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Laboratory
Research Triangle Park NC 27711

Technology Transfer

EPA

Capsule Report

Disposal of Flue Gas Desulfurization Wastes

Shawnee Field Evaluation

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October 1980

This report was developed by the
Industrial Environmental Research Laboratory
Research Triangle Park NC 27711

Typical filling operation of waste disposal evaluation pond

1. Introduction

This capsule report summarizes activities and results of the U.S. Environmental Protection Agency (EPA) Shawnee Flue Gas Desulfurization (FGD) Field Disposal Evaluation Project. As a result of the Resource Conservation and Recovery Act of 1976 (Public Law 94-580), guidelines and criteria for FGD wastes are being developed. Current regulatory development efforts are based, in part, on data derived from the Shawnee project.

The Shawnee project was initiated in September 1974 to evaluate methods and costs for disposing of byproducts from wet, nonregenerable FGD systems. The effects of various disposal techniques, scrubber reagents and operations, weather, and field operation procedures on the environmental quality of the disposal site are being studied to determine environmentally sound disposal methods. Because water quality and land reclamation are of principal interest, periodic sampling, analyses, and assessments are being conducted of leachate, supernate, runoff, ground water, and soil and waste cores. The Aerospace Corporation is responsible for the project planning, coordination, selected water and solids analysis, performance assessment and evaluation, and reporting. Site construction, maintenance, coring, water sampling, and water analysis are performed by the Tennessee Valley Authority (TVA). Completion of the technical effort is scheduled for September 1980.

Project Description

The project is located at the TVA Shawnee Steam Plant near Paducah, Kentucky. Of the 10 field sites currently being evaluated, 8 are small ponds up to 0.1 acre (0.04 ha) in area with a waste depth of 3 to 4 ft (0.9 to 1.2 m), and 2 are surface disposal sites that measure up to 70 ft × 70 ft (21 m × 21 m). Waste materials for the project are produced by two scrubber systems—either a turbulent contact absorber (TCA®, of UOP, Inc.) or a venturi and spray tower (VST)—which operate as an EPA/TVA test facility at the Shawnee plant. Using lime or limestone slurries as the sulfur dioxide (SO_2) absorbent, each scrubber is capable of treating flue gas from a system producing up to 60×10^6 Btu/h (10 MWe equivalent). The Shawnee project provides a broad data base for evaluating the control of flue gas SO_2 by combining the results of field disposal operations and laboratory analyses.

This report evaluates FGD wastes that were either chemically treated, left untreated, or force-oxidized to gypsum. Figure 1 illustrates the relationship of the FGD waste to the four disposal alternatives that are being evaluated at Shawnee—landfill, pond disposal, underdrained pond disposal, and surface stacking. Disposal of FGD wastes in coal mines and the oceans is being evaluated in other EPA projects.

FGD Waste Characteristics

The disposal ponds were filled with FGD wastes representing a cross section of scrubber effluent conditions. The various waste disposal sites are discussed by treatment category: chemically treated, untreated, and force-oxidized. Table 1 lists all the project disposal sites, provides pertinent information, and gives the current status of each site.

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

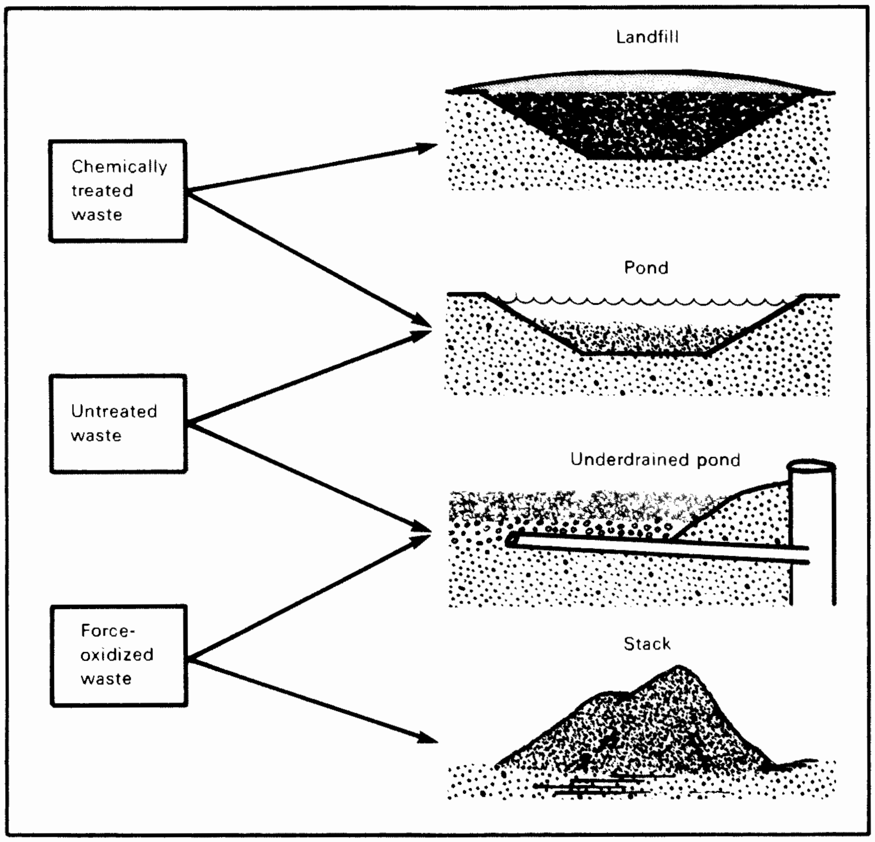


Figure 1.

FGD Waste Disposal Alternatives

The physical properties considered in the disposal of FGD wastes include viscosity, bulk density, moisture content, bearing strength, porosity, and permeability. Viscosity is particularly important in the transport of the waste to a disposal site; the other properties concern the weight and volume of the disposal material, as well as the suitability of the waste as a load-bearing material and as a means of preventing seepage from a disposal site.

The physical properties of FGD wastes depend on the characteristics and interaction of the liquid and the solid constituents. These wastes contain finely divided particulate matter in an aqueous medium. Depending on the particulate size distribution and crystal structure, these particles—the majority being calcium sulfite hemihydrate ($CaSO_3 \cdot \frac{1}{2}H_2O$), calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), and fly ash—influence the physical properties of the wastes. Both calcium sulfite and calcium sulfate scrubber waste products tend to have particles in the same size range as fly ash, that is, between

Table 1.

Description of Shawnee Disposal Sites

Site	Fill date	Scrubber type[a]	FGD waste	Waste treatment	Remark
A	Oct. 8, 1974	VST	Lime, filter cake	None	Out of service on Apr. 15, 1976
A1	May 10, 1976	VST	Lime, filter cake	None	Control pond, transferred from Site A
B	Apr. 15, 1975	TCA®	Limestone, clarifier underflow	Chemical[b]	Underwater disposal
C	Apr. 23, 1975	TCA®	Lime, centrifuge cake	Chemical[c]	Pond converted to runoff mode in Mar. 1979
D	Feb. 5, 1975	TCA®	Limestone, clarifier underflow	None	Control pond
E......	Dec. 7, 1974	TCA®	Limestone, clarifier underflow	Chemical[d]	Covered in Nov. 1977
F......	Feb. 3, 1977	TCA®	Limestone, clarifier underflow, fly ash remixed	None	Underdrained pond, covered in Nov. 1977
G	Oct. 5, 1976	VST	Lime, centrifuge cake, fly ash remixed and layered	None	Underdrained pond, covered in Apr. 1980
H	Sept. 2, 1977	VST	Limestone, gypsum clarifier underflow	Oxidation	Underdrained during filling
H	Sept. 30, 1977	VST	Limestone, gypsum filter cake	Oxidation	Surface site, unreacted limestone (13% by dry weight)
J......	Dec. 31, 1978	VST	Limestone, gypsum filter cake	Oxidation	Surface site (adipic acid used in scrubber)
K	Mar. 29, 1979	VST	Limestone, gypsum filter cake	Oxidation	Surface site, unreacted limestone (25% by dry weight)

[a]VST = venturi and spray tower; TCA® of UOP, Inc. = turbulent contact absorber.

[b]Dravo Corporation.

[c]IU Conversion Systems, Incorporated.

[d]Chemfix Corporation.

Table 2.

Chemical Analysis of Disposal Site Input Liquor

Site[a]	pH	Concentration (mg/l)												
		Calcium	Sulfate	Chloride	Sulfite	Total dis-solved solids	Arsenic	Boron	Lead	Mag-nesium	Sodium	Sele-nium	Mercury	Chemical oxygen demand
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	7.1	1,300	1,930	3,500	([b])	9,200	<0.003	120	<0.01	540	62	0.14	<0.0002	130
H	([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.

1 and 100 μm. Fly ash forms as spheres (typically about 10 μm), whereas sulfite wastes form as platelets (limestone) or rosettes (lime), sulfates are blocky in shape, and typically all are somewhat larger than fly ash. Unreacted calcium carbonate ($CaCO_3$) from the limestone or precipitated from the lime process usually is present in the waste and contributes an additional shape parameter. Table 3 lists the solids analysis of all waste before treatment, oxidation, or disposal as appropriate.

Table 3.

Solids Analysis of Disposal Site Untreated Input Wastes[a]

Site	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	33	0.2	98.0	1.8	0
H	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.

2. FGD Waste Disposal Methods

Chemically Treated Waste

The physical stabilization of FGD wastes by chemical treatment can prevent water pollution and permit site reclamation. Chemical treatment has the following characteristics:

- Converts the waste to a structural material
- Decreases the waste's coefficient of permeability
- Reduces the initial concentration of soluble salt constituents in the leachate
- Permits disposal in a pond or a landfill above or below grade
- Allows contouring of waste to promote the runoff of rainwater

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

Chemically treated Site E, containing trapped water, supporting drilling rig during waste coring operation

Typical chemical characteristics of leachates from the wastes that were treated chemically are presented in Figure 2. Chemical treatment did not achieve substantial reductions in the concentration of trace elements in the leachates. In some instances, the concentrations of these minor constituents in the leachates are somewhat higher than the concentration in the untreated input liquors. These higher concentrations probably result from trace elements present in the treatment additives.

Because FGD wastes are subject to any State and local ordinances (they are temporarily exempt from Federal regulation under the new Hazardous Waste Management System), the following data are presented. Of more than 600 leachate analyses of chemically treated wastes analyzed for trace elements from these sites, 2 showed concentrations greater than 10 times the level of the National Interim Primary Drinking Water Regulations (i.e., 13 and 20 times the regulation for selenium). The TDS concentration of leachate from treated ponds initially ranged from 2,500 to 5,000 mg/l (approximately half the concentration of the untreated liquor), and after approximately 2 years the concentration decreased to 2,000 to 3,000 mg/l.

A general procedure for managing rainfall runoff from a full-scale chemically treated waste site is to collect the runoff in a peripheral ditch, which directs the water to a settling pond. Depending on the quality of the water [concentration of TDS and total suspended solids (TSS)] in the pond, it can be decanted to a stream or returned to the scrubber system. After closure of part or all of the site, it is capped with soil to support the growth of vegetation and to prevent erosion.

All the chemically treated materials (Table 4) demonstrate high ultimate bearing capacities. For example, Site B exhibits ultimate bearing capacities between 150 and

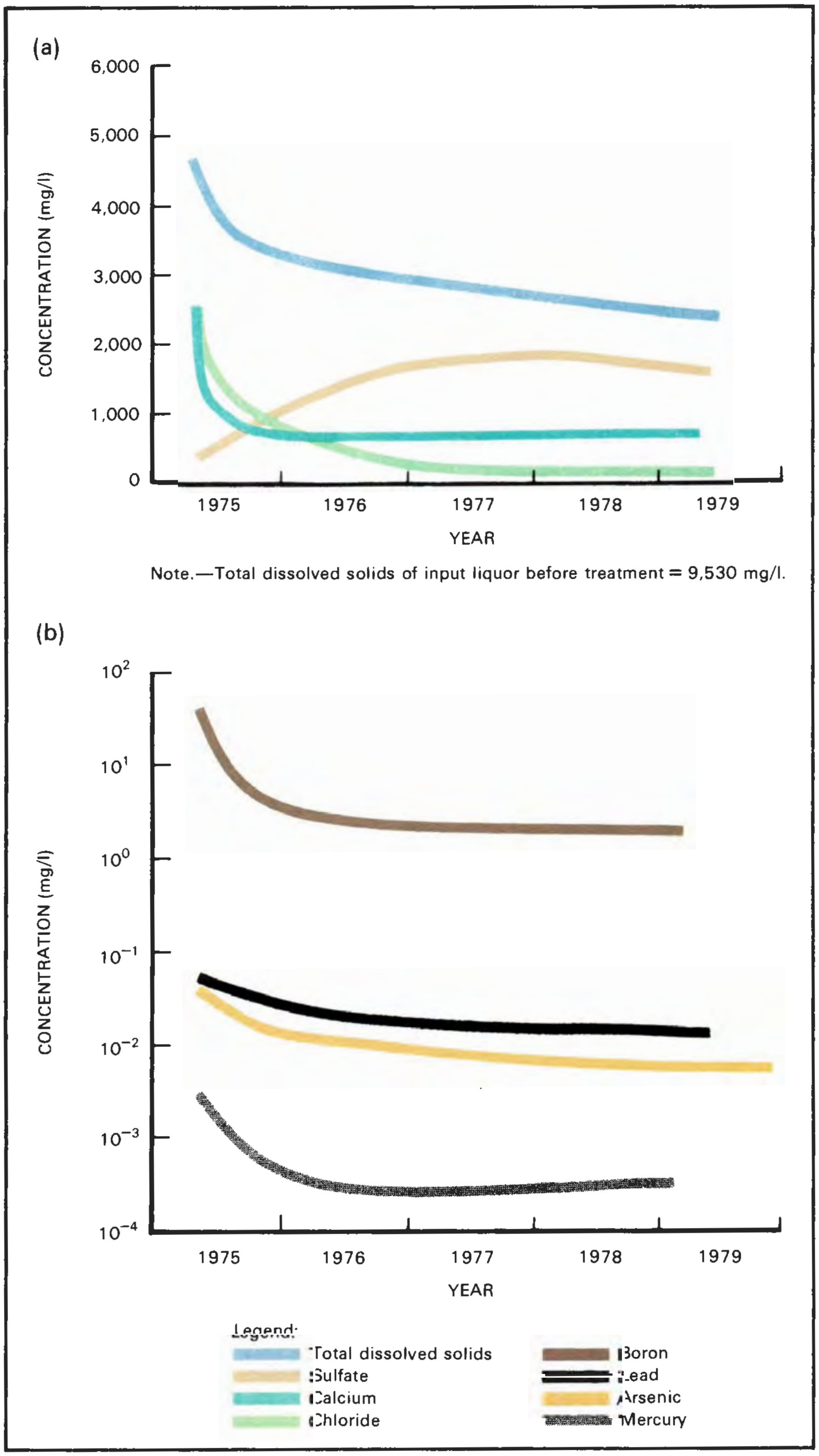


Figure 2.

Concentrations in Typical Chemically Treated Pond Leachate: (a) Total Dissolved Solids and Major Species and (b) Minor Species

Table 4.

Ultimate Bearing Capacity of FGD Wastes

Site	Waste treatment	Ultimate bearing capacity (lb/in^2)
B	Chemical[a]	150 to 300
C	Chemical[b]	Greater than 330
E	Chemical[c]	300 to greater than 330
F	None (underdrained)	60 to 75
G	None (underdrained)	180 to 240
H	None (underdrained)[d]	135 to greater than 330

[a]Dravo Corporation.

[b]IU Conversion Systems, Incorporated.

[c]Chemfix Corporation.

[d]Clarifier underflow.

Note.—Shawnee clay soil has an ultimate bearing capacity of 240 to 300 lb/in^2.

300 lb/in^2 (1,034 and 2,068 kPa), and Sites C and E exceed 330 lb/in^2 (2,275 kPa), which is near the upper limit of the field testing device.

The pollution potential of waste effluent 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 the leachate must pass. Laboratory analyses of core materials from these three chemically treated ponds (see Table 5) show widely varying coefficients of permeability as a result of cracks that appear in some core samples. The coefficient of permeability is approximately the same for the wastes in Sites C and E, which are somewhat less permeable than Site B. Although the materials in Sites B, C, and E have a permeability of about 4×10^{-6} in/s (10^{-5} cm/s), which is at least one order of magnitude less than the untreated wastes, several samples from Sites C and E showed coefficients in the range of 4×10^{-7} to 4×10^{-8} in/s (10^{-6} to 10^{-7} cm/s). A time-dependent trend in the permeability of core samples of the wastes is not evident.

Other physical parameters of core materials include solids content, porosity (or void fraction), and unconfined compressive strength. Typical solids contents for the cores from the three ponds are 45 percent for Site B, 61 percent for Site C, and 52 percent for Site E. The average void fractions are 0.75, 0.63, and 0.71 for samples from Sites B, C, and E, respectively. There are wide variations in the unconfined compressive strength of free-standing samples of these materials (Table 5). These large variations may be attributed in part to random cracks that occurred in some of the test samples.

Untreated Waste

Pond Disposal. 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. Clay or synthetic liners may be placed in the base and on the slopes of such ponds. All three types of liners—indigenous clay, purchased clay, and synthetic—are in use today. Any pond continually exposed to the elements, however, eventually is subject to a degree of seepage because liners are not completely impermeable and long-term durability is uncertain. FGD wastes are thixotropic in nature; therefore, ponds are nonstructural sites that usually are difficult to reclaim, except possibly in areas of low rainfall and high evaporation.

Control ponds for untreated lime and limestone waste disposal were installed at the Shawnee site and are being monitored principally for the determination of chemical characteristics of the leachate. These ponds, which are identified in Table 1 as Sites A, A1, and D, are totally saturated (except for periods of extreme drought).

The initial leachates of the untreated waste ponds contained TDS concentrations ranging from 5,000 to 14,000 mg/l. The depletion of TDS from the leachate as a function of

Table 5.

Physical Characteristics of Impounded, Chemically Treated FGD Waste Core Samples

Characteristic	Site B	Site C	Site E
Solids content (% by weight)	45	61	52
Unconfined compressive strength, wet (lb/in^2)	28 to 84	40 to 996	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 6.9×10^{-7}

time is depicted in Figure 3a, which shows that the chloride content of the waste was essentially depleted after approximately 2 years. Thereafter, the leachates were saturated with gypsum and have remained so after 5 years. Analyses have been made for the concentration of the more significant minor species present in these wastes (Figure 3b). Except for boron, which decreases steadily with time, the minor species have shown only slight reductions after 5 years of seepage. Of nearly 900 analyses of untreated leachate from these sites, only 4 showed concentrations of trace elements greater than 10 times the National Interim Primary Drinking Water Regulations. Three samples were 12, 14, and 20 times the regulation for arsenic, and one sample was 11 times the regulation for selenium.

The dewatering characteristics of FGD wastes are important to the various disposal techniques because 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 method used and the ability of a waste to be dewatered depend on a number of solids characteristics—including the size and distribution of particles and the crystalline structure of the particles—that are principally a function of the absorbent and scrubber operating parameters. In typical laboratory tests four dewatering methods were evaluated: settling and decanting, settling by free drainage, centrifugation, and vacuum filtration (see Table 6).

The highest density was obtained by vacuum-assisted filtration. However, there were relatively small density differences between filtration and centrifugation. For most FGD wastes, settling by free drainage yields a slightly greater density than dewatering by settling only. This slight gain, coupled with the associated higher solids content, significantly increases load-bearing strength. Table 6 shows

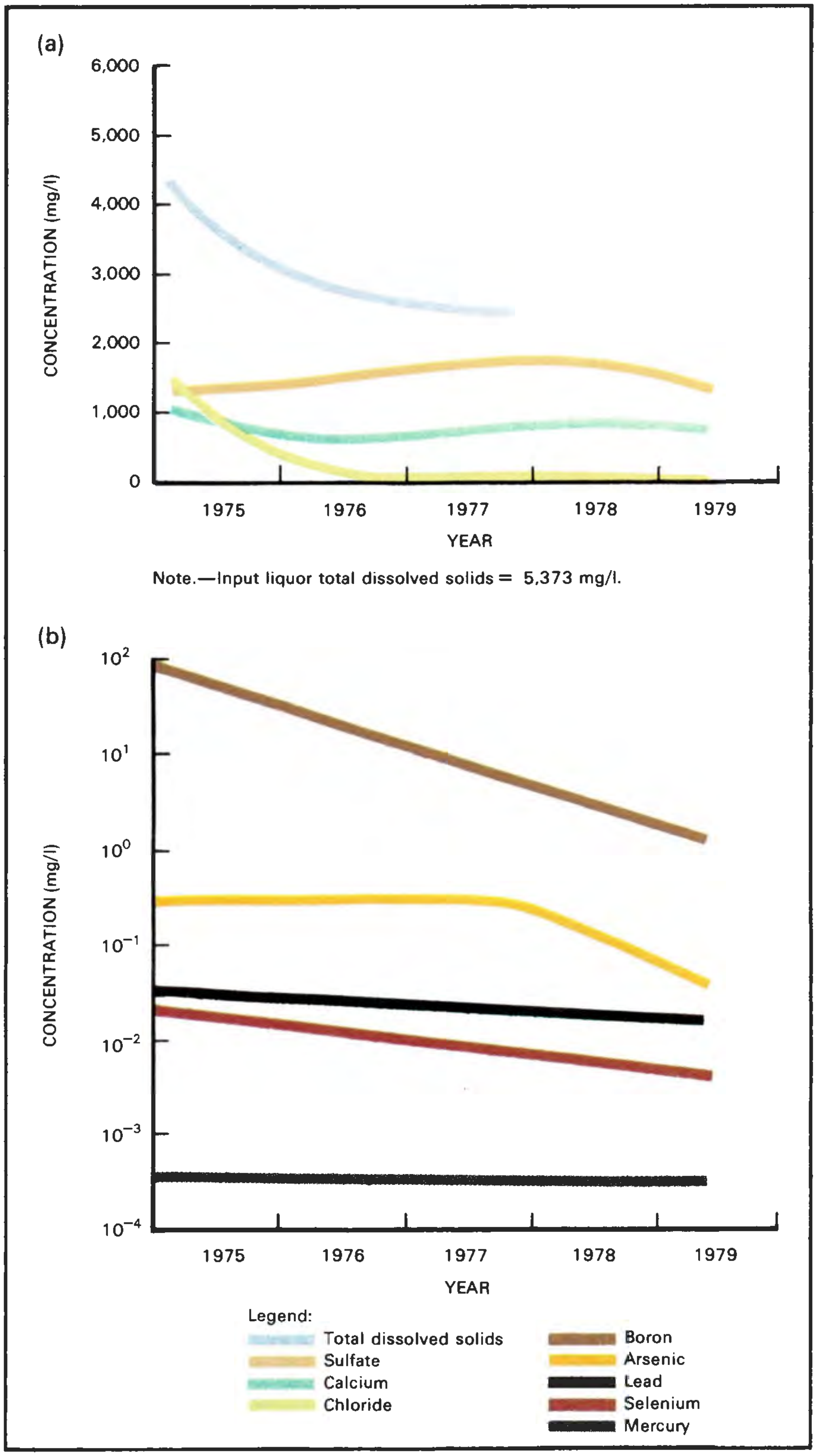


Figure 3.

Concentrations in Untreated Leachate at Site D: (a) Total Dissolved Solids and Major Species and (b) Minor Species

Table 6.

Bulk Densities of Untreated FGD Wastes

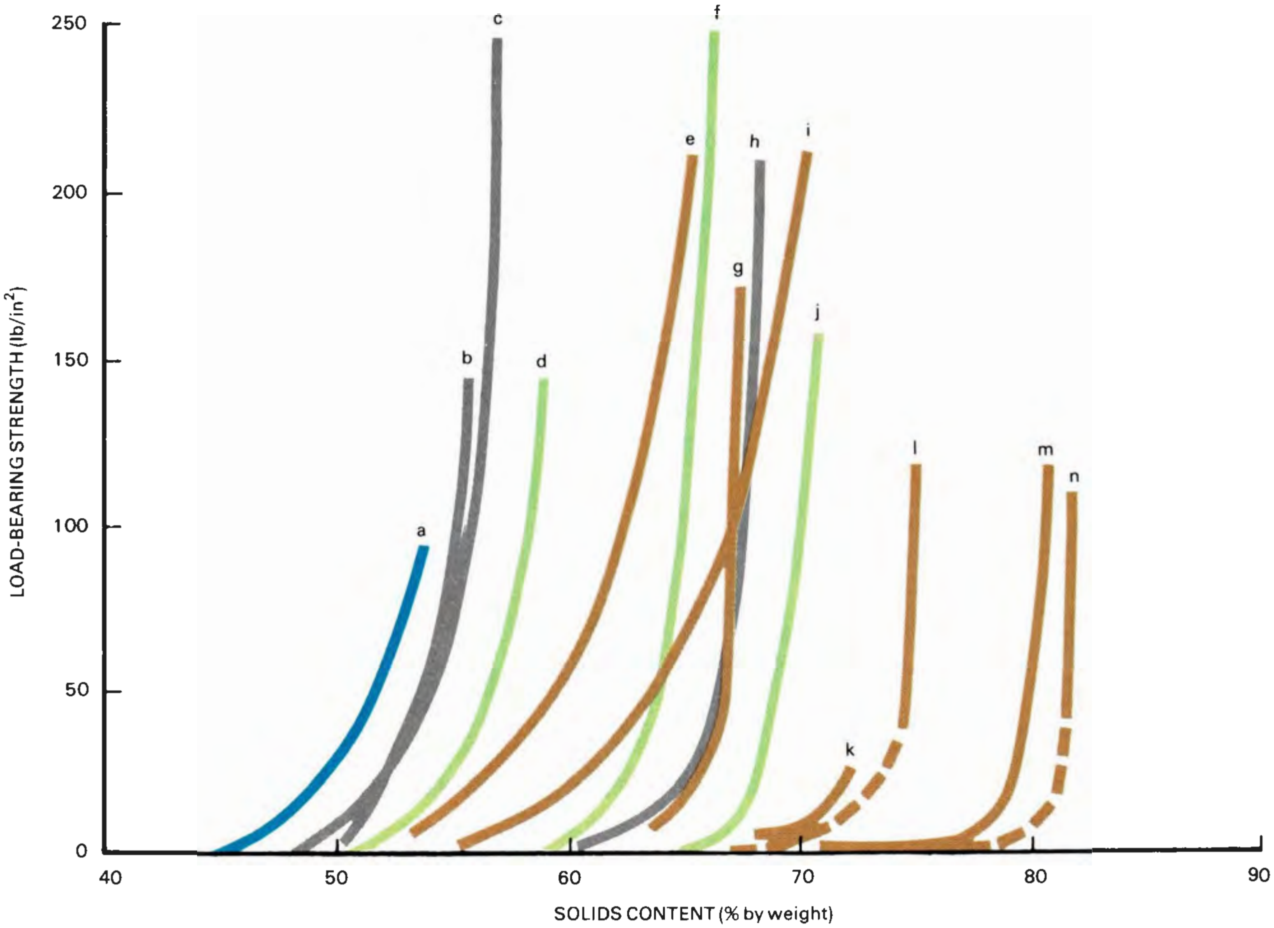
Shawnee source and sampling date	Fly ash (% by dry weight)	Dewatering method[a]							
		Settling and decanting		Settling by free drainage		Centrifugation		Vacuum filtration	
		Solids (% by weight)	Density (g/cm^3)	Solids (% by weight)	Density (g/cm^3)	Solids (% by weight)	Density (g/cm^3)	Solids (% by weight)	Density (g/cm^3)
Limestone:									
Feb. 1, 1973	20	49	1.45	56	1.51	60	1.56	65	1.65
June 15, 1974	40	53	1.46	58	1.53	63	1.60	66	1.64
Lime:									
Mar. 19, 1974	40	42	1.34	43	1.36	50	1.44	56	1.51
Sept. 8, 1976	40	45	1.34	58	1.50	53	1.44	61	1.54
Sept. 8, 1976	~0	47	1.37	51	1.41	48	1.38	57	1.49

[a]Using laboratory equipment.

that the wet-bulk densities of limestone FGD wastes ranged from a low of approximately 90.5 lb/ft^3 (1.45 g/cm^3) for settled wastes to a high of 103 lb/ft^3 (1.65 g/cm^3) for vacuum-filtered wastes. Values for lime FGD wastes were approximately 7 percent less than for limestone wastes.

Figure 4 presents load-bearing strengths of untreated FGD wastes—including gypsum—as a function of moisture, fly ash content, and waste origin (power plant, type of absorbent). Among other considerations, the data highlight the criticality of solids content on the load-bearing strength of untreated wastes. Solids content is particularly important in the disposal of slurried gypsum, gypsum filter cake, and untreated wastes that are underdrained because these types of disposal depend on dewatering to attain a desired material-bearing strength. The data indicate that these wastes may

Chemically treated Site C, which sheds water after conversion to a runoff configuration



Legend:
- Carbide lime absorbent
- Soda ash absorbent, double alkali
- Lime absorbent
- Limestone absorbent
- Limestone absorbent (extrapolated)

Curve	Power plant	Absorbent	Fly ash (% solids by dry weight)	Sampling date
a.	Paddy's Run	Carbide lime	12	July 1976
b.	Scholz	Soda ash, double alkali	<1	June 20, 1976
c.	Scholz	Soda ash, double alkali	30	June 27, 1976
d.	Shawnee	Lime	<1	Sept. 8, 1976
e.	Shawnee	Limestone	<1	Nov. 30, 1976
f	Shawnee	Lime	40	Sept. 8, 1976
g.	RTP[a]	Limestone	<1	Dec. 4, 1975
h.	Gadsby	Soda ash, double alkali	9	Aug. 9, 1974
i	Shawnee	Limestone	40	Nov. 30, 1976
j	Phillips	Lime	60	June 17, 1974
k.	RTP[a]	Limestone	40	Sept. 30, 1975
l	Shawnee[b]	Limestone	<1	Sept. 1977
m	Cholla	Limestone	59	Apr. 1, 1974
n.	Shawnee[c]	Limestone	<1	May 2, 1979

[a]Gypsum, contains 5% sulfite.

[b]Gypsum slurry.

[c]Gypsum cake with 13% unreacted calcium carbonate.

Figure 4.

Load-Bearing Strength as a Function of Moisture, Fly Ash Content, and Waste Origin 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 4 also illustrates the effect of the absorbent and fly ash on dewatering characteristics. Limestone FGD wastes are capable of being dewatered to higher solids contents, whereas lime wastes yield a higher load-bearing strength at lower solids contents. The presence of fly ash enhances dewatering in both wastes; however, for any specific solids content of a given waste, the load-bearing strength is less with fly ash than without.

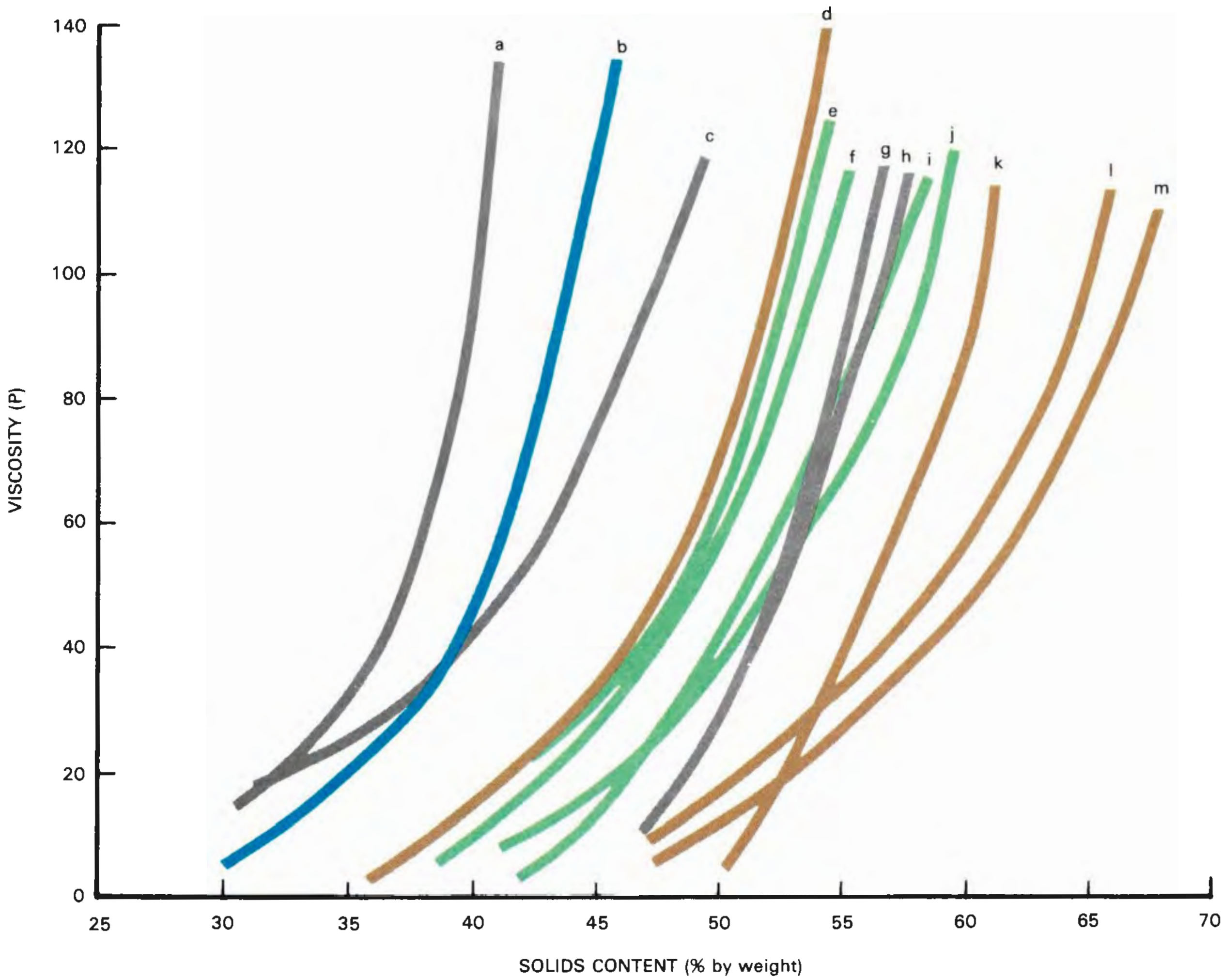
The permeability coefficient of untreated wastes (lime and limestone) containing fly ash is approximately 8×10^{-5} in/s (2×10^{-4} cm/s), which is comparable to typical values of 4×10^{-5} in/s (10^{-4} cm/s) for silty sand.

Typical condition of chemically treated Site B, in which supernate covers 3 ft of stabilized FGD waste

The viscosity of an FGD waste indicates its pumpability, which could affect both the mode and cost of transport. The results of viscosity tests for various untreated wastes define dewatering limits for certain waste materials if they are to be pumped. The tests also show that easily pumpable mixtures [less than 20 P (2 Pa·s)] range from a high solids content of approximately 55 percent by weight to a low of 30 percent by weight, depending on waste origin, absorbent, and ash content (see Figure 5). This figure also shows that FGD wastes of a given type are more pumpable if they contain fly ash. For example, Shawnee limestone waste with ash is pumpable [less than 20 P (2 Pa·s)] at a solids content up to 52 percent, whereas Shawnee limestone waste without ash is pumpable at 42 percent. Of those tested, the most difficult to pump would be the GM Parma and Utah Power and Light double alkali wastes and the Louisville Gas and Electric carbide lime wastes, all of which contain low percentages of fly ash and are pumpable only up to solids contents of 32 to 35 percent.

Underdrained Pond Disposal. An underdrainage system at the disposal site can collect all seepage for return to the scrubber system, thus maintaining control of leachate during the fill period. Underdrainage also enhances dewatering, which results in a material that can support personnel and construction equipment. This type of disposal requires an earthen cap that is contoured and maintained to shed water after disposal site closure.

Sites F and G and the initial phase of Site H are ponds containing untreated FGD wastes deposited in an underdrained impoundment. Perforated plastic pipes are imbedded in pea gravel under the 1-ft- (0.3-m-) thick sand layer at the base of each impoundment. Leachate that seeped through the waste is fed by the plastic pipes through a gravity drain system to a sump. Water is pumped from the sump to remove all seepage. At an operational site, the underdrainage (and all unevaporated rainfall on the disposal pond) would be recycled to the scrubber, thereby reducing the normal amount of fresh makeup water. Recycling would increase the concentration of soluble salts (i.e., chloride) in



Legend:
- Soda ash absorbent, double alkali
- Carbide lime absorbent
- Limestone absorbent
- Lime absorbent

Curve	Power plant	Absorbent	Fly ash (% solids by dry weight)	Sampling date
a.	Parma	Soda ash, double alkali	7	July 18, 1974
b.	Paddy's Run	Carbide lime	12	July 1976
c.	Gadsby	Soda ash, double alkali	9	Aug. 9, 1974
d.	Shawnee	Limestone	<1	Sept. 28, 1976
e.	Shawnee	Lime	<1	Sept. 8, 1976
f	Shawnee	Lime	40	Mar. 19, 1974
g.	Scholz	Soda ash, double alkali	<1	June 20, 1976
h.	Scholz	Soda ash, double alkali	30	June 27, 1976
i	Shawnee	Lime	40	Sept. 8, 1976
j	Phillips	Lime	60	June 17, 1974
k.	Shawnee	Limestone	20	Feb. 1, 1973
l	Shawnee	Limestone	40	June 15, 1974
m	Shawnee	Limestone	41	July 11, 1973

Figure 5.

Viscosity of Untreated FGD Wastes

Untreated underdrained Site G supporting personnel during filling operation

the scrubber loop. Approximate scrubber design considerations may be necessary in some instances of high chloride content.

A low hydrostatic pressure exists at the pond/subsoil interface because the hydraulic head is interrupted at the porous base and the system is vented to the atmosphere. For example, if the subsoil coefficient of permeability were 4×10^{-7} in/s (10^{-6} cm/s), the penetration with underdrainage would be 14 in/yr (36 cm/yr) only in the vicinity of the trenches holding the drainage pipes. These pipes may be approximately 100 ft (30 m) 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 pond. By comparison, the subsoil seepage from a similar, nondrained pond would be about 6 ft/yr (1.8 m/yr) from the entire pond bottom. Considering the depth of seepage and the pond base area contributing to the seepage, the underdrained pond would release about 0.4 percent as much water as the nondrained pond. Additionally, the underdrained pond would be closed, capped, and reclaimed, thereby preventing future seepage.

Underdrainage enhances dewatering of the material by removing the occluded water, which causes additional settling and results in an untreated material with very high bearing capacities when contained in an impoundment (see Table 4). The highly porous base material facilitates rapid draining at Sites F, G, and H, which supported personnel during the pouring operation in which all input material was thixotropic. The ponds containing lime FGD waste (Site G) and gypsum (Site H) supported wheeled vehicles within 1 day after waste placement, whereas the limestone waste pond (Site F)—the weaker of the three—did not drain as rapidly but still attained high bearing strength within 1 week after filling.

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 local clay. This clay cap, which was contoured and planted with grass so that its surface would shed rainwater, was approximately 3 ft (0.9 m) thick at the centerline and 2 ft (0.6 m) thick at the edges. In the spring of 1979, the clay cap was flattened to a constant thickness of 2 ft (0.6 m) for a separate TVA project that included an experimental planting of young trees.

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

Force-Oxidized Waste

The oxidation of FGD wastes to gypsum results in a material that is readily dewatered by vacuum filtration or by centrifuging to a solids content in the range of 75 to 85 percent by weight. When stacked above grade, filter cake may crack under freeze-thaw or wet-dry cycling, thereby allowing the entry of rainwater. Additionally, it may erode when exposed to rainfall and produce a runoff containing high concentrations of dissolved solids. 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.

The disposal of slurried gypsum that is allowed to drain or settle in an impoundment (e.g., the base of Site H) produces a structurally stable material. Operationally, excess moisture would have to be decanted or underdrained and returned to the scrubber. Stacking of settled gypsum slurry may be superior to the stacking of filter cake, but this procedure has not yet been evaluated at the Shawnee site.

Sites J, K, and the stacked portion of Site H contain limestone scrubbing FGD wastes that were force-oxidized to gypsum and filtered. (The evaluation of the lower portion of Site H, which contains clarifier underflow slurry, was discussed in the preceding subsection on underdrained pond disposal.) Input

Gypsum filter cake stacked on the upper portion of Site H

conditions are presented in Tables 1, 2, and 3. The composition of these filter cake materials represents a range of oxidation, with unreacted limestone concentrations at 1, 13, and 25 percent by dry weight for Sites J, H, and K, respectively. Tests at these sites determined the impact of stacking FGD gypsum on the ground. Observations have been made of erosion, runoff water quality, surface crust formation, crust bearing strength, and strength loss when moisture content is increased.

Chemical analyses have been made of leachate collected in the underdrainage system and of runoff samples from Site H. The analysis of underdrainage is similar to that of an untreated FGD waste leachate shown in Figure 3. The TDS concentrations in both underdrainage and runoff samples decrease with time. The runoff has a TDS slightly in excess of 2,000 mg/l and a TSS that ranges between 4 and 300 mg/l, indicating the need to control runoff in this type of disposal to prevent seepage into underground supplies of drinking water or direct discharge into streams.

At Sites H and J, FGD gypsum filter cake was stacked so that a natural slope occurred with a conical shape, producing a surface of about 35° to the horizontal. It is likely that erosion would be a problem with disposal of FGD gypsum in this manner. For example, at Site H, after 18 months of weathering, approximately 20 percent of the mass flowed to the base, producing a slope of about 45°. At Site J, which was stacked the following year, the same erosion pattern is developing.

Several tests were made with a D-8 Caterpillar tractor at Site J to determine the maximal 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° to the horizontal. After approximately six passes over the same spot, the material became so moist that it could not support personnel.

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 2 in (5 cm) near the peak to 5 in (13 cm) at midheight, and 11 in (28 cm) at the base. Bearing capacities of the crust varied from 60 lb/in^2 (414 kPa) near the peak to 450 lb/in^2 (3,103 kPa) near the base. The crust, however, absorbs water and, during periods of continued rainfall, reverts to a material characteristic of the original FGD gypsum filter cake. When water is allowed to collect, the gypsum increases in moisture content and approaches a slurried condition.

Two sets of FGD gypsum samples were obtained from the pilot FGD scrubber at EPA's Industrial Environmental Research Laboratory

Gypsum filter cake at Site J, which shows signs of slumping and erosion 6 mo after placement

at Research Triangle Park. After filtration, one set of samples that was completely oxidized exhibited substantially higher unconfined compressive strength [60 lb/in^2 (414 kPa)] than the other set [20 to 25 lb/in^2 (138 to 172 kPa)], which contained about 5 percent sulfite. The unconfined compressive strength of the samples containing about 5 percent calcium sulfite was approximately equal to that of an FGD waste that is predominantly calcium sulfite. Also, the addition of fly ash had little effect on any of these samples.

Typical wet-bulk densities for gypsum filter cake with 80 percent solids content are between 81 and 87 lb/ft^3 (1.3 and 1.4 g/cm^3). For the Shawnee gypsum clarifier underflow that is saturated and settled in the impoundment beneath the Site H filter cake pile (see Table 1), the wet-bulk density is approximately 106 lb/ft^3 (1.7 g/cm^3).

3. FGD Waste Disposal Costs

Periodic cost estimates are made for FGD waste disposal by various methods related to the type of disposal evaluation being conducted at Shawnee. The cost estimates for the disposal methods given in Table 7 are based on the conditions summarized in Table 8. The costs, given in mid-1980 dollars, are engineering estimates that are typical for each type of disposal. Cost-effective and environmentally sound disposal methods—namely, chemical treatment, untreated with underdrainage, and gypsum with an indigenous liner and surface drainage—cost between 1.05 and 1.25 mills/kWh.

The disposal cost of chemically treated waste is an average of costs derived from data provided by the three treatment contractors who participated in the Shawnee project. This average was updated to current conditions.

For the indigenous liner case, a soil permeability coefficient of 4×10^{-8} in/s (10^{-7} cm/s) 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 if a synthetic liner must be added. The estimated installed cost of a synthetic liner is $5/yd^2.

For the underdrained pond, a seepage model (with replenishment) based on Darcy's Law was created to derive pipe spacing relationships with various sand bed depths for installation beneath a disposal pond. Using a layer of sand 1 ft (0.3 m) thick and following the requirements of a theoretical water level in the drain of zero, the maximal spacing between drains in a

The underdrainage system, which drains seepage from the bottom of the pond and promotes dewatering of the waste (pipes may be spaced 100 ft or more in an operational site)

Table 7.

Disposal Cost Estimates

Disposal method	Cost estimate		
	mills/kWh	Waste, dry ($/short ton)	Coal ($/short ton)
Chemically treated waste landfill	1.25	11.85	3.60
Untreated waste pond:			
Indigenous liner	0.65	5.90	1.75
Synthetic liner	1.40	12.50	3.80
Underdrained	1.05	9.40	2.85
Force-oxidized waste with surface drainage:			
Indigenous liner	1.20	10.20	3.15
Synthetic liner	1.75	15.05	4.65

Note.—Mid-1980 cost basis. All waste includes ash.

Table 8.

Summary of Base Conditions

Item	Base condition
Cost basis	Mid-1980 dollars
Plant characteristics	Two 500-MWe units burning coal at 9,000 Btu/kWh
Coal burned	3.5% sulfur; 12,000 Btu/lb; 14% ash
Annual operating hours	4,250 h, with 48.5% capacity factor for 30-yr life (average)
Plant disposal site lifetime	30 yr
Sulfur dioxide removal	90%
Waste generated:	
Untreated limestone pond (settled to 50% solids)	4.8×10^5 short tons/yr, dry
Force-oxidized slurry (settled to 65% solids)	4.9×10^5 short tons/yr, dry
Limestone utilization:	
Untreated waste	80%
Force-oxidized waste	100%
Annual capital charges, 30-yr average	17%
Cost of land used for disposal	$5,000/acre
Disposal site location	Within 1 mi of plant
Total disposal area requirements (including berm requirements) for a 30-ft waste depth:	
Chemically treated waste (lime/fly ash additive)	480 acres
Untreated waste	540 acres
Force-oxidized waste	440 acres

horizontal base was found to be 133 ft (41 m). A pond designed for a minimal sand bed depth is the lowest cost design for this type of disposal. Ten 50-acre (20-ha) ponds are required for this disposal mode according to the baseline conditions in Table 8. The cost of the underdrainage components, including sand, gravel, pipes, and fittings, is approximately 20 percent of the total capital cost.

In the disposal of force-oxidized FGD waste, it was assumed that a 15-percent slurry is pumped to the site where it settles to 65 percent solids and the supernatant water is recycled. The cost of the oxidation equipment is included as part of the disposal costs.

This report was prepared jointly by The Aerospace Corporation of Los Angeles CA and the Centec Corporation of Reston VA for the U.S. Environmental Protection Agency. Paul R. Hurt, Paul P. Leo, Jerome Rossoff, and Jack R. Witz of Aerospace are the principal investigators. Photographs were provided by The Aerospace Corporation. Julian W. Jones is the EPA Project Officer.

Comments on or questions about this report or requests for information regarding the disposal of flue gas desulfurization wastes should be addressed to:

Emissions/Effluent Technology Branch
Utilities and Industrial Power Division
Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency (MD 61)
Research Triangle Park NC 27711

COVER PHOTOGRAPH: Untreated FGD waste disposal evaluation pond at Shawnee showing coring locations, access pier, leachate well, and weather station

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