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Project Summary

Disposal of Flue Gas Desulfurization Wastes: EPA Shawnee Field Evaluation, Final Report

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This report summarizes the results of the Flue Gas Desulfurization (FGD) Waste Disposal Field Evaluation Project sponsored by the U.S. Environmental Protection Agency at the Tennessee Valley Authority (TVA) Shawnee Steam Plant, Paducah, Kentucky. This pilot scale project, which was initiated in 1974 and completed in September 1980, evaluated methods and costs for disposing of wastes produced from wet, nonregenerable scrubbing of sulfur dioxide from coal-fired utility boiler flue gases. The environmental effects of various disposal techniques were studied, including evaluations of untreated, chemically treated, and oxidized wastes utilizing lime or limestone scrubber absorbents.

Because water quality and land reclamation are of principal interest, analyses of leachate, supernate, runoff, and ground water were conducted and physical properties of the wastes were evaluated. No measurable effect on the ground water quality at the disposal site was detected during the course of the program. Chemical treatment and underdrainage of untreated waste yielded structurally sound materials. Cost-effective and environmentally sound disposal methods for FGD waste and slurried gypsum appear to be ponding with underdrainage and chemical treatment/landfilling of the FGD waste. Disposal costs for these methods range from about 0.8 to 1.5 mills/kWh, based on a high-sulfur (e.g., 3%) coal application.

This Project Summary was developed by EPA's Industrial Environmental Research Laborabory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

This report summarizes activities and results of the EPA Shawnee Flue Gas Desulfurization (FGD) Field Disposal Evaluation Project. This project, initiated in September 1974, was designed to evaluate various ponding and landfill alternatives and to develop cost estimates for the disposal of by-products from wet, nonregenerable scrubbing of sulfur dioxide (SO_2) from coal-fired utility boiler flue gases. The environmental effects of various disposal techniques, as well as scrubber reagent, operations, weather, and field operating procedures, were assessed with the goal of determining environmentally sound disposal methods. Water quality and land reclamation are of principal interest and, to that end, periodic sampling, analyses, and assessments were conducted of leachate, supernate, runoff, ground water, and soil and waste cores. The Aerospace Corporation was responsible for the project planning, coordination, selected water and solids analysis, assessment and evaluation of the various disposal methods, and reporting. Site construction, maintenance, coring, water sampling, and routine water analyses were performed by TVA. The technical effort described in this report was completed in September 1980.

Ten field sites were evaluated in this project, which is located at the TVA Shawnee Steam Plant near Paducah, Kentucky. Of the ten sites, eight ranged in size up to 560 m^2 (6000 ft^2) with a waste depth of 0.9 m (3 ft) to 1.2 m (4 ft), while two are surface disposal sites at about 190 m^2 (2000 ft^2). Waste materials for this project were produced by two scrubber systems. Using lime or limestone slurries as the SO_2 absorbent, each of the scrubbers, a UOP, Inc., turbulent contact absorber (TCA), and a Chemico, Inc., venturi spray tower (VST), treated a flue gas slipstream equivalent to 10 MW from one of the boilers. Waste produced by both scrubbers was evaluated. The disposal techniques consisted of the following: (a) untreated waste ponding, (b) chemical treatment and landfilling, (c) chemical treatment and ponding, (d) calcium sulfite oxidation to gypsum and subsequent disposal, and (e) untreated waste ponding with underdrainage. Figure 1 illustrates the relationship of the FGD waste to the disposal alternatives that were evaluated at Shawnee. This project has provided a broad data base for the evaluation of the control of SO_2 scrubber wastes by combining analyses of results from field disposal operation and laboratory tests.

Summary

The data obtained in the Shawnee FGD waste disposal evaluation are summarized and discussed in this report. The physical characteristics of the wastes were obtained by analysis of the materials prior to disposal and of core samples after disposal. Water samples from each site were analyzed (i.e., leachate or underdrain, runoff, supernate, and ground water) for the evaluation of the chemical characteristics.

Site Description

A description of the disposal sites is summarized in Table 1. A view of the disposal site is shown in Figure 2. Seven ponds or surface sites contained un-

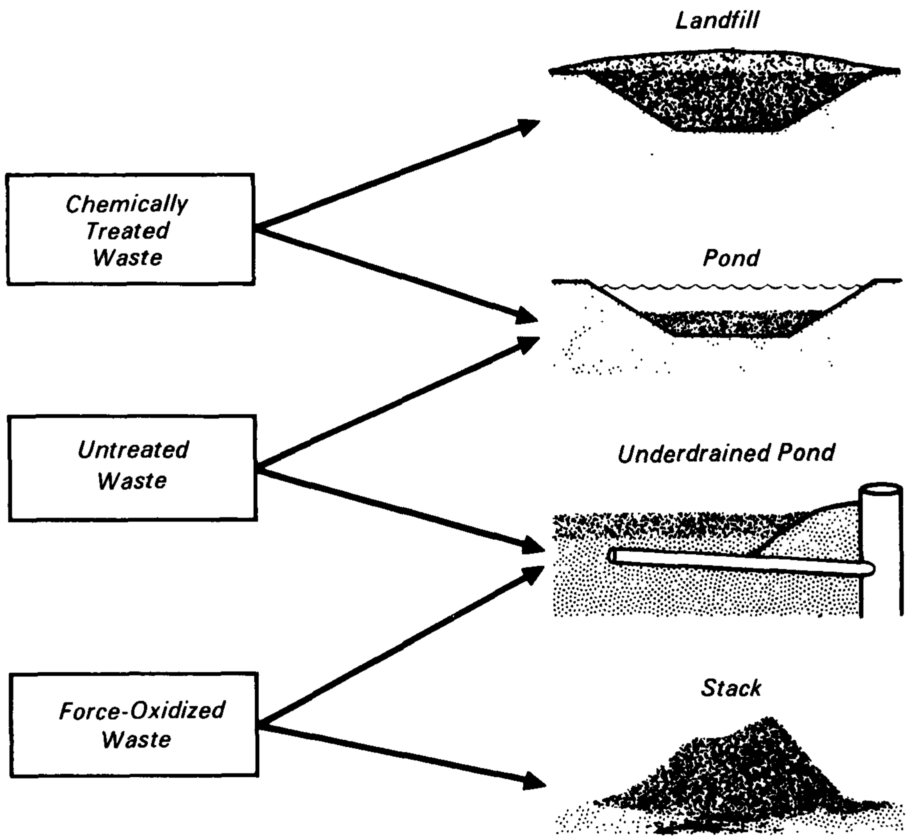


Figure 1. FGD waste disposal alternatives.

Figure 2. Overview of disposal sites with Shawnee Steam Plant in Background.

Table 1. *Shawnee Disposal Sites*

Site	Fill Date	Scrubber Type[a]	Waste: Absorbent	Waste: Source[b]	Solids Content, wt%[c]	Treatment	Remarks
A	10/8/74	VST	Lime	F	46	Untreated	Out of service 4/15/76
AI	5/10/76	VST	Lime	F	46	Untreated	Control pond, transferred from Site A
B	4/15/75	TCA	Limestone	CU	38[d]	Dravo	Underwater disposal
C	4/23/75	VST	Lime	CE	55[d]	IUCS	Site converted to runoff mode 3/79
D	2/5/75	TCA	Limestone	CU	38	Untreated	Control pond
E	12/7/74	TCA	Limestone	CU	38[d]	Chemfix	Covered 11/77
F	2/3/77	TCA	Limestone	CU	47	Untreated	Underdrained site, covered 11/77
G	10/5/76	VST	Lime	CE	47	Untreated	Underdrained site, covered 4/80
H[e]	9/2/77	VST	Limestone	CU	33	Untreated[f]	
H[g]	9/30/77	VST	Limestone	F	86	Untreated[f]	Surface site: unreacted limestone, 13% by dry weight
J	12/31/78	VST	Limestone	F	81	Untreated[f]	Surface site: adipic acid additive
K	3/29/79	VST	Limestone	F	80.	Untreated[f]	Surface site: unreacted limestone, 25% by dry weight

[a]*Venturi and spray tower (VST); bulent contact absorber (TCA).*
[b]*Filter (F), clarifier underflow (C /, and centrifuge (CE).*
[c]*Site H is ash-free. All others: fly ash is approximately 40 wt% of solids content. In Site G, half of fly ash was mixed with waste; the remaining portion was placed in six equally spaced layers.*
[d]*Prior to chemical treatment.*
[e]*Lower (below grade) portion.*
[f]*Upper (above grade) portion.*
[g]*Force-oxidized to gypsum.*

treated waste, and three were filled with chemically treated material. The untreated sites include AI, D, F, G, H, J, and K. Sites AI and D were considered control sites with lime and limestone (absorbent) waste disposed in ponds containing indigenous soil. Sites F and G were underdrained ponds containing limestone and lime scrubbing wastes. Sites H, J, and K contained wastes that were force-oxidized to gypsum; Site H had a lower ponded portion of underdrained clarifier underflow slurry and an above-ground stack of gypsum filter cake; and Sites J and K had gypsum filter cake stacked on the surface. A total of 14 ground water wells were situated in and around the disposal area and were sampled periodically to monitor any potential effects of the disposal sites on the ground water quality.

Sites B, C, and E were filled with chemically treated material. Site B was filled in April 1975, with clarifier underflow (limestone absorbent), treated by the Dravo Corporation. Site C (Figure 3), also filled in April 1975, contained centrifuge cake (lime absorbent), treated by IU Conversion Systems, Inc. Site E was filled in December 1974 with clarifier underflow (limestone absorbent), treated by Chemfix, Inc.

Several of the sites were modified since initial placement (Table 1) to evaluate site retirement and reclamation methods. Chemically treated Site E and underdrained Sites F and G were covered with clay, which was then contoured and planted with grass. Site C was converted to a runoff configuration in March 1979. As a separate EPA/TVA project, the crown of the clay covering of Sites E and F was removed, and several species of small trees were planted in the spring of 1979.

Waste Characteristics

The disposal sites were filled with FGD waste representing a cross section of scrubber effluent conditions. The discussion of the various methods of waste disposal is divided into the following categories: untreated wastes, chemically treated wastes, gypsum (oxidized calcium sulfite) filter cake, and untreated wastes with underdrainage. Specific properties related to those wastes and methods of treatment are included.

The chemical composition of waste input liquor, water from site runoff, supernate, leachate/underdrainage, and ground water from 14 wells in and around the disposal area was analyzed for a variety of chemical species. The composition of the waste input liquor (before treatment, if any) is summarized in Table 2 and shows a wide range in the concentration of chemical species for the different FGD wastes.

The physical properties considered in the disposal of FGD waste include viscosity, bulk density, moisture content,

Table 2. *Chemical Analysis of Disposal Site Input Liquor*

Site[a]	pH	Calcium	Sulfate	Chloride	Sulfite	Total Dissolved Solids	Arsenic	Boron	Lead	Magnesium	Sodium	Selenium	Mercury	Chemical Oxygen Demand
		Concentration (mg/l)												
A	8.3	2,100	1.525	4,600	4	8,560	0.024	44	0.49	290	(b)	0.005	<0.0001	(b)
B	8.9	1,060	1,875	1,850	3	5,160	0.004	97	<0.02	2.5	17	0.020	0.00024	140
C	8.9	2,720	1,575	4,700	45	9.240	0.002	34	<0.01	33	46	0.018	<0.0001	140
D	9.2	1,880	1,500	2,950	56	6,750	0.24	93	<0.02	50	56	0.014	0.0003	140
E	9.4	1,880	1,400	2,700	32	6,190	0.004	80	<0.01	12	41	0.014	0.00033	110
F	12.2	1,990	1,100	2,000	(b)	6,700	0.002	76	<0.01	0.3	70	0.042	<0.0002	43
G	7.8	150	6,600	3,600	(b)	14,000	0.14	93	<0.01	5,000[c]	12	0.63	<0.0002	53
H[d]	7.1	1,300	1,930	3,500	(b)	9,200	<0.003	120	<0.01	540	62	0.14	<0.0002	130
H[e]	(b)	1,510	1,875	6,600	(b)	10,756	(b)	140	(b)	1,100	116	(b)	(b)	(b)
J	5.8	1,250	1,438	3,500	(b)	9,398	0.09	105	0.67	681	107	0.008	0.002	(b)
K	6.9	550	2,250	2,450	(b)	6,694	0.03	95	0.13	764	68	0.035	0.0007	(b)

[a]Table 1 lists type of waste at each site.
[b]Not determined
[c]Magnesia added to lime absorbent
[d]Lower (below grade) portion
[e]Upper (above grade) portion

Figure 3. *Chemically treated Site C showing original landfill condition.*

bearing strength, void fraction, and permeability. Viscosity is important in the transport of the waste to a disposal site; other concerns are the weight and volume of the disposal material, as well as the suitability of the waste as a load-bearing material and deterrent to seepage from a disposal site.

The physical properties of the wastes are dependent upon the characteristics of both the liquid and the solid constituents (Table 3), as well as the interaction between them. These wastes contain finely divided particulate matter in an aqueous medium and consist of three major phases having markedly different morphologies: calcium sulfite hemihydrate ($CaSO_3 \cdot 1/2H_2O$), calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), and fly ash. Both the particle size distribution and phase morphology are believed to influence the physical properties of the wastes. Calcium sulfite and sulfate scrubber waste products tend to have particle sizes in the same range as fly ash, between 1 and 100 μm. However, fly ash is formed as spheres (typically about 10 μm); sulfite waste forms as platelets (limestone) or rosettes (lime); and sulfates are blocky in shape. Unreacted calcium carbonate ($CaCO_3$), from the limestone or precipitated from the lime process, is usually present in the waste and contributes an additional shape parameter.

Untreated Waste Disposal

A rotary drum mixing truck (ready-mix cement truck) was used to haul the waste to the sites in order to maintain a homogenous mix during loading and transport from the scrubber. Dispersal of the waste in the pond was achieved by dumping at various locations in the pond, from which the waste was allowed to settle and seek its natural level. Two control ponds for untreated lime and limestone scrubbing waste disposal were installed and were monitored principally for the determination of chemical characteristics of the leachate. The material in these ponds, which are identified in Table 1 as A/A1 and D, was totally saturated (except for extended periods of no rainfall).

The total dissolved solids (TDS) concentration of the initial leachates of the untreated sites A/A1 and D ranged from 6800 to 8600 mg/l. After approximately 1 year the chloride content of the waste was essentially depleted. Thereafter, the leachate was essentially a saturated gypsum solution, with a TDS concentration of approximately 2500 mg/l. This is illustrated in Figure 4 for Site D leachate. The concentration of the more significant minor species present in these wastes has also been determined (Figure 5). Except for boron, which decreased steadily with time, the

Table 3. *Solids Analysis of Disposal Site Untreated Input Wastes*

Site[a]	Solids Content (% By Weight)	Percent Solids by Dry Weight: Calcium Sulfite	Calcium Sulfate	Calcium Carbonate	Fly Ash
A	46	(b)	(b)	(b)	(b)
B[c]	38	30.3	10.7	14.2	35
C[c]	55	38.8	9.7	0	40
D	38	29.4	10.9	18.6	33
E[c]	38	27.9	9.4	18.3	34
F	47	33.3	14.8	8.3	40
G	47	(b)	(b)	(b)	20
H[d]	33	0.2	98.0	1.8	0
H[e]	86	0.1	86.8	13.1	0
J	81	0.1	63.7	1.2	35
K	80	0.1	47.1	25.0	28

[a]*Table 1 lists type of waste at each site*
[b]*Not analyzed*
[c]*Subsequently treated chemically*
[d]*Lower (below grade) portion*
[e]*Upper (above grade) portion*

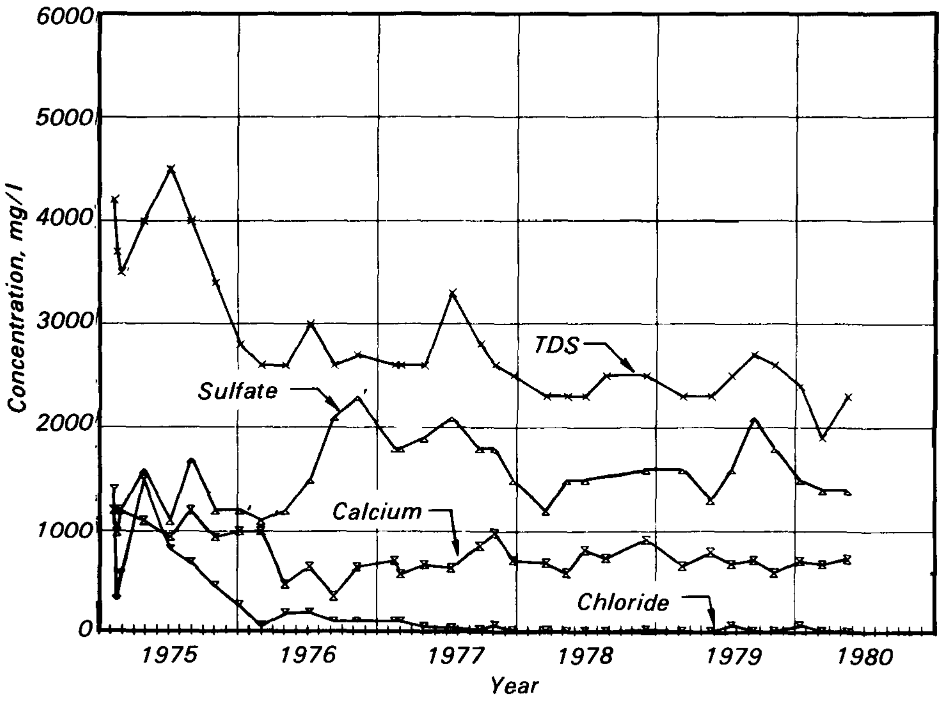


Figure 4. *Concentration of TDS and major species in Site D leachate.*

minor species have shown only slight reductions after 5 years of seepage. For nearly 900 untreated leachate analyses, 4 showed the concentration of minor species to be greater than 10 times the National Interim Primary Drinking Water Regulations (12, 14, and 20 times greater for arsenic and 11 times greater for selenium). Under the new Hazardous Waste Management System, all FGD wastes are temporarily exempt from the Federal regulations covering hazardous materials. However, they are subject to state and local regulations; these may include Federal criteria for nonhazardous wastes.

The dewatering characteristics of FGD wastes are important to the various disposal techniques in that they affect the volume of the disposal basin, the waste handling methods, and the condition of the wastes in their final disposal state. The effectiveness of the dewatering methods used and the ability of FGD waste to be dewatered are a function of a number of solids characteristics, including the size and distribution of particles and the crystalline structure of the particles, which are a function of the scrubber system and its operating parameters. In laboratory dewatering tests, four methods were evaluated, using FGD wastes from Shawnee: settling and decanting, settling by free drainage, vacuum filtration, and centrifugation (Table 4).

The highest density was obtained principally by vacuum-assisted filtration. However, the density differences between filtration and centrifugation were relatively small. For most wastes, settling by free drainage yields a slightly greater density than by settling only. Table 4 shows that the wet-bulk densities of limestone scrubbing wastes ranged from a low of approximately 1.45 g/cm^3 for settled wastes to a high of 1.65 g/cm^3 for vacuum filtered. Values for lime scrubbing waste were approximately 7% less than those for limestone scrubbing wastes.

Confined load-bearing strengths of untreated FGD wastes (including gypsum) as a function of solids, absorbent, and fly ash content are presented in Figure 6. Among other considerations, the data highlight the criticality of solids content on the load-bearing strength of untreated wastes. This is of particular importance when considering the disposal of slurried gypsum or untreated FGD wastes that are underdrained, because these types of disposal depend on dewatering to achieve material bearing strength. The test data indicate that these wastes may be dewatered to a narrow range of solids content, above which the load-bearing strengths increase rapidly to values well above the minimum for safe access of personnel and equipment. In addition, the critical concentration appears to be unique for each type of waste tested. Figure 6 also illustrates the effect of the absorbent and fly ash on dewatering and load-bearing characteristics. Limestone scrubbing wastes have critical solids content higher than lime scrubbing wastes. Likewise, the presence of fly ash enhances dewatering in both types of wastes; however, for any specific solids content of a given FGD waste, the

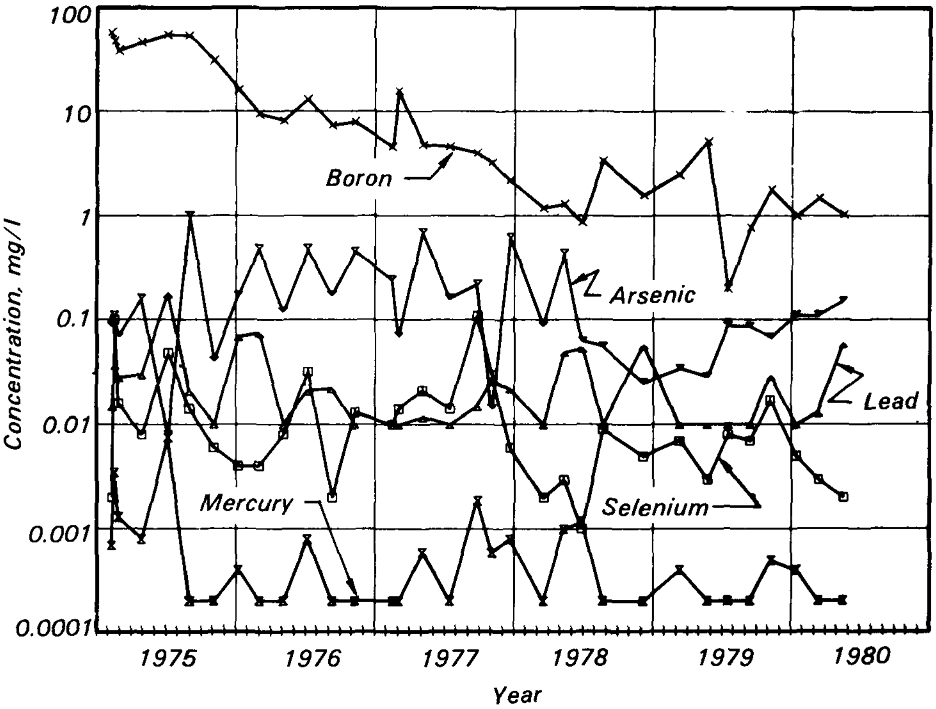


Figure 5. *Concentration of minor species in Site D leachate.*

load-bearing strength is less when fly ash is present.

The pollution potential of waste liquor seeping into ground waters is governed by the mobility of leaching waters; this mobility is limited by the coefficient of permeability of the various media through which this leachate must pass. The permeability coefficient of untreated wastes (lime and limestone) containing fly ash is approximately 2 x 10^{-4} cm/sec, which is comparable to typical values for silty sand (10^{-4} cm/sec).

The viscosity of FGD waste is indicative of its pumpability, which could affect both the mode and cost of transport. The results of viscosity tests conducted in the laboratory for various untreated wastes define dewatering limits for certain waste materials if they are to be pumped. The tests also show that pumpable mixtures (considered to be less than 2 pascal-sec (20 poise) for slurries) range from a high solids content of 55 wt% to a low of 30 wt% (Figure 7), depending on the absorbent and ash content. For example, the viscosity of the limestone scrubbing at a solids content of 50% is less than lime scrubbing waste at the same solids content. The results also show that FGD wastes of a given type are less viscous if they contain fly ash.

Disposal of untreated material in a pond is usually the least costly method of FGD waste disposal. If the pond does not have a base material considered to be impermeable, a liner must be added to prevent seepage, thereby increasing the disposal costs significantly. Clay or polymeric liners may be placed at the base and on the slopes of such ponds. Any pond continually exposed to weathering, however, may eventually be subject to a degree of seepage because liners are not completely impermeable and, in the case of polymeric membranes, may be subject to varying degrees of physical damage and deterioration. Because FGD wastes are thixotropic in nature, ponds of untreated wastes are nonstructural and are generally difficult to reclaim, except possibly in areas of low rainfall and high evaporation.

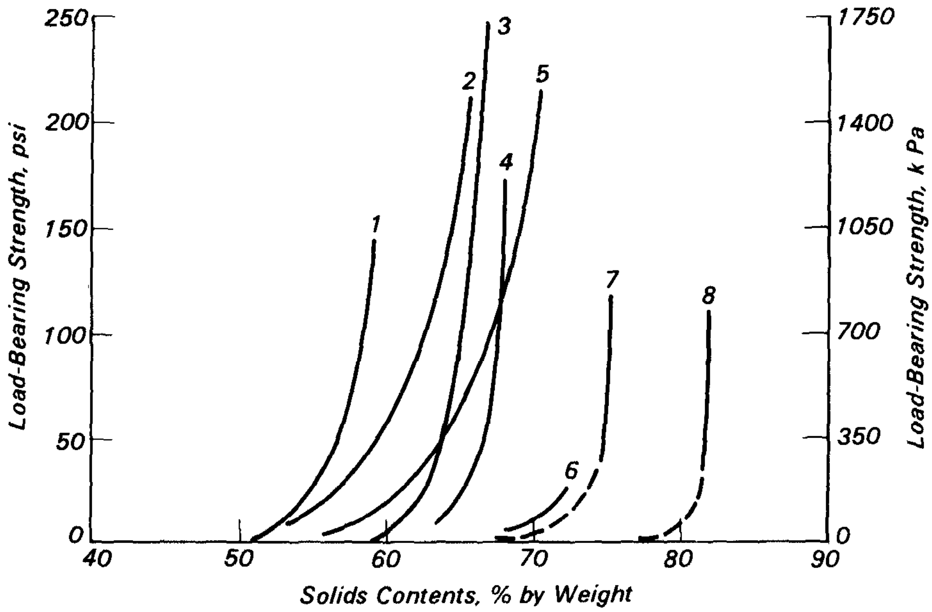
Chemically Treated Waste Disposal

Sites B, C, and E contain wastes that were chemically treated by the Dravo Corporation IU Conversion Systems, Inc., and Chemfix, Inc., respectively, during late 1974 and early 1975. Site B simulates a disposal condition in which the waste cures underwater and remains underwater, except for periods of extended drought. Site C initially represented a depression in a landfill in which rainwater collected, and Site E represents a landfill that traps rainwater that collects in a sump at its lower end. Site B has remained as originally configured; Site C was converted in March 1979 to a runoff configuration; and in November 1977 Site E was covered

Table 4. *Bulk Densities of Untreated FGD Wastes*

		Dewatering Method[a]							
		Settling and Decanting		Settling by Free Drainage		Centrifugation		Vacuum Filtration	
Shawnee Source and Sampling Date	Fly Ash (% by Dry Weight)	Solids (% by Weight)	Density (g/cm³)	Solids (% by Weight)	Density (g/cm³)	Solids (% by Weight)	Density (g/cm³)	Solids (%by Weight)	Density (g/cm³)
Limestone									
1 Feb 73	20	49	1.45	56	1.51	60	1.56	65	1.65
15 Jun 74	40	53	1.46	58	1.53	63	1.60	66	1.64
Lime									
19 Mar 74	40	42	1.34	43	1.36	50	1.44	56	1.51
8 Sep 76	40	45	1.34	58	1.50	53	1.44	61	1.54
8 Sept 76	~0	47	1.37	51	1.41	48	1.38	57	1.49

[a]*Using Laboratory Equipment*



Curve	Power Plant	Absorbent	Fly Ash (% Solids by Dry Weight)	Date
1	Shawnee	Lime	<1	8 Sep 76
2	Shawnee	Limestone	<1	30 Nov 76
3	Shawnee	Lime	40	8 Sep 76
4	RTP[a]	Limestone	<1	4 Dec 75
5	Shawnee	Limestone	40	30 Nov 76
6	RTP[a]	Limestone	40	30 Sep 75
7	Shawnee[b]	Limestone	<1	Sep 77
8	Shawnee[c]	Limestone	<1	2 May 79

[a]Gypsum, contains 5% sulfite

[b]Gypsum slurry

[c]Gypsum cake with 13% unreacted calcium carbonate

Figure 6. *Confined load-bearing strength of untreated wastes: laboratory data.*

with clay, which was then contoured and planted with grass.

Concentrations of major species in the leachate of chemically treated waste for Sites B and C are presented in Figures 8 and 9, respectively. For Site B leachate, there appeared to be a slow depletion of chloride compared to that of the untreated wastes, while the TDS, sulfate, and calcium concentrations did not change appreciably. In contrast, the Site C leachate showed an initial decrease in TDS. The leachate well for Site C was pumped dry prior to filling. The initial TDS is due to the TDS concentration in the occluded water and is representative of undiluted seepage from the inital placement of waste material. The TDS concentration of all the chemically treated waste leachates generally showed a slight decrease in TDS after the filling period, initially ranging from about 2000 to 5000 mg/l (approximately half the concentration of the untreated liquor) and gradually decreasing in concentration to approximately 2500 mg/l, which is typical of gypsum saturation (Figure 10).

Generally, chemical treatment did not appreciably reduce the concentration of trace elements in the leachate (as shown in Figure 11 for Site C). In some instances, the concentrations of minor constituents in the leachate are somewhat higher than the concentrations in the untreated input liquors. To some extent, this may have resulted from trace elements present in the treatment additives, or from the mobilization of trace elements, such as arsenic and selenium, caused by the pH increase inherent to the treatment process. Of the more than 600 Shawnee leachate analyses of chemically treated wastes, two showed concentrations greater than 10 times the National Interim Primary Drinking Water Regulations; i.e., 13 and 20 times the regulation for selenium.

Physically, all the chemically treated materials (Table 5) exhibited high bearing capacities. Pond B exhibited ultimate bearing capacities of between 1030 and 2070 kPa (150 and 300 psi), and Sites C and E exceeded 2280 kPa (330 psi), which is near the upper limit of the field testing device. However, Site C, which is currently exposed to the weather, developed nearly 0.1 to 0.15 m (4 to 6 in.) of granular material on the surface. Similarly, the treated waste in Site B, whose surface is generally underwater, developed a layer of silty

Curve	Absorbent	Date	Fly Ash, wt % (Dry)
1	Lime	9/ 8/76	1
2	Limestone	9/28/76	1
3	Lime	3/19/74	4
4	Lime	9/ 8/76	40
5	Limestone	2/ 1/73	20
6	Limestone	6/15/74	40
7	Limestone	7/11/73	41

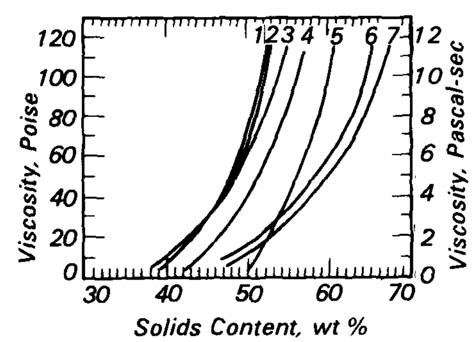


Figure 7. *Viscosity of Shawnee FGD wastes.*

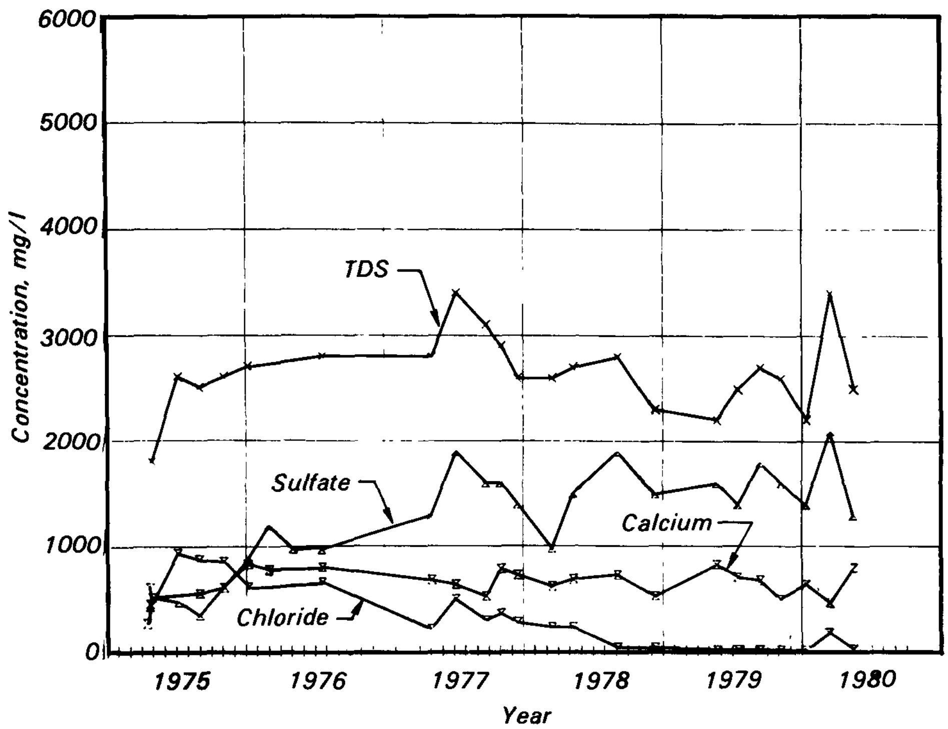


Figure 8. *Concentration of TDS and major species Site B in leachate.*

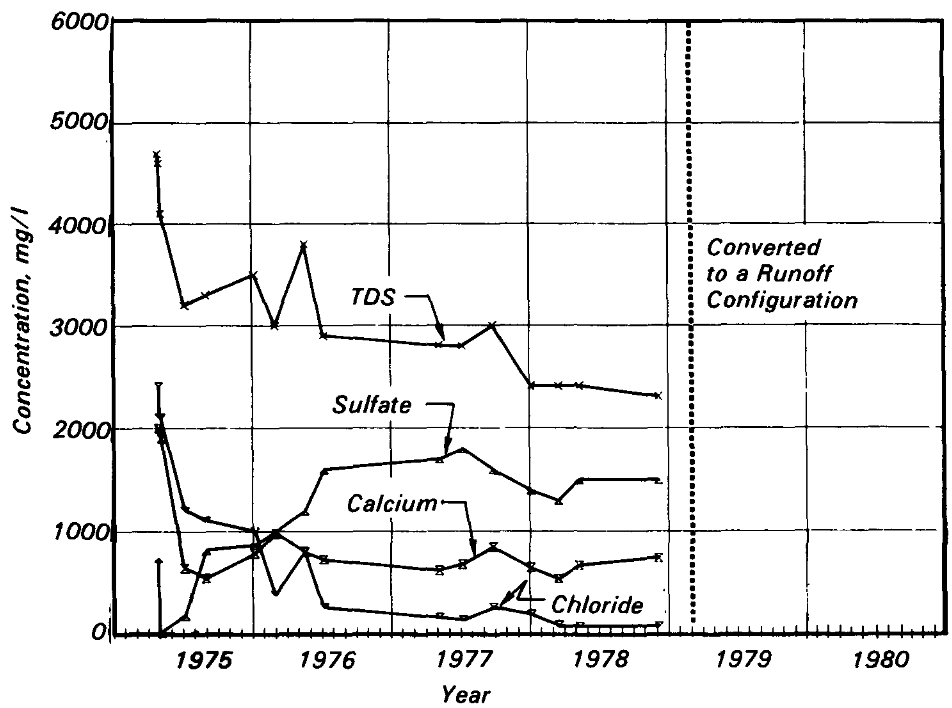


Figure 9. *Concentration of TDS and major species Site C in leachate.*

material, increasing to a depth of 0.15 r (6 in.) at present. These material exhibit very low bearing capacities.

Laborabory analyses of core sample from these three chemically treate FGD waste sites show widely varyin coefficients of permeability as a result c cracks that were present in some cor samples (Table 6). In general, the coeff cient of permeability for the wastes i Sites C and E is approximately the sam and is somewhat less permeable tha the Site B material. Although all mate rials have a permeability of about 10˙ cm/sec, which is at least one order c magnitude less than the untreate wastes, several samples from Sites (and E showed coefficients in the rang of 10^{-6} to 10^{-7} cm/sec. There does nc appear to be a time-dependent trend ii the permeability of core samples of th waste.

Other physical parameters includin solids content, void fraction, and uncon fined compressive strength are given ii Table 6. Typical solids content for th cores from the three sites were 45% fo Site B, 61% for Site C, and 52% for Sit E. The average void fractions were 0.75 0.66, and 0.70 for samples from Sites B C, and E, respectively. The wide range o values for the unconfined compressiv strength of free-standing samples o these materials may be attributed ii part to random cracks that were presen in some of the test samples.

Stabilization of FGD wastes by chemi cal treatment offers a solution to th disposal problem in that the potentia water pollution can be minimized an the site can be reclaimed. Chemica treatment converts the waste into a structural material, decreases its coeffi cient of permeability and seepage rate relative to untreated wastes by one to three orders of magnitude, reduces the initial concentration of soluble sal constituents in the leachate by approx imately 50%, is amenable to subgrade or above-grade landfilling, and can be contoured to promote the runoff o rainwater.

A general procedure for managing rainfall runoff from a full-scale chemi cally treated waste disposal site includes collection of the runoff in a periphera ditch, which directs the water to a settling pond. Depending on the quality of water (e.g., concentration of TDS and total suspended solids (TSS) decanted from this site), it can be discharged to a stream or returned to the scrubber system. After closure of the site, the waste is capped with soil and contoured

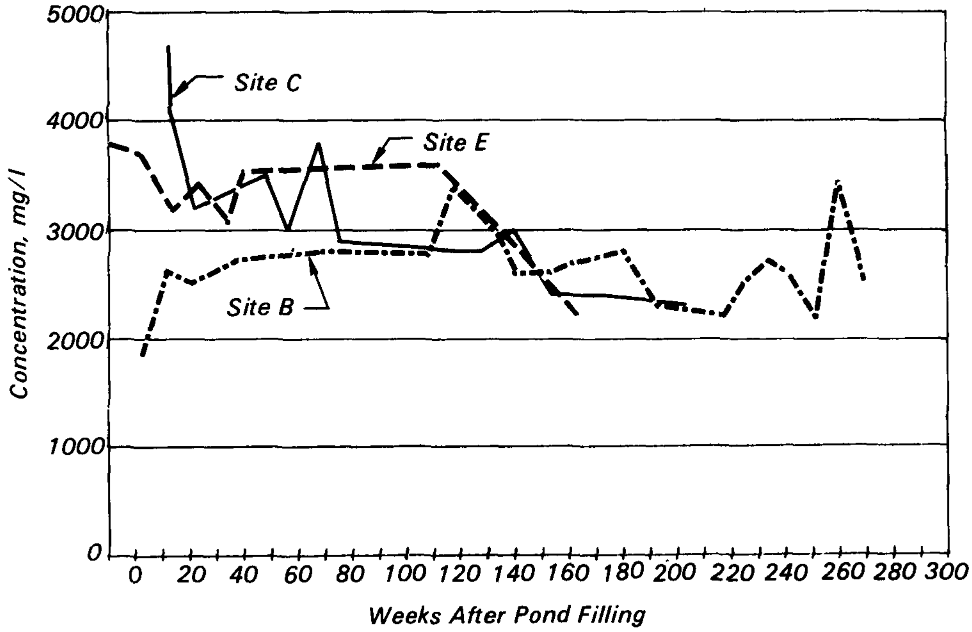


Figure 10. *Concentration of TDS in chemically treated waste leachate (Sites B, C, and E).*

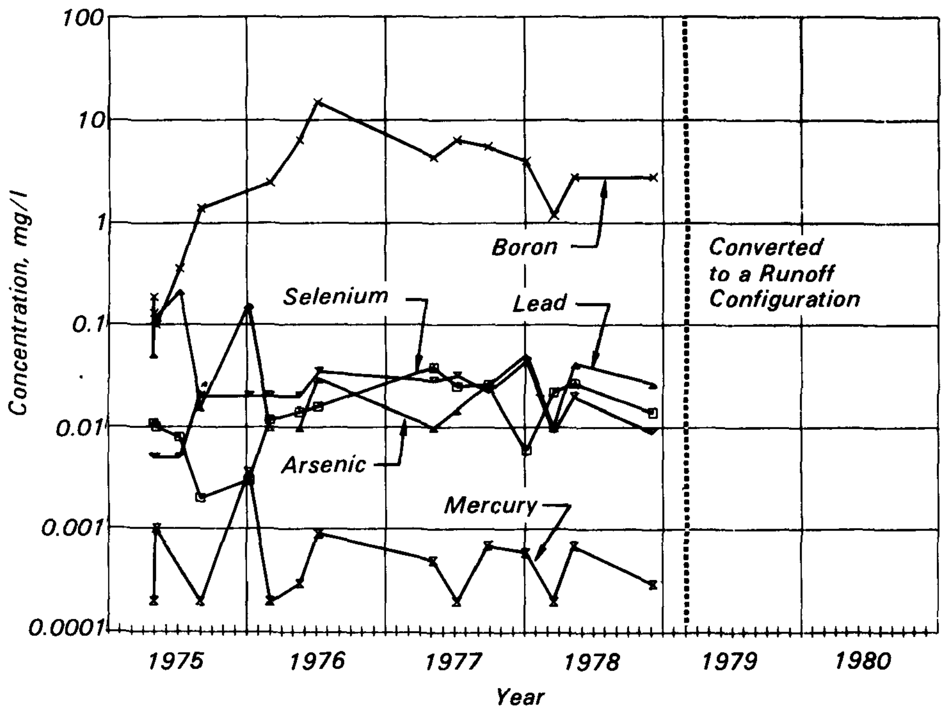


Figure 11. *Concentration of minor species in Site C leachate.*

to support the growth of vegetation and to minimize seepage of rainwater into the waste.

Gypsum Filter Cake Disposal

Sites J and K and the stacked portion of Site H are limestone scrubbing FGD wastes that were force-oxidized to gypsum and filtered. (The evaluation of the lower portion of Site H, containing clairifier underflow slurried gypsum, is discussed in the following section on underdrained disposal). Input waste characteristics are summarized in Tables 1, 2, and 3. The composition of filter cake samples represented a range of limestone utilization of 97, 80, and 52% corresponding to unreacted limestone concentrations of 1, 13, and 25% for Sites J, H, and K, respectively. Although the filter cake at Site K has a relatively high unreacted limestone content of 25%, it is considered to approximate a portion of the gypsum that will be produced by forced oxidation at the TVA Widows Creek Steam Plant.

These three sites were constructed to determine the impact of piling or stacking FGD gypsum on the ground. Observations were made of the erosion, runoff, water quality, and surface characteristics of the filter cake and crust bearing strength and strength loss when moisture content is increased. Sites H and J were generally conical in shape and approximately 10 ft high, whereas Site K reflected the random dumping of piles of gypsum over an area of 150 m^2 (1600 ft^2). Because of the limited size of the piles, compacting of the gypsum during stacking was not performed.

Chemical analyses were made of the leachate collected in the underdrainage system and of runoff samples from Site H. The analysis of the underdrainage is typical of an untreated waste leachate, with concentrations of major and minor chemical species similar to those shown earlier with an initial TDS value of 4000 mg/l, which is continuing to decline toward a saturated gypsum concentration. The concentration of major species in the runoff of Site H shows a slight decrease in TDS over time. The runoff had TDS slightly in excess of 2000 mg/l and TSS ranging between 4 and 300 mg/l, which indicates the need to control runoff in this type of disposal to prevent seepage into underground drinking water supplies or direct discharge into streams. The minor species (Figure 12) show a general decrease in boron, lead, and mercury. However,

Table 5. *Ultimate Bearing Capacity of FGD Wastes*

Site	Waste Treatment	Ultimate Bearing Capacity kPa	Ultimate Bearing Capacity psi
B	Chemical [a]	1035 to 2070	150 to 300
C	Chemical [b]	> 2280	> 330
E	Chemical [c]	2070 to > 2280	300 to >330
F	None (underdrained)	410 to 520	60 to 75
G	None (underdrained)	1240 to 1650	180 to 240
H	None (underdrained)[d]	930 to > 2280	135 to > 330

[a]Dravo Corporation
[b]IU Conversion Systems, Inc.
[c]Chemfix Corporation
[d]Clarifier underflow
Note: Shawnee clay soil has an ultimate bearing capacity of 1650 to 2070 kPa.

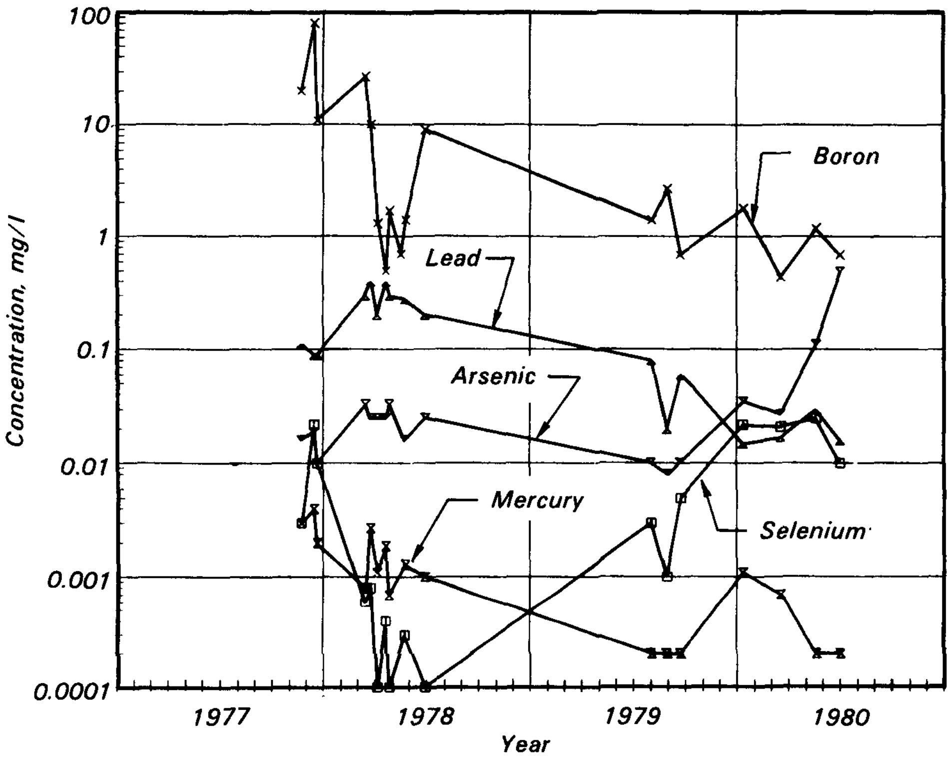


Figure 12. Concentration of minor species in Site H runoff.

recent data indicate an increase in arsenic and selenium in the runoff samples. The most recent runoff samples yielded values of arsenic approximately 10 times the National Interim Primary Drinking Water Regulation standards and values of selenium nearly equal to those standards.

At Sites H and J, the gypsum filter cake was stacked so that a natural slope occurred in a conical shape, producing a surface of about 35 degrees to the horizontal. These tests show that erosion would be a potential problem for FGD gypsum filter cake disposed of in this manner. For example, at Site H, after 18 months of weathering, approximately 20% of the mass flowed to the base. At Site J, which was stacked the following year, the same erosion trend developed.

Field penetrometer readings were taken of ultimate bearing capacity on the gypsum stacks. During periods of dry weather, a crust was observed with a thickness varying from approximately 5 cm (2 in.) near the peak to 13 cm (5 in.) at midheight, and 28 cm (11 in.) at the base. Bearing capacities of the crust varied from 410 kPa (60 psi) near the peak to 3100 kPa (450 psi) near the base. Several tests were made with a D-8 Caterpillar tractor at Site J to determine the maximum angle at which the vehicle could negotiate the slope of this material. During testing, the cleats of the tractor broke through the crust, and the vehicle lost traction at an angle of 17 degrees to the horizontal. After approximately six passes over the same spot, the material became so moist that it could not support personnel.

The crust also absorbed water and, during periods of continued rainfall, reverted to a material characteristic of the original FGD gypsum filter cake. When water collected, the gypsum increased in moisture content and approached a slurried condition.

Table 6. *Physical Characteristics of Impounded, Chemically Treated FGD Waste Core Samples*

Characteristics	Site B	Site C	Site E
Solid Content (% by Weight)	45	61	52
Unconfined Compressive Strength, Wet kPa (psi)	190 to 580 (28 to 84)	280 to 6900 (40 to 996)	190 to 1800 (24 to 260)
Density (g/cm^3):			
Wet	1.37	1.52	1.36
Dry	0.63	0.92	0.70
Void Fraction	0.75	0.63	0.71
Permeability Coefficient (cm/s)	2.1×10^{-4} to 3.7×10^{-5}	5.2×10^{-5} to 3.2×10^{-7}	1.1×10^{-4} to 6.9 x 10-7

Two sets of FGD gypsum samples that were produced at the pilot FGD scrubber at the EPA Industrial Environmental Research Laboratory at Research Triangle Park were obtained. After laboratory filtration, one set of gypsum samples exhibited substantially higher unconfined compressive strength, 410 kPa (60 psi), than the other set, 140 to 170 kPa (20 to 25 psi), which contained about 5% sulfite. The unconfined compressive strength of the samples with the 5% calcium sulfite was approximately equal to that of an FGD waste that is predominantly calcium sulfite.

Typical wet bulk densities for gypsum filter cake with 80% solids content were determined to be in the range of 1.3 to 1.4 g/cm^3. Wet bulk density of Shawnee gypsum clarifier underflow that settled in the impoundment beneath the Site H filter cake pile and was saturated with moisture was approximately 1.7 g/cm^3

The oxidation of FGD wastes to gypsum results in a waste material that is readily dewatered by vacuum filtration to a solids content in the range of 75 to 85 wt%. When stacked above grade, the filter cake may crack under freeze-thaw or wet-dry conditions, thereby allowing rainwater to enter into the material. Additionally, it may erode when exposed to rainfall and produce a runoff containing concentrations of dissolved solids of approximately 2500 mg/l. These observations indicate that special site maintenance may be required on an operational scale to reconfigure the disposal pile after weathering and to control the runoff. On the basis of experience in phospho-gypsum waste management in the fertilizer industry, this is not unexpected.

Underdrain Disposal of Untreated Wastes

Sites F and G and the lower portion of gypsum Site H (Figure 13) were evaluated for disposal of untreated FGD waste deposited in an underdrained impoundment. The underdrainage system consisted of a 0.3-m (1-ft) thick sand layer at the base of each impoundment, under which perforated plastic pipes, imbedded in pea gravel, collected and fed leachate that seeped through the waste to a sump, through a gravity drain system. Water was pumped from the sump to remove all seepage.

In a properly designed operational site, the underdrainage (and all rainfall on the disposal site) could be recycled to the scrubber. This would effectively reduce the normal amount of fresh makeup water. However, it would increase the concentration of soluble salts (e.g., chloride) in the scrubber loop. The resultant chloride concentration could be as high as 9000 mg/l for lime/limestone scrubber waste and 25,000 mg/l for gypsum waste. These concentrations are not anticipated to be detrimental to scrubber operation; however, steps to prevent scrubber corrosion would be necessary.

The underdrainage enhances dewatering of the material such that the additional settling that results from the removal of the occluded water results in an untreated material with very high bearing capacities when contained in an impoundment (Table 5); these ponds drain rapidly because of their highly porous base. In the Shawnee testing, the underdrained material could support personnel during the pouring operation. Sites G (untreated lime scrubbing waste) and H (gypsum) supported wheeled vehicles within a day after placement (Figure 14). Site F (untreated limestone scrubbing waste), the weakest of the three, did not drain as rapidly as the others but still attained high bearing strength within 1 week after filling.

Use of an underdrainage system at the disposal site allows for the collection of all seepage for return to the scrubber system, thus, maintaining control of leachate during the full period. Reclamation of this type of disposal method would require an earthen cap that is contoured and maintained to shed water after disposal site closure. After Site F had been in service for 9 months, all water was removed from the underdrain sump, and the site was covered with a layer of indigenous soil, using a rubber-tired earth mover. This cap, which was contoured and planted with grass so that its surface would shed rainwater, was approximately 0.9 m (3 ft) thick at the center line and 0.6 m (2 ft) thick at the edges. In the spring of 1979, the soil cap was recontoured and reduced to a constant thickness of 0.6 m (2 ft) for a separate EPA/TVA project that included an experimental planting of young trees. Recently, Site F (and chemically treated Site E) has shown increased seepage. This may be due, however, to the recontouring of the soil covering and puncturing of the soil cap for the trees. Underdrained Site G was covered in April of 1980, but (because of low rainfall since construction) the evaluation of this type of reclamation is inconclusive.

Regarding seepage into the subsoil from an underdrain system, a low hydrostatic pressure exists at the site and subsoil interface because the hy-

Figure 13. Filling lower portion of Site H with scrubber clarifier underflow that has been force-oxidized to gypsum.

draulic head is interrupted at the porous base and the system is vented to the atmosphere. If, for example, the subsoil coefficient of permeability were 10^{-6} cm/sec, the penetration with underdrainage would be 0.36 m/yr (14 in./yr) only in the vicinity of the trenches holding the drainage pipes, which may be approximately 0.25 x 0.25 m (10 in. x 10 in.) and as much as 30 m (100 ft) apart. Penetration of the water into the soil between the drainage trenches would be negligible because the water would be only a film on the base of the site. By comparison, the subsoil seepage from a similar pond without underdrains would be about 1.8 m/yr (6 ft/yr) from the entire pond bottom. Considering the depth of seepage and the pond base area contributing to the seepage, the underdrained site would release about 0.4% as much water as the nondrained pond.

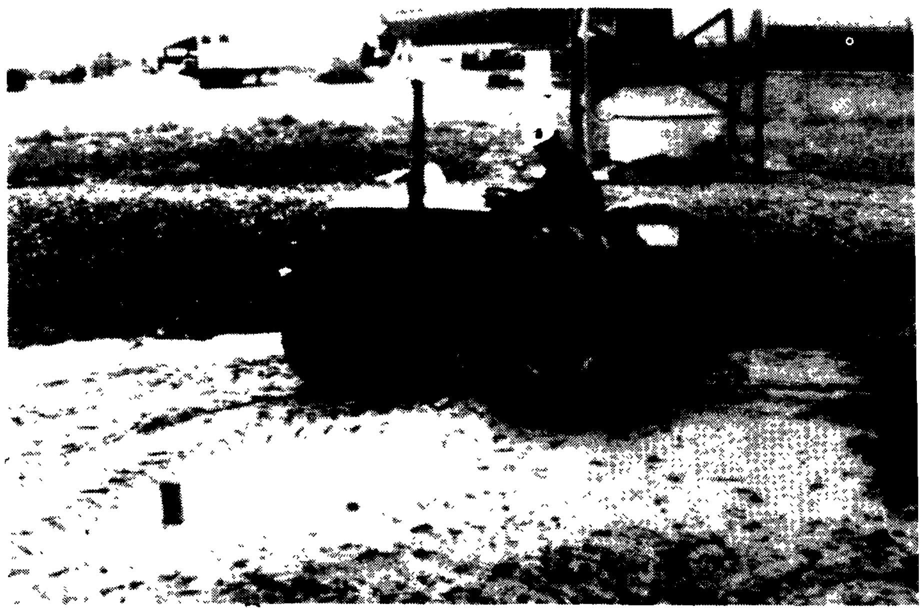


Figure 14. Untreated underdrained Site G showing physcial stability within : days after filling.

Cost Estimates of FGD Waste Disposal

Costs were estimated for the various FGD waste disposal methods related to the type of disposal evaluation conducted at Shawnee. The engineering cost estimates for the disposal methods summarized in Table 7 are based on mid-1980 dollars and on other conditions summarized in Table 8. Cost-effective and environmentally sound disposal methods—namely, chemical treatment, untreated with underdrainage, and gypsum with a low permeability indigenous clay liner and surface drainage—cost between 0.79 and 1.46 mills/kWh The disposal cost of chemically treate(waste of 1.46 mills/kWh is based or costs derived from data provided by the three treatment contractors who participated in the Shawnee project and ha: been updated to mid-1980 dollars.

Table 7. Cost Comparison of Disposal Alternatives (Mid-1980 Dollars)[a]

Disposal	Annual Disposal Costs[c] Mills/kWh	$/Tonne of Dry Waste	$/Tonne of Coal	Capital Investment Cost $/kW	Significant Cost Items[b]
Untreated Waste Pond					
Indigenous Liner	*0.51*	*5.01*	*1.51*	*14.80*	*Land (780 acres)*
Synthetic Liner (Polymeric)	*1.23*	*11.96*	*3.62*	*38.70*	*Land and liner*
Bentonite Clay Liner	*2.06*	*20.01*	*6.04*	*66.20*	*Land, clay liner, and clay transportation*
Volclay SS-100 Liner	*0.94*	*9.13*	*2.76*	*29.00*	*Land and liner*
Underdrained	*0.86*	*8.33*	*2.51*	*26.00*	*Land and underdrainage system*
Force-Oxidized Waste with Surface Drainage					
Indigenous Liner	*0.79*	*7.10*	*2.19*	*21.20*	*Oxidation equipment*
Synthetic Liner (Polymeric)	*1.28*	*12.22*	*3.78*	*39.20*	*Oxidation equipment and synthetic linei*
Chemically Treated Waste Landfill	*1.46*	*14.16*	*4.78*	*17.78*	*Dewatering equipment and chemical reagents*

[a]Cost comparisons are for conditions summarized in Table 8.
[b]Relative to the various alternatives presented.
[c]Includes disosal of ash in the waste.

Table 8. Summary of Base Conditions for Cost Estimation

Item	*Base Condition*
Dollar Base	*Mid-1980*
Electric Utility Plant Size	*Two 500-MW units*
Coal Burned	*3.5% sulfur: 2.8×10^7 J/kg (12,000 Btu/lb)* *14% fly ash*
Heat Rate	*9.5×10^6 J/kWh (9000 Btu/kWh)*
Annual Operating Hours	*5694 hr (30-yr average for a 65% lifetime capacity factor)*
Disposal Site Lifetime	*30 yr*
SO_2 Removal	*90%*
FGD Waste Generated	*5.8×10^5 tonnes (6.4×10^5 tons)/yr, dry (general case)* *6.0×10^5 tonnes (6.6×10^5 tons)/yr, dry (gypsum case)*
Limestone Utilization	*80% for limestone scrubbing; 100% for forced oxidation to gypsum*
Annual Capital Charges, 30-yr Average	*17%*
Cost of Land Used for Disposal	*$4940/ha ($2000/acre)*
Disposal Site Location	*Within 1 mile of steam plant*
Total Disposal Area Requirements, (Including Berm) for a 9-m (30-ft) Waste Depth	
Chemically Treated Waste	*263 ha (650 acres)*
Force-Oxidized Waste	*236 ha (582 acres)*
Untreated Waste	
Lined	*295 ha (730 acres)*
Underdrained	*316 ha (780 acres)*

These cost estimates differ slightly from those presented in previous reports on this project as a result of a revision upward in average unit capacity factors for the power stations and a reduction in disposal land costs. Based on a sampling of U.S. power companies and government agencies, the estimated cost of land was changed from $12,400 to $5000/ha ($5000 to $2000/acre). Also, on the basis of recent data, the 30-year average unit capacity factor for new coal-fired utility power plants is now projected at 65% rather than 48.5%. Both of these factors caused reductions of about 0.17 mills/kWh for untreated disposal and about 0.44 mills/kWh for the gypsum disposal cases and are reflected in Table 7.

The cost of chemically treated waste disposal increased by 0.21 to 1.46 mills/kWh (Table 7). Although costs declined as a result of the land and capacity factor revisions indicated here, the decrease was offset by the inclusion of capital investment contingency, startup, and modification costs and interest during construction (Table 9), which had been previously applied only to the untreated and gypsum disposal costs.

For the indigenous clay liner case, a soil permeability coefficient of 10^{-7} cm/sec was taken to be representative of clay to be used for pond lining, and consequently no cost was associated with liner material. The cost of pond construction for disposing of untreated and force-oxidized wastes increases to 1.28 mills/kWh if a synthetic liner must be added compared to a cost of 0.79 mills/kWh without a liner. The estimated installed cost of a synthetic liner is $6.46/m^2 ($5.40/yd^2).

For the underdrained site, a design for a minimal sand bed using a 0.3 m (1 ft) thick sand layer and pipe spacing of 41 m (133 ft) is the lowest cost design for this type of disposal. Ten 20-ha (50-acre) sites are required for this disposal mode according to the baseline conditions, and the cost is 0.86 mills/kWh. The cost of the underdrainage components, including sand, gravel, pipes, and fittings, is approximately 20% of the total capital cost.

Disposal of force-oxidized FGD waste includes a 15% slurry pumped to the site, where it settles, on the basis of test site data, to approximately 65% solids and the supernate water is recycled to the scrubber. The cost of the oxidation equipment is included as part of the disposal costs.

Differences in capital investment costs for the various alternatives shown in Table 7 are attributable to differing requirements for each type of disposal; e.g., land requirements, whether a synthetic liner or underdrainage system is installed, and the necessity for dewatering, oxidation, or special slurry

Table 9. Contingency and Miscellaneous Capital Investment Costs

Item	Cost
Engineering	*10% of capital equipment*
Miscellaneous Services	*0.5% of capital equipment*
Contingency	*12% of capital equipment, plus engineering, and miscellaneous services*
Startup and Modification Allowance	*6.7% of capital equipment, plus all of the above*
Interest During Construction[a]	*1.6% of capital equipment, plus all of the above*

[a]*Estimated as 4 months.*

handling equipment. The least capital intensive method at $14.80/kW is for the untreated case and involves waste disposal in ponds with an indigenous clay base. The most capital intensive technique is for forced oxidation of the waste prior to gypsum and disposal in a pond lined with polymeric material; the cost associated with this option is $39.20/kW. As shown in Table 7, the use of a liner has a marked effect on the cost of disposal. Use of treated bentonite clay liner (Volclay SS-100), a polymeric liner, and a pure bentonite clay liner increased the untreated waste disposal cost from $14.80/kW to $29.00, $38.70, and $66.20/kW, respectively.

Findings

The results obtained from the FGD waste disposal evaluation project indicate several cost effective methods that physically stabilize the wastes, prevent water pollution, and permit site reclamation. These methods include chemical treatment, underdrainage of untreated waste, and surface drainage of ponded gypsum.

The results show that:

1. Chemical treatment reduces the coefficient of permeability by at least one order of magnitude and reduces the initial concentration of major species in leachate by about 50%. Chemical treatment converts the waste into a structural material, is amenable to subgrade or abovegrade landfilling, and can be contoured to promote the runoff of rainwater. Typically, chemical treatment did not appreciably reduce the concentration of trace elements in the leachate. However, of the more than 600 leachate analyses conducted, only two showed concentrations in excess of 10 times the National Interim Primary Drinking Water Regulations for selenium (13 and 20 times the standard).
2. Typically, after approximately 2 years, the concentrations of the TDS in the leachates of the chemically treated and untreated ponded wastes have approached levels that approximate saturation with gypsum (approximately 2500 mg/l).
3. The ground waters associated with all sites show no effects attributable to the waste disposal operations.
4. Runoff from waste that was force-oxidized to gypsum shows a TDS concentration of between 2500 and 3200 mg/l, and TSS in the same runoff ranges between 4 and 300 mg/l. When stacked above grade, uncompacted gypsum filter cake exhibits cracking under exposure to freeze/thaw or wet/dry conditions, thereby allowing rainwater to enter into the material. For structural strength of the gypsum filter cake to be maintained, the site should be managed to reconfigure the disposal pile after weathering to shed water so that it is not allowed to reslurry by wetting.
5. The underdraining of untreated waste results in a structurally sound material in an impoundment with all seepage and rainfall being controlled. Operationally the water would be returned to the scrubber and reused.
6. Site closure by draining, covering, and contouring with indigenous clay of one chemically treated and two untreated underdrained sites has been shown to be adequate to support construction vehicles.
7. Ponding of untreated material is generally the least costly method of FGD waste disposal, but if the pond does not have a base material considered to be impermeable a liner must be added to reduce seepage, thereby significantly increasing the disposal cost. Since FGD wastes are thixotropic in nature, ponds of untreated wastes are considered nonstructural sites and are generally difficult to reclaim, except possibly in areas of low rainfall and high evaporation.
8. Chemical treatment, ponding with underdrainage, gypsum with an indigenous liner and surface drainage, and chemical treatment with landfilling cost between 0.79 and 1.46 mills/kWh ($7.10 to $14.15/tonne waste, dry basis).

Recommendations

It is recommended that the following FGD waste disposal, site closure, and reclamation techniques be further evaluated:

1. *Long-term monitoring of covered disposal sites to evaluate the effectiveness of site closure, reclamation, and repair.* The two sites (one underdrained and one chemically treated) which were covered with soil and sloped to facilitate runoff of rainwater have experienced seepage. This may be due to the recontouring and puncturing of the soil cap for the planting of trees and appears amenable to repair. Another underdrained site, which was covered in April of 1980, has not been effectively evaluated because of the low rainfall since construction.
2. *Investigation of the disposal of slurried force-oxidized waste.* It has been noted that stacking of gypsum filter cake is subject to slumping and erosion. Although hard surface layers (crusts) form during dry periods, these are not permanent and revert to the original condition during wet periods. Above-ground disposal and costs of slurried FGD gypsum similar to the phosphate gypsum disposal in central Florida have not been assessed.
3. *Long-term evaluation of the effects of the time and weather on the physical and structural characteristics of the chemically treated materials.* Recent tests of treated waste core samples have shown that although permeabilities are within the range of previous results,

values are typically on the lower side. Weathering of a chemically treated site that was converted to a runoff configuration has resulted in the formation of approximately 10 cm (4 in.) of granular waste on the surface. In addition, the top 10 to 15 cm (4 to 6 in.) of waste in Site B, which is generally underwater, has deteriorated into a soft silty material with minimum physical strength.

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***Julian W. Jones** is the EPA Project Officer (see below).*
The complete report, entitled "Disposal of Flue Gas Desulfurization Wastes: EPA Shawnee Field Evaluation, Final Report," (Order No. PB 81-212 482; Cost: $21.50, subject to change) will be available only from:
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