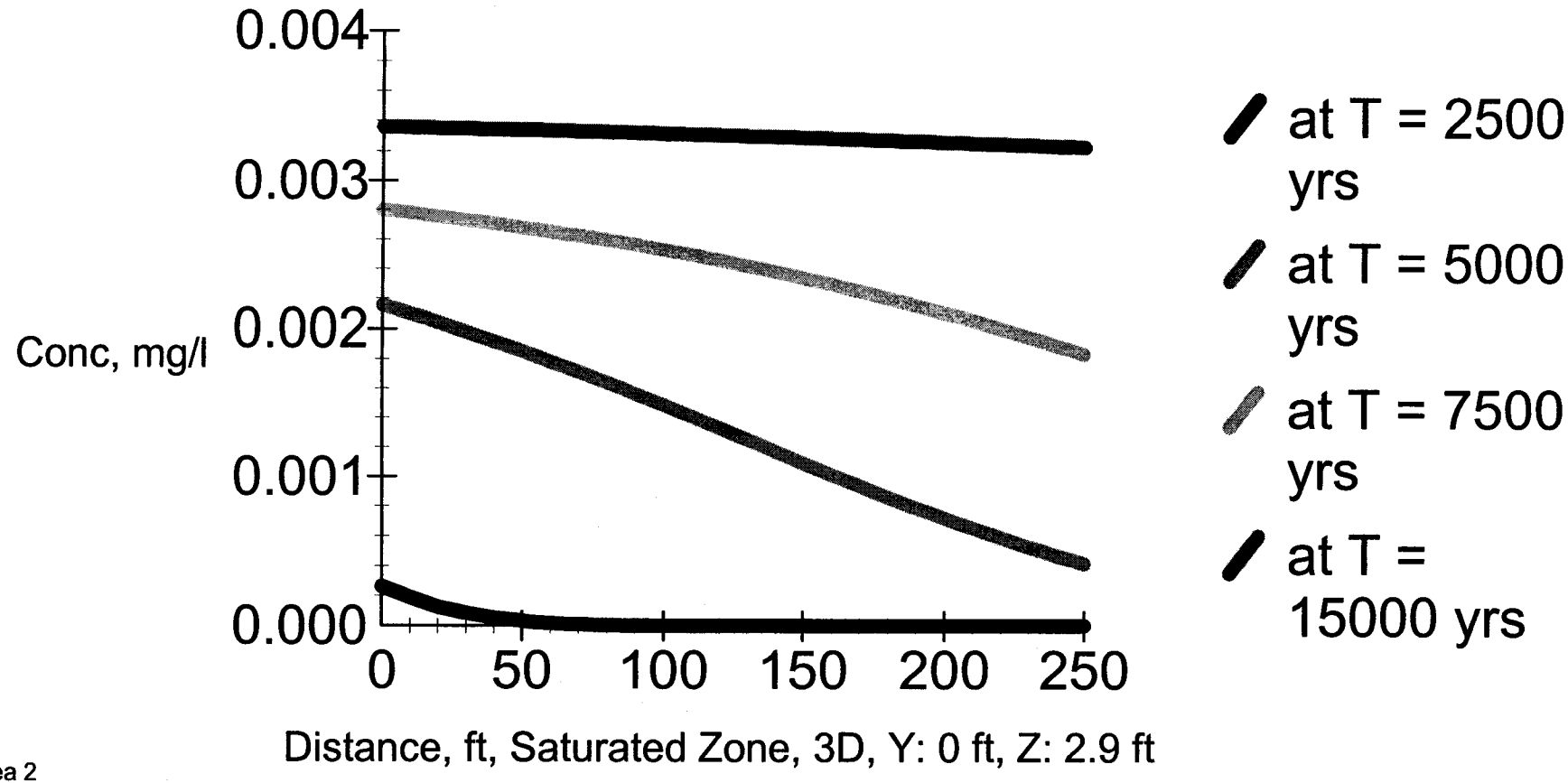
Source Concentration

	Time On, yrs	Conc, mg/l
1	2003.000	0.007
2	12008.000	0.007
3	12008.000	0.000

Source Concentration

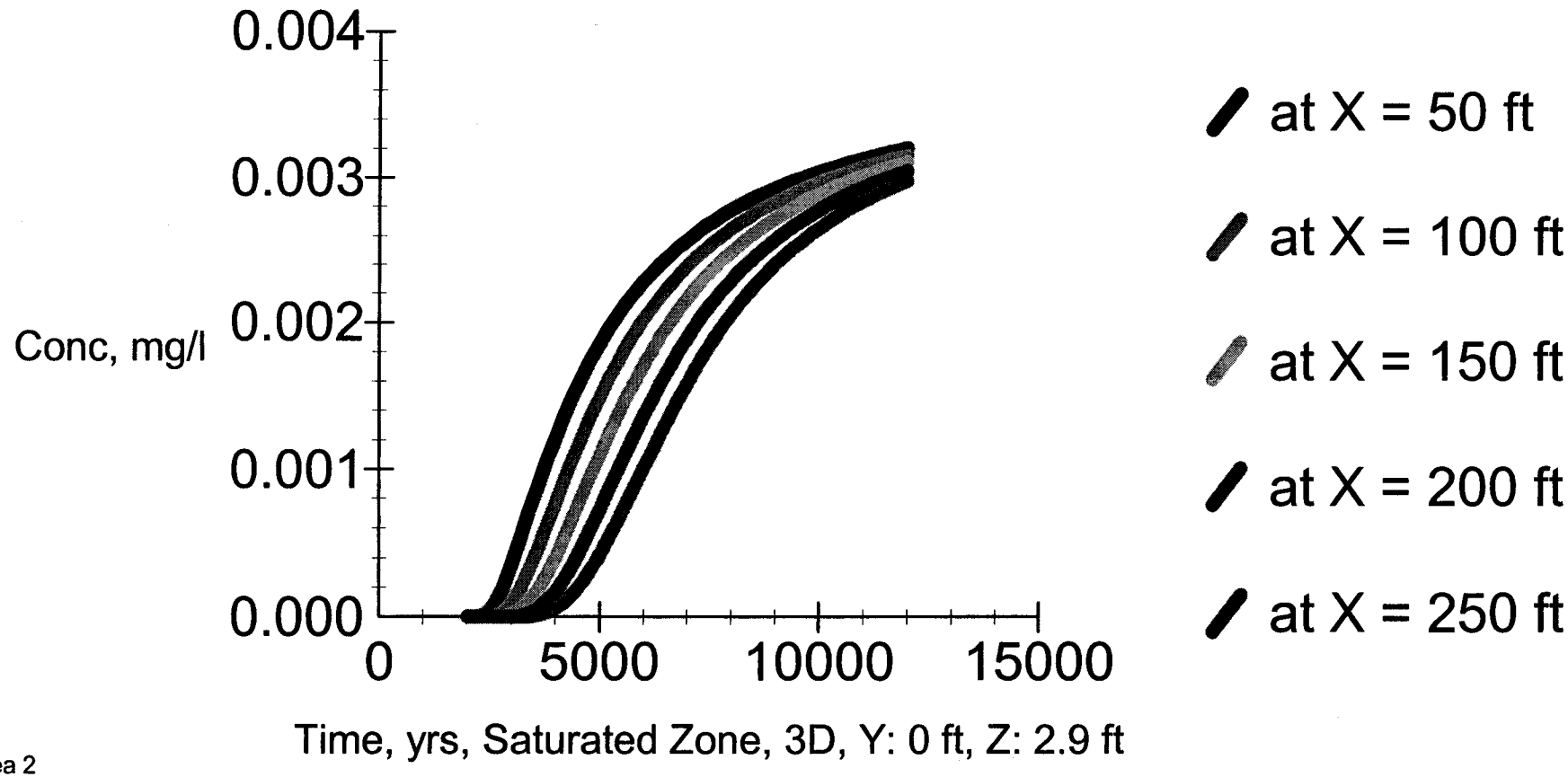


Cadmium Concentrations vs Distance



Area 2

Cadmium Concentrations vs Time



Area 2

Input Parameters

Description	Units	Value	Note
General Parameters			
Site		Duke Power Belews Creek Ash Landfill	
Description		Area 2	
Notes			
Solute Name		Selenium	
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	0.088	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2008	
Unsat Infiltration After Switch	ft/yr	0.0013	
Unsat Moisture Content	ft3/ft3	0.228	
Unsat Dispersion Coeff in Z	ft2/yr	0.154	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		48.7	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	645	
Source Length	ft	1550	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	104	
Dispersion along Y	ft2/yr	10.4	
Dispersion along Z	ft2/yr	1.04	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	2.9	
Seepage Velocity	ft/yr	4.16	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.15	
Hydraulic Gradient	ft/ft	0.043	
Hydraulic Conductivity	ft/yr	14.5	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	2.9	Calc'd
Source Penetration Depth After	ft	2.9	Calc'd

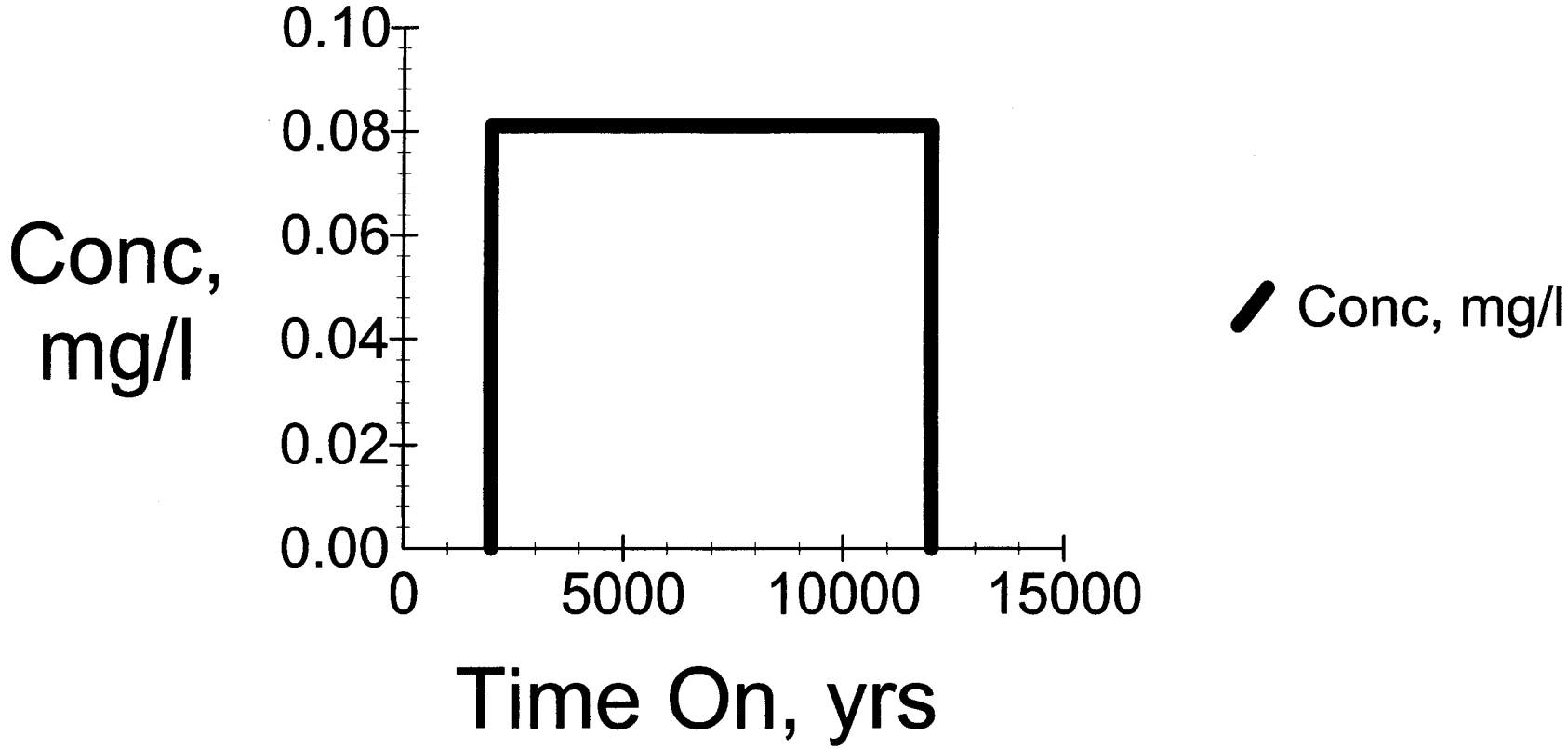
Input Parameters

Description	Units	Value	Note
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.31	
pH		5.5	
Rd (inorganic)		73.5	Calc'd
Partition Coeff, Kd	ml/g	8.3	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	0	

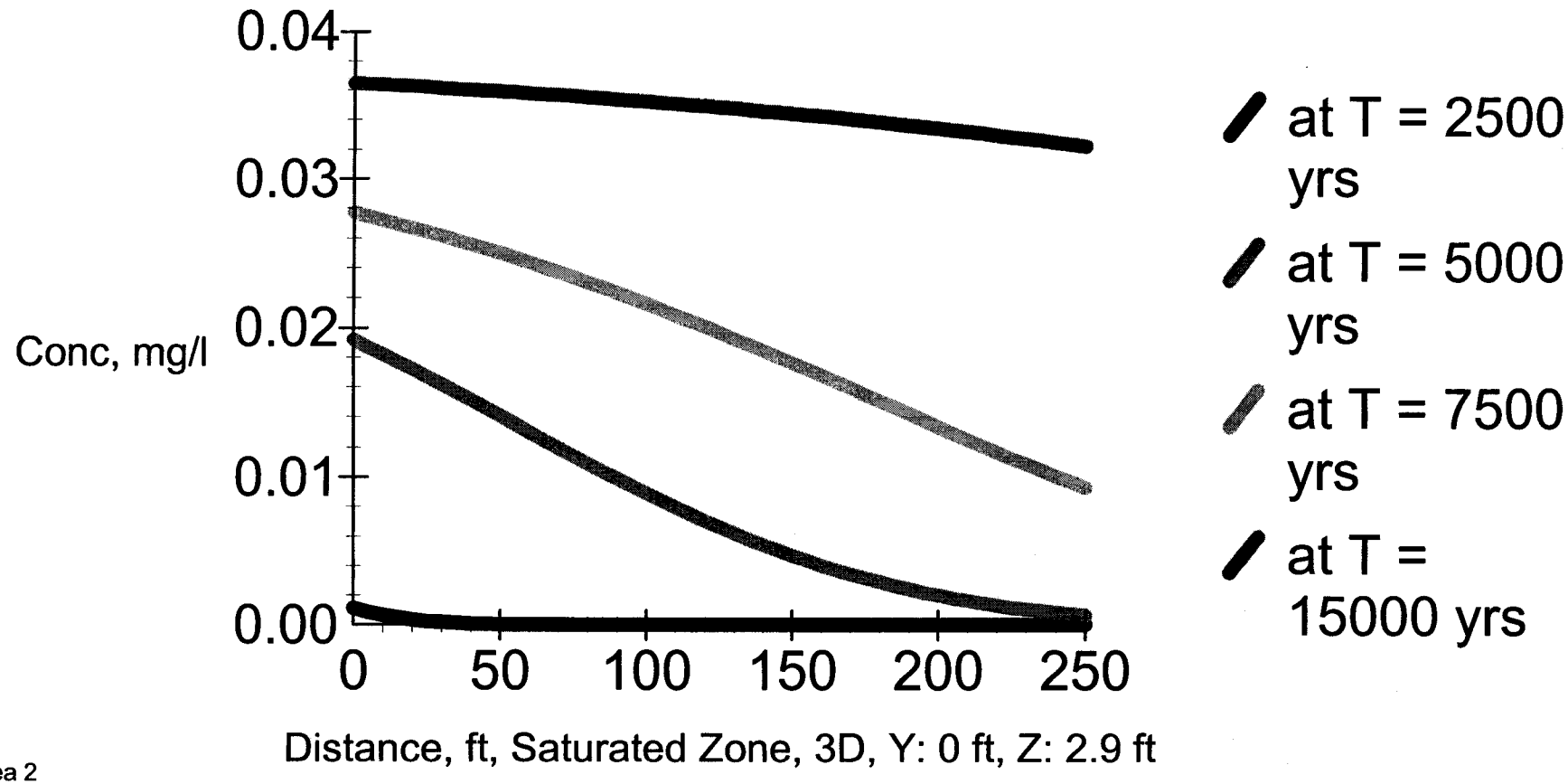
Source Concentration

	Time On, yrs	Conc, mg/l
1	2003.000	0.081
2	12008.000	0.081
3	12008.000	0.000

Source Concentration

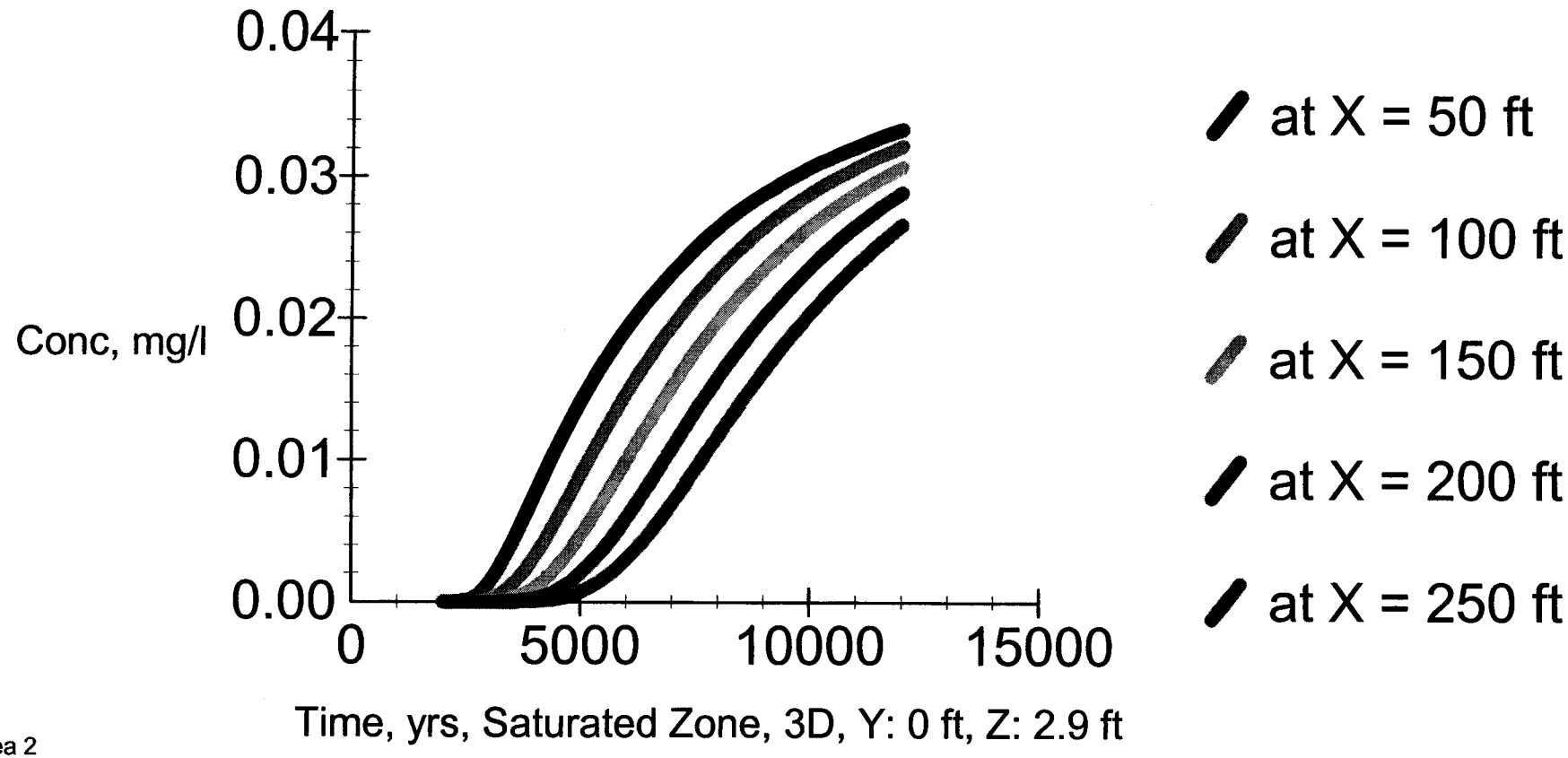


Selenium Concentrations vs Distance



Area 2

Selenium Concentrations vs Time



Area 2

MYGRT Results

Area 3

Cadmium, Selenium

Input Parameters

Description	Units	Value	Note
General Parameters			
Site		Duke Power Belews Creek Ash Landfill	
Description		Area 3	
Notes			
Solute Name		Cadmium	
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	0.623	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2008	
Unsat Infiltration After Switch	ft/yr	0.0013	
Unsat Moisture Content	ft3/ft3	0.228	
Unsat Dispersion Coeff in Z	ft2/yr	1.09	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		32.6	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	375	
Source Length	ft	615	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	232	
Dispersion along Y	ft2/yr	23.2	
Dispersion along Z	ft2/yr	2.32	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	8.3	
Seepage Velocity	ft/yr	9.28	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.15	
Hydraulic Gradient	ft/ft	0.096	
Hydraulic Conductivity	ft/yr	14.5	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	8.3	Calc'd
Source Penetration Depth After	ft	8.3	Calc'd

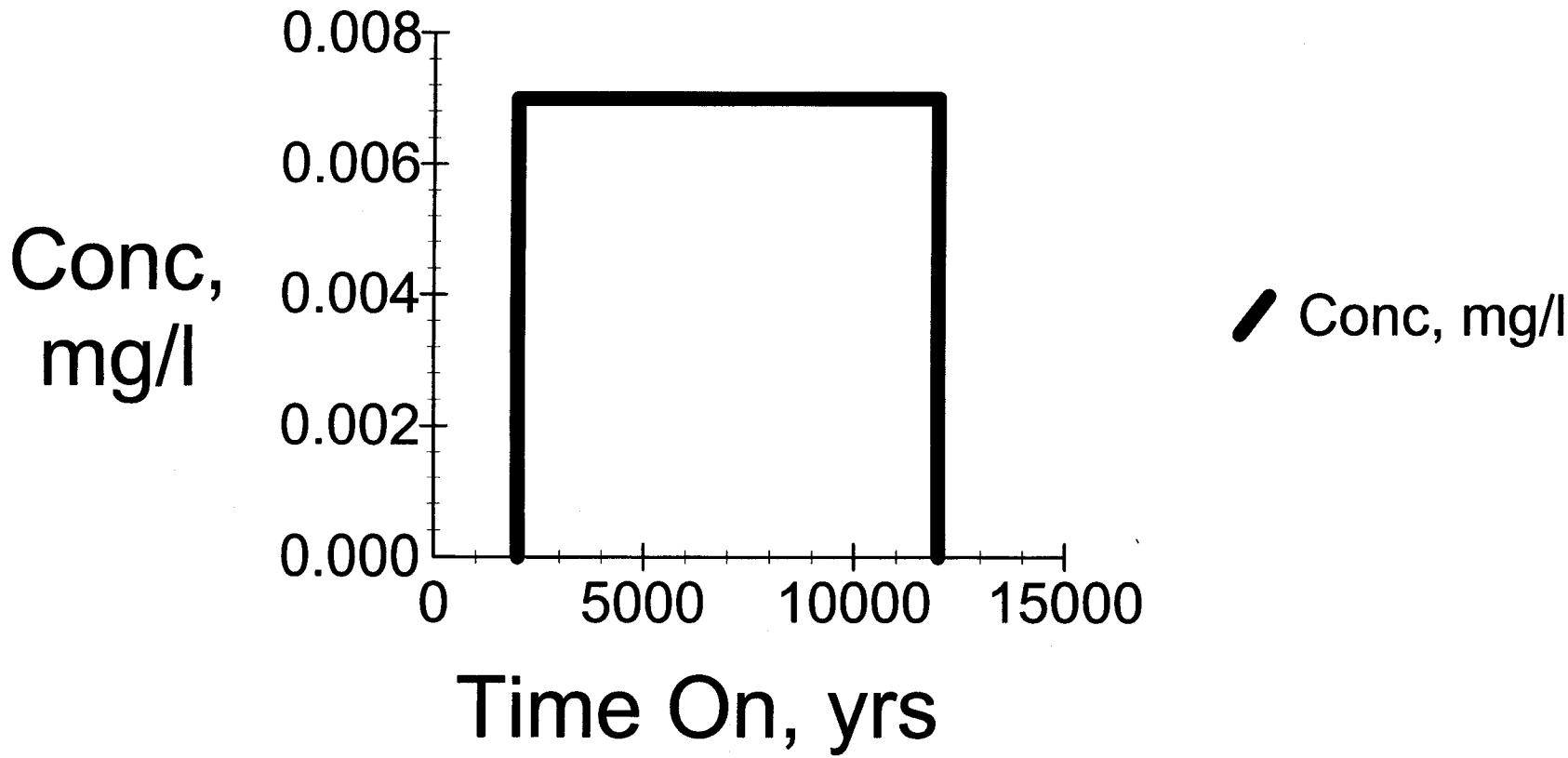
Input Parameters

Description	Units	Value	Note
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.31	
pH		5.5	
Rd (inorganic)		49	Calc'd
Partition Coeff, Kd	ml/g	5.5	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	0	

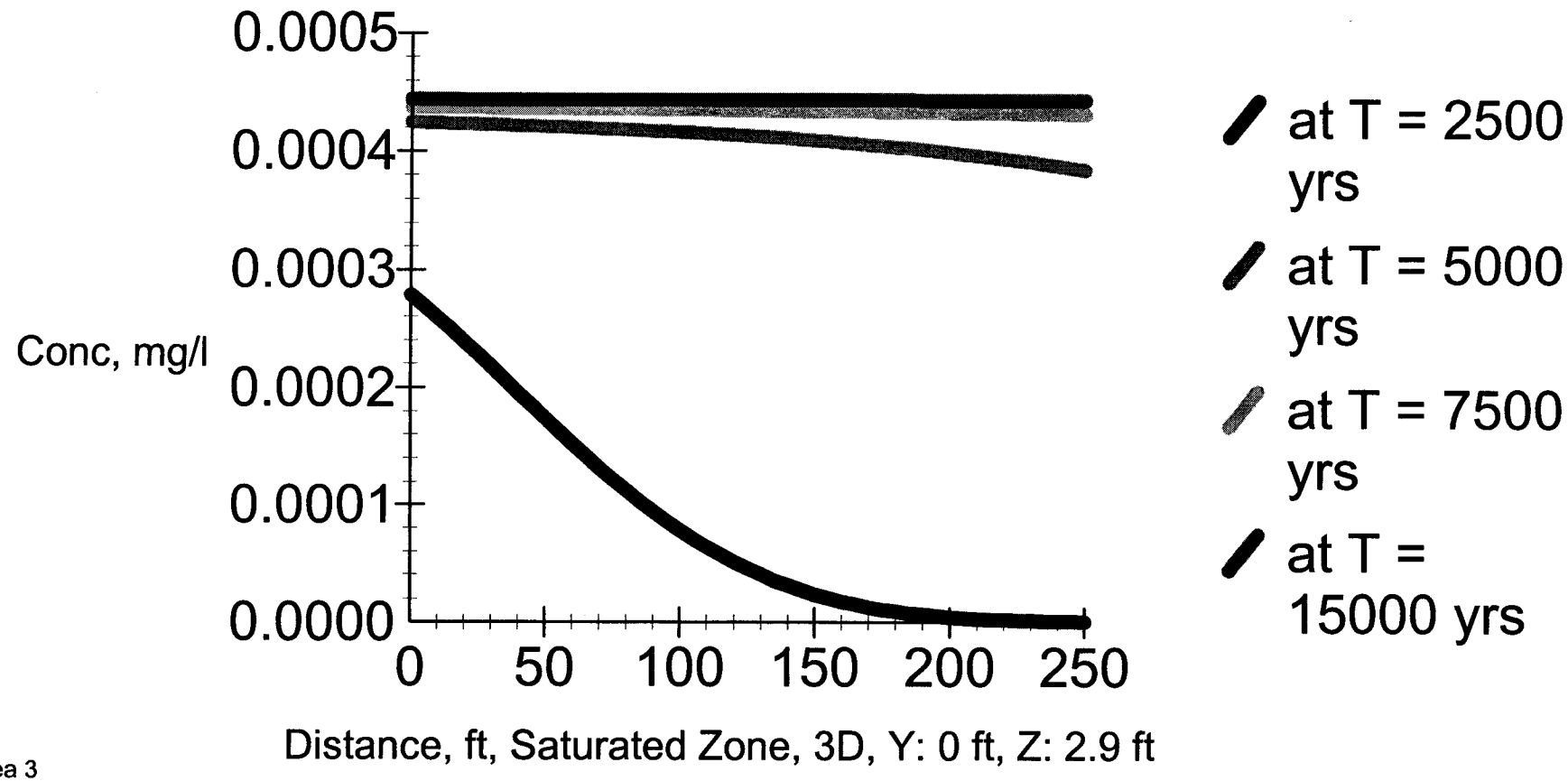
Source Concentration

	Time On, yrs	Conc, mg/l
1	2003.000	0.007
2	12008.000	0.007
3	12008.000	0.000

Source Concentration

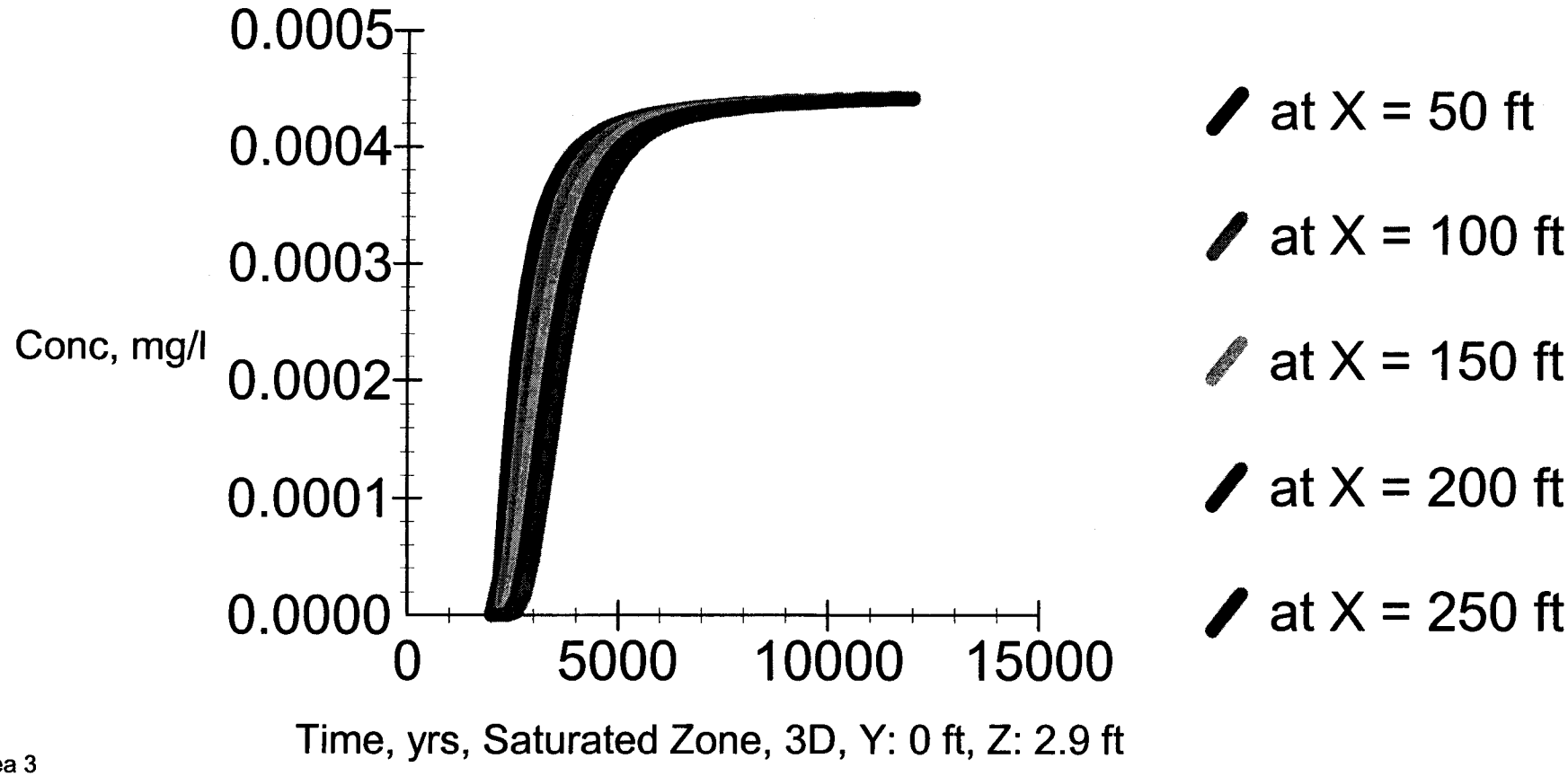


Cadmium Concentrations vs Distance



Area 3

Cadmium Concentrations vs Time



Area 3

Input Parameters

Description	Units	Value	Note
General Parameters			
Site		Duke Power Belews Creek Ash Landfill	
Description		Area 3	
Notes			
Solute Name		Selenium	
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	0.623	
Infiltration Switching		Yes	
Time to Switch Infiltration	yr	2008	
Unsat Infiltration After Switch	ft/yr	0.0013	
Unsat Moisture Content	ft3/ft3	0.228	
Unsat Dispersion Coeff in Z	ft2/yr	1.09	Calc'd
Depth to water table	ft	4	
Unsat Retardation Coeff		48.7	
Dispersion Calculated		Yes	
Source Parameters			
Width of Source	ft	375	
Source Length	ft	615	
Saturated Zone Properties			
Zone Length	ft	32.8084	
Dispersion along X	ft2/yr	232	
Dispersion along Y	ft2/yr	23.2	
Dispersion along Z	ft2/yr	2.32	
Distance for Dispersion	ft	250	
Dispersion calculated		Yes	
Aquifer Thickness	ft	8.3	
Seepage Velocity	ft/yr	9.28	Calc'd
Sat Volumetric Porosity	ft3/ft3	0.15	
Hydraulic Gradient	ft/ft	0.096	
Hydraulic Conductivity	ft/yr	14.5	
Horozontal Velocity calculated		Yes	
Source Penetration Depth	ft	8.3	Calc'd
Source Penetration Depth After	ft	8.3	Calc'd

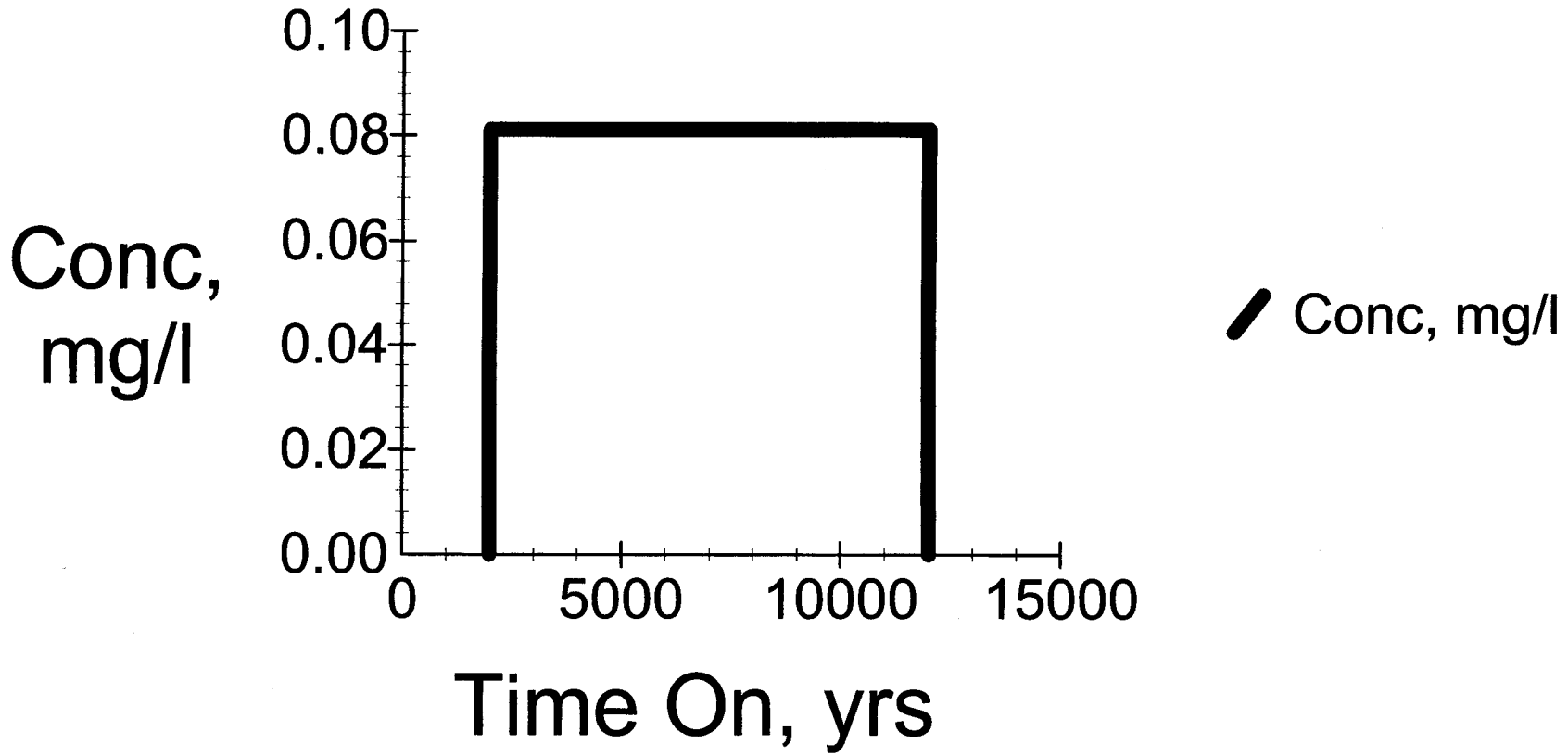
Input Parameters

Description	Units	Value	Note
Mixing Depth Calculated		Yes	
Mixing Depth (2) Calculated		Yes	
Solute Plume Description			
Background Concentration	mg/l	0	
Bulk Density	g/ml	1.31	
pH		5.5	
Rd (inorganic)		73.5	Calc'd
Partition Coeff, Kd	ml/g	8.3	
Rd calculated		Yes	
Distance to Top of Source	ft	0	
Distance to Bottom of Source	ft	0	

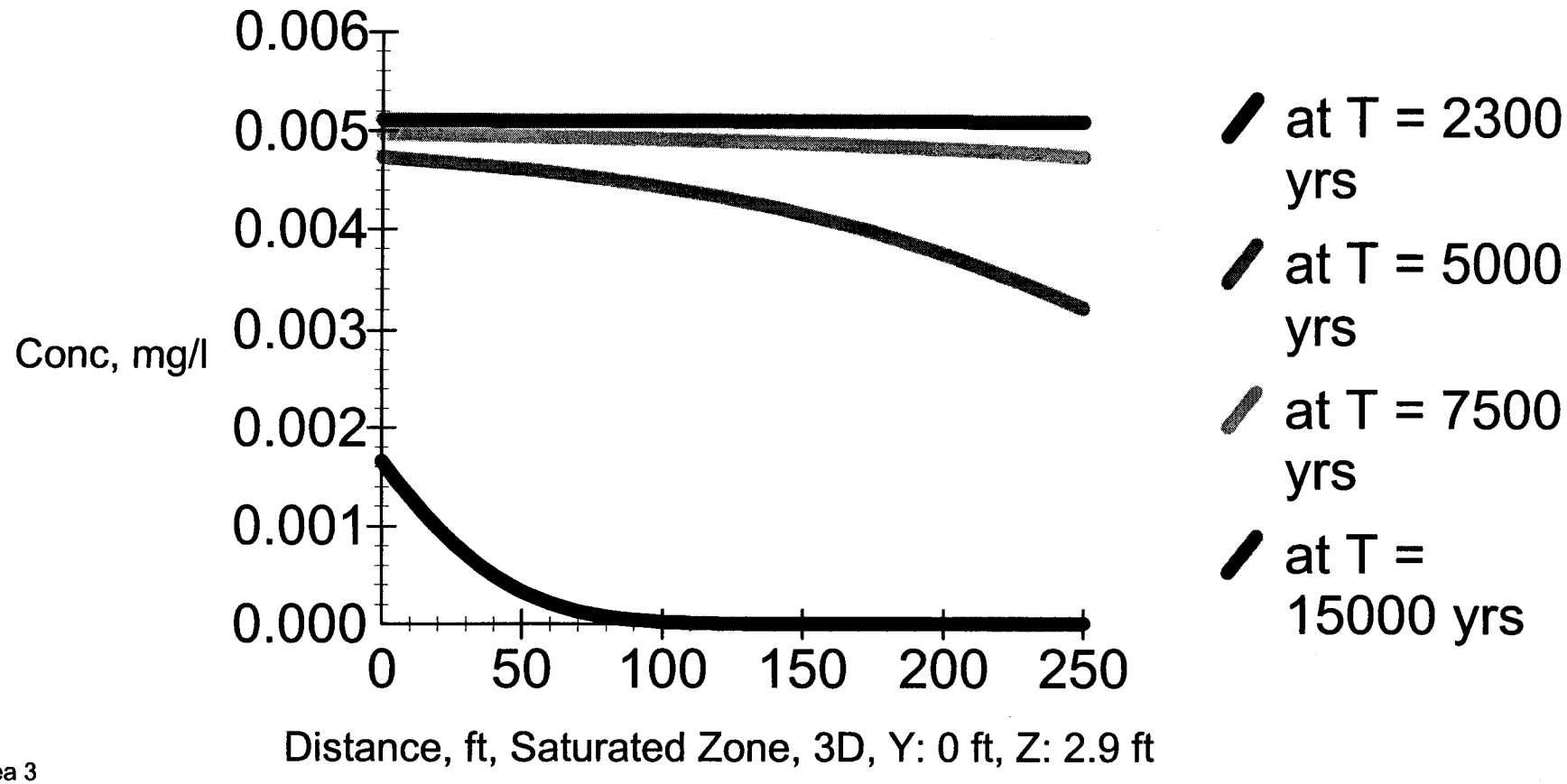
Source Concentration

	Time On, yrs	Conc, mg/l
1	2003.000	0.081
2	12008.000	0.081
3	12008.000	0.000

Source Concentration

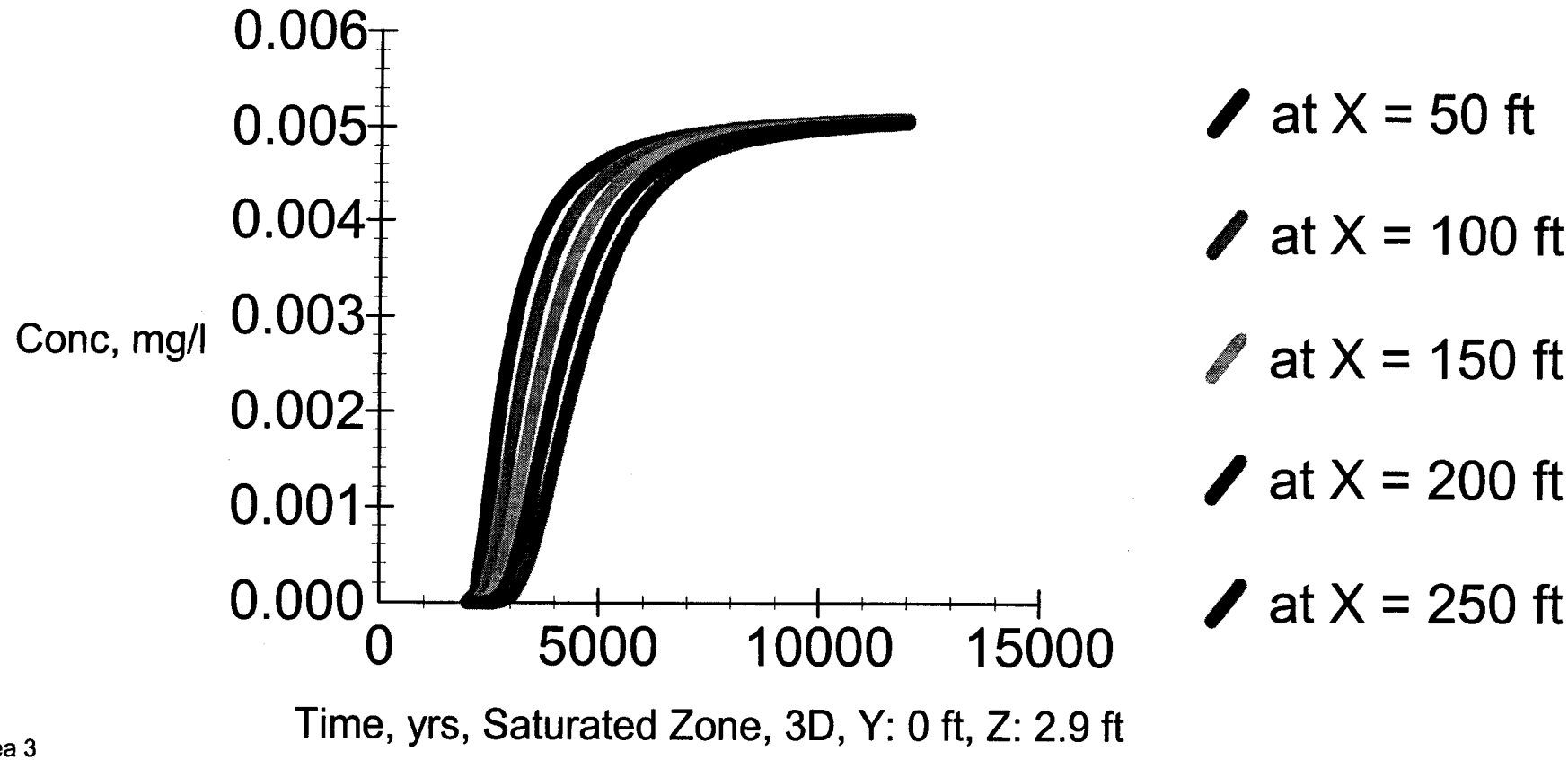


Selenium Concentrations vs Distance



Area 3

Selenium Concentrations vs Time



Area 3