LAND APPLICATION USES FOR DRY FLUE GAS DESULFURIZATION BY-PRODUCTS

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**DRAVO LIME COMPANY
THE OHIO STATE UNIVERSITY**

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Land Application Uses for Dry Flue Gas Desulfurization By-Products

Executive Summary January, 1999

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INTRODUCTION

Flue gas desulfurization (FGD) scrubbing technologies create several types of by-products. This project focused primarily on by-product materials obtained from what are commonly called “dry scrubbers” which produce a dry, solid material consisting of excess sorbent, reaction product that contains sulfate and sulfite, and coal fly ash. Prior to this project, dry FGD by-products were generally treated as solid wastes and disposed in landfills. However, landfill sites are becoming scarce and tipping fees are constantly increasing. The major objective of this project was to develop beneficial uses, via recycling, capable of providing economic benefits to both the producer and the end user of the FGD by-product. It is equally important, however, that the environmental impacts be carefully assessed so that the new uses developed are not only technically feasible but socially acceptable.

A study titled “Land Application Uses for Dry Flue Gas Desulfurization By-Products” was initiated in December, 1990 to develop and demonstrate large volume, beneficial uses of FGD by-products. The Phase 1 and Phase 2 reports have been published by the Electric Power Research Institute (EPRI), Palo Alto, CA. The Phase 3 report is being formatted for publication at a later date. This Executive Summary provides an overview of all three reports and summarizes the most important findings of the study.

Specific objectives developed for this project were derived over an 18-month period during extensive discussions with personnel from industry, regulatory agencies and research institutions. These were stated as follows:

- Objective 1. To characterize the material generated by dry FGD processes.
- Objective 2. To demonstrate the utilization of dry FGD by-product as a soil amendment on agricultural lands and on abandoned and active surface coal mines in Ohio.
- Objective 3. To demonstrate the use of dry FGD by-product as an engineering material for soil stabilization.
- Objective 4. To determine the quantities of dry FGD by-product that can be utilized in each of these applications.

Objective 5. To determine the environmental and economic impacts of utilizing the material.

Objective 6. To calibrate environmental, engineering, and economic models that can be used to determine the applicability and costs of utilizing these processes at other sites.

The focus and objectives of the project evolved slightly with time to include some work with wet FGD by-product materials.

This study was conducted at The Ohio State University main campus (Columbus), at The Ohio Agricultural Research and Development Center (Wooster), at The Ohio State University Branch stations, at field-scale active and abandoned coal mine sites and at various other sites in Ohio.

Readers who are interested in obtaining details of any portion of this study are encouraged to obtain the Phase reports from the Electric Power Research Institute (see citations at the back of this Executive Summary). Each Phase report includes a list of additional references of papers derived from this project that have been published as symposium proceedings and technical journal articles.

CHARACTERIZATION OF MATERIALS

A total of 58 dry FGD samples were collected for analyses of chemical, physical, mineralogical and engineering properties during Phase 1. Written quality assurance/quality control procedures were developed and followed for each step of the sampling and analyses. The samples were collected from 13 sources representing nine dry FGD processes. These nine processes are representative of the four dry FGD technologies described below. In addition, other types of dry FGD by-products collected from various places in the scrubbing process, and thus not totally representative of actual end-product, were collected and analyzed. During Phase 2, we also began studies on wet FGD samples.

Duct Injection. Sorbent (hydrated lime) is injected into the flue gas as it enters an humidification chamber in the ductwork downstream of the boiler and air heater. The sorbent reacts with the sulfur dioxide gas and a dry FGD by-product is formed that is removed from the flue gas stream in a baghouse or electrostatic precipitator. This by-product contains the reaction products, fly ash and unspent sorbent. In most configurations, recycling and reinjection of the FGD by-product with fresh hydrated lime is a option to reduce requirement for fresh sorbent.

Lime Injection Multistage Burner (LIMB). In the LIMB process, a calcium-based sorbent is injected into the boiler where it calcines to CaO and reacts with sulfur dioxide and oxygen to form calcium sulfate. The reaction product and unspent sorbent are collected with particulate emission control systems.

Fluidized Bed Combustion (FBC). In FBC systems, a calcium-based sorbent (usually limestone or dolomite) and crushed coal are introduced together into the boiler bed where they are “fluidized” or suspended by jets of air. The fluidizing process intimately mixes the coal and sorbent. Two FGD by-products are created—the heavier, granular-bed ash material and the smaller particles suspended in the flue gas which are removed with the particulate emission control systems.

Spray Dryer. Flue gases enter a separate scrubber vessel located downstream of the boiler and air heater where sorbent, usually a slurry of hydrated lime, is injected. The scrubber vessel increases the residence time of the flue gas and therefore lengthens the time period the injected sorbent can react with sulfur dioxide. Reaction products and unspent sorbent are removed together with the fly ash in the particulate emission control systems.

Wet FGD By-Products. Wet FGD by-product materials are created when a mist of hydrated lime slurry is injected into the flue gas downstream from the particulate removal devices. The sulfur dioxide reacts with the lime to primarily form calcium sulfite which is separated from the slurry by a belt filter. The filter cake is then combined with fly ash and 2-3% additional lime to improve the handling characteristics and strength development for landfilling. In some cases, air is forced into the reaction to create a product that is primarily calcium sulfate instead of calcium sulfite.

Analytical results of six dry FGD samples, after first applying the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP) dilute acetic acid extraction method, indicates that these materials are characterized by high pH (Table 1). These high pH values are due to the presence of unspent CaO and Ca(OH)_2 sorbents in the samples. Upon aging and exposure to moisture and atmospheric or soil CO_2 , the CaO and Ca(OH)_2 will carbonate to form calcium carbonate (CaCO_3) and pH will decrease to around 8.3. The relatively high concentrations of total dissolved solids (TDS) and sulfate (SO_4^{2-}) are primarily due to the dissolution of CaSO_4 which is created during the scrubbing process. With one exception (i.e., EDG-LIM-14), sulfite (SO_3^{2-}) was found to be increased only for the duct injection and spray dryer materials where FGD is created under more reducing conditions of low temperature and high relative humidity. The lower total S content in the leachates from the BEV-DUC-02 and OSU-SPD-03 samples is due to the lower solubility of the CaSO_3 , found in these samples, than CaSO_4 which is the dominant sulfur form in the other samples. Concentrations of the eight metals regulated by the Resource Conservation and Recovery Act (RCRA) (Ag, As, Ba, Cd, Cr, Hg, Pb, and Se) were below drinking water standards. Concentrations of other trace metals were also generally low.

The TCLP results reflect the chemical composition of the various FGD samples which is dominated by Ca, S, Al, Fe and Si (Table 2). The data in Table 2 represent the means of the concentrations of all of the FGD samples present within a given sample category. The variability around each mean for a category was, however, sufficiently large as to prohibit any

Table 1. TCLP Acetic Acid Leachate Results for Six Dry FGD By-Product Materials^a.

Chemical Constituent	BEV-DUC-02	OSU-SPD-03	EDG-LIM-14	TID-FLB-03	TID-FLB-04	GMC-FLB-03
pH	11.95	11.98	12.01	9.58	9.61	12.12
	-----mg/L-----					
TDS ^b	11,840	12,050	13,790	12,870	11,980	13,670
Ag	<0.024	<0.024	<0.024	<0.024	<0.024	<0.024
Al	0.20	0.20	0.20	0.12	0.14	0.22
As	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	2.17	4.67	3.46	0.767	0.543	9.03
Ba	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Be	0.159	0.348	0.250	0.141	0.141	0.693
Ca	3,130	3,220	3,860	1,380	1,740	3,690
Cd	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Co	<0.014	0.016	0.017	0.026	0.017	<0.014
Cr	0.028	0.009	0.007	0.011	<0.005	<0.005
Cu	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013
Fe	<0.029	<0.029	<0.029	<0.029	<0.029	<0.029
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
K	3.5	22.1	1.3	21.1	3.0	1.5
Li	0.15	0.09	0.04	0.18	0.07	0.04
Mg	<0.04	0.05	0.07	1,360	882	0.21
Mn	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mo	0.059	0.088	0.103	0.025	0.031	0.208
Na	4.86	3.64	1.32	9.82	1.67	2.62
Ni	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P	<0.12	<0.12	<0.12	<0.12	<0.12	<0.12
Pb	0.001	0.017	0.005	<0.001	<0.001	0.002
S	132	206	582	979	737	492
Sb	<0.24	<0.24	<0.24	<0.24	<0.24	<0.24
Se	0.004	0.004	0.005	<0.001	0.001	0.005
Si	0.10	0.14	0.10	0.33	0.31	0.25
Sr	3.38	2.96	2.55	1.21	0.83	1.33
V	0.022	<0.019	0.021	0.022	0.024	0.056
Zn	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Cl ⁻	43.6	45.5	67.8	19.6	28.5	38.0
SO ₃ ²⁻	41.6	23.4	43.2	<1.0	<1.0	<1.0
SO ₄ ²⁻	236	460	1,460	2,800	2,270	1,430

^aBEV-DUC-02 (duct injection sample), OSU-SPD-03 (spray dryer sample), EDG-LIM-14 (LIMB sample), TID-FLB-03 (fluidized bed combustion cyclone ash sample), TID-FLB-04 (fluidized bed combustion bed ash sample), and GMC-FLB-03 (fluidized bed combustion bed and cyclone mixture ash sample).

^bTDS, total dissolved solids.

Table 2. Mean Total Element Content in Dry FGD By-Product Materials.

Source of Samples	Number of Samples in Mean	Total Element Content								Total Element Content			
		Al	Ba	Ca	Fe	K	Mg	S	Si	As	B	Be	Cd
		----- Weight % -----								----- mg/kg -----			
Spray Dryer	13	3.1	0.03	27.8	2.9	0.32	1.82	11.3	5.0	44.1	418	4.0	4.9
Duct Injection	7	5.8	0.02	24.3	5.5	0.76	0.59	7.1	10.8	67.0	240	5.3	2.1
LIMB	12	6.6	0.03	18.9	6.8	0.91	4.61	4.3	11.4	186	374	10.8	2.1
FBD- Bed Ash	6	1.3	0.01	31.2	1.6	0.12	9.18	10.3	2.5	74.7	145	1.6	2.3
FBC - Cyclone Ash	10	4.0	0.02	21.0	5.5	0.65	4.08	5.3	12.1	63.6	280	5.5	3.1
Other	7	7.4	0.02	12.2	11.0	0.88	1.96	5.8	13.9	57.3	319	15.1	1.7

Table 2 (continued). Mean Total Element Content in Dry FGD By-Product Materials.

Source of Samples	Number of Samples in Mean	Total Element Content												
		Co	Cr	Cu	Li	Mn	Mo	Ni	P	Pb	Se	Sr	V	Zn
		----- mg/kg -----												
Spray Dryer	13	14.2	28.4	30.8	33.5	127	12.2	29.0	437	38.4	10.1	565	52.3	108
Duct Injection	7	27.0	49.2	39.8	82.1	133	13.3	52.5	220	29.4	12.7	367	89.0	124
LIMB	12	45.6	53.1	48.3	57.4	176	25.5	80.6	601	59.2	15.2	528	108	208
FBD- Bed Ash	6	8.9	16.9	177	11.4	207	8.6	33.0	141	11.3	3.6	308	15.0	119
FBC - Cyclone Ash	10	20.6	39.0	36.4	33.1	206	9.2	51.5	302	33.4	6.7	342	68.8	111
Other	7	40.9	76.6	251	84.7	171	15.1	71.0	297	30.4	8.1	321	122	163

observation of a specific technology discriminating for or against a specific chemical element. Apparently the variation within the composition of the inputs (coal or sorbent materials) and within the operating conditions of each coal-fired facility was greater than any specific effect of scrubbing technology. The one exception to this general statement was the element B, which decreased in concentration in the FGD by-products in the order spray dryer > LIMB > cyclone ash from fluidized bed combustion > duct injection > bed ash from fluidized bed combustion.

Mineral composition of the various FGD samples varied according to the technology used during the combustion of coal and scrubbing of sulfur dioxide from the flue gases (Table 3). Fly ash was a significant component in all samples and CaCO_3 was also found in all samples. The weight percent of fly ash and CaCO_3 , however, was highly variable. Periclase and dolomite was found in samples where dolomitic limestone was used as a source of sorbent. No attempt was made to quantify the fly ash mineralogy, but x-ray diffraction analyses of the acid-insoluble residues showed that all were composed of glass, quartz (SiO_2), hematite, (Fe_2O_3), mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), and a magnetic phase with the characteristic properties of partially oxidized magnetite (Fe_3O_4).

Particle size analyses indicated that all fly ash materials were very fine with those from the duct injection, spray dryer and lime injection processes having greater than 80% by weight finer than 0.025 mm effective diameter. The fly ash particles from the fluidized bed combustion process were somewhat coarser and the bed ash materials were, as expected, very coarse averaging 98.6% by weight greater than 0.25 mm effective diameter. Uniformity coefficients were less than 2.4 for all materials except the bed ash materials (which had a coefficient value of 11.8). A uniformity coefficient of less than 2.0 is indicative of a very uniform particle size distribution.

Particle densities from the spray dryer, lime injection and fluidized bed fly ash were similar, ranging from 2.5 to 2.7 g/cm^3 , while those from the duct injection process were somewhat less and the bed ash had somewhat greater particle densities. Specific surface areas were positively related with particle size data and ranged from 1.3 m^2/g for the bed ash materials to approximately 9.4 m^2/g for the duct injection and spray dryer materials.

After compaction at 1.73×10^5 Pa (25 lb/in^2), bulk densities were surprisingly low having values of 0.79, 0.63, 0.91, 1.29 and 1.29 g/cm^3 for the duct injection, spray dryer, lime injection, bed ash and fly ash samples, respectively.

Table 3. Semiquantitative Mineralogy of Various Dry FGD By-Product Materials.

Sample	Fly Ash	Calcite (CaCO ₃)	Lime (CaO)	Portlandite [Ca(OH ₂)]	Anhydrite (CaSO ₄)	CaSO ₃ • 1/2H ₂ O	Dolomite [CaMg(CO ₃) ₂]	Periclase (MgO)	Total
----- % (wt/wt) -----									
BEV-DUC-02	28	9		38		21			96
BEV-DUC-03	23	12		40		24			99
BEV-DUC-05	46	8		10		33			97
BEV-DUC-06	30	4		36		26			96
BEV-DUC-07	46	8		11		29			94
BEV-DUC-08	48	5		5		28			86
OSU-SPD-01	29	33		10		29			101
OSU-SPD-02	18	18		28		31			95
OSU-SPD-03	21	17		29		31			98
OSU-SPD-05	28	15		22		28			93
OSU-SPD-10	12	15		27		44			98
EDG-CLS-1	71	13		5		7			96
EDG-LIM-03	49	22	12	10	11				104
EDG-LIM-04	57	16		4	14			16 ^a	107
EDG-LIM-05	35	15		9	21 ^b			23 ^c	104
EDG-LIM-06	48	10	5	3	21			16	103
EDG-LIM-07	42	14	4	2	24			18	104
EDG-LIM-08	79	7	7	2	7				102
EDG-LIM-09	38	14	10	4	18			21	105

Table 3 (continued). Semiquantitative Mineralogy of Various Dry FGD By-Product Materials.

Sample	Fly Ash	Calcite (CaCO ₃)	Lime (CaO)	Portlandite [Ca(OH) ₂]	Anhydrite (CaSO ₄)	CaSO ₃ • 1/2H ₂ O	Dolomite [CaMg(CO ₃) ₂]	Periclase (MgO)	Total
----- % (wt/wt) -----									
EDG-LIM-10	71	8	6	3	13				101
EDG-LIM-11	51	10	10	5	25				101
EDG-LIM-12	67	9	8	3	15				102
EDG-LIM-13	52	14	11	5	22				104
EDG-LIM-14	30	15	28	5	25				103
TID-FLB-01	33	9			20		31	11	104
TID-FLB-02	10	29	4		36			26	105
TID-FLB-03	32	12			22		25	12	103
TID-FLB-04	10	27	4	1	36			27	105
TID-FLB-05	40	3			46		17	4	110
TID-FLB-06	40	13			22		17	18	110
TID-FLB-07	11	17	6		47			26	107
GMC-FLB-02	49	3	12		31				95
GMC-FLB-03	19	1	21	3	51			7	102

^aIncludes 10% Mg(OH)₂.

^bIncludes 11% CaSO₄•2H₂O.

^cIncludes 19% Mg(OH)₂.

Engineering tests were conducted to determine the suitability of FGD by-products for certain structural or other engineering applications. In these tests, compaction was conducted at various initial water contents. The results (Table 4) indicated that the optimum densities and moisture contents varied among types of materials. For each material, however, the data show that the maximum density is not particularly sensitive to slight variations in the water content in the vicinity of the optimum. Most FGD by-products can be considered light weight materials with compacted densities lower than those of a typical natural soil. Lightweight fills impose smaller loads on the natural soils upon which they are placed, resulting in less settlement in the underlying soils and less likelihood that the loaded soils will fail.

Application of FGD for engineering purposes also depends on both the swelling properties of the material and on the strength that can be achieved when compacted. Swelling primarily occurred in samples containing free lime and occurred in two episodes. The first occurred almost immediately after water addition and is attributed to hydration reactions, e.g. the hydration of lime (CaO) to portlandite [$\text{Ca}(\text{OH})_2$] and that of anhydrite (CaSO_4) to hemihydrate ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$). The second swelling episode usually began after about 10 days and is thought to be due to formation of secondary minerals such as ettringite. The strengths achieved varied when FGD samples were compacted at optimum water content and, in some cases, reached values of 8.97×10^6 Pa (1300 lb/in²) which is almost half the strength of conventional concrete. In general, however, strengths ranged from 3.45×10^5 to 1.66×10^6 Pa (50 to 240 lb/in²) (Table 4). Strengths for samples were found to increase with curing time with values being higher after 28 days than after 10 days.

During Phase 2, work began on characterizing wet FGD as a raw material for engineering applications. The wet FGD samples were collected as either filter cake containing only spent sorbent or a stabilized by-product consisting of spent sorbent, fly ash and additional lime. To reduce the water content, additional fly ash was mixed with the FGD and the mixture air dried for a period of several days. Lime was also sometimes added to the mixture to facilitate the drying process. Eight different mixtures of FGD by-product, ash and lime were created. The relative percentages, on a dry weight basis, of the various constituents of each sample were designated by the following notation:

Mixture No: FGD by-product / Fly ash / Boiler slag / Bottom ash / Lime1 / Lime2

Table 4. Engineering Properties of Various Dry FGD By-Product Materials.

Sample	Calcium Carbonate Equivalency	Available Lime	Optimum Density	Optimum Moisture Content ^a	Unconfined Compressive Strength ^b
	%	%CaO, CaOH	g/cm ³	%	lb/in ²
EDG-CLS-01			1.100	32	410
EDG-LIM-06	61.6	12.3	1.200	43	518
EDG-LIM-07	74.8	12.3	1.120	48	485
EDG-LIM-08	19.7		1.300	28	872
EDG-LIM-09	85.8		1.055	50	267
EDG-LIM-10	22.1		1.069	43	268
EDG-LIM-11	35.0		1.019	50	298
EDG-LIM-12	27.7		1.118	42	202
EDG-LIM-13	42.5		1.042	45	246
EDG-LIM-14	59.4		0.789	40	61
OSU-SPD-01	66.7	13.6	0.909	50	52
OSU-SPD-02	64.5	22.3	0.833	68	71
OSU-SPD-03	64.7	24.1	0.845	63	51
OSU-SPD-11			1.056	40	88
HST-SPD-01	54.2	0.8	0.974	53	55
HST-SPD-03	66.7	7.0	0.881	65	34
HST-SPD-05	53.8	1.7	0.933	50	107
BEV-DUC-05	44.7	9.8	1.132	42	240
BEV-DUC-06	63.3		1.084	40	111
TID-FLB-1(60%):2(40%)			1.807	18	ND ^c
TID-FLB-1(50%):2(50%)			1.815	18	2200
TID-FLB-3(40%):4(60%)			1.830	18	1290
TID-FLB-05			1.359	35	238
TID-FLB-06			1.582	25	1530
PED-RCB-01			1.272	35	1290
BUR-SNR-01			1.146	35	73

^aWeight of water to weight of solids.

^bStrengths were measured after 28 days. To convert to Pa, multiply by 6,900.

^cND, not determined.

where FGD by-product refers to either filter cake or stabilized by-product, Lime1 is the percentage of lime added to the fly ash, boiler slag and/or bottom ash prior to air drying the FGD, and Lime2 is the lime added after the mixture was sufficiently dried and immediately prior to compaction. The results clearly indicate that the strengths of the mixtures are strongly affected by curing time and lime additives (Table 5). Strength gain appears to be relatively uniform with time for all samples treated with at least 5% added lime. No significant gain in strength occurred over time for the stabilized FGD sample to which no additional lime was added prior to strength testing. In those samples where FGD by-product was filter cake, the increase in strength resulting from the addition of Lime2 was substantial.

For FGD to be used in various types of engineering applications in the field, it is imperative to have information on its performance during temperature fluctuations. Several samples of wet FGD were subjected to alternating cycles of freeze-thaw. Material strength after this treatment was strongly dependent on water content with higher water contents at time of freezing yielding the poorest results. However, if the samples were allowed sufficient curing time before freezing, the strengths compared satisfactorily with those obtained for samples not subjected to cyclic temperature changes.

It is also important to understand the chemical reactions that occur when FGD is applied to soil or spoil and the FGD/soil(spoil) mixtures are permitted to weather. Studies were conducted over a 132 day period to evaluate the solution chemistries of two different coal mine spoil materials allowed to react with various concentrations of dry FGD materials (i.e. LIMB, spray dryer, and pressurized fluidized bed cyclone ash materials). The concentrations of various chemical elements and chemical species such as sulfate ions, metal ions, etc. were then entered into a thermodynamic computer model. This model, MINTEQA2, has been rigorously tested and is in common use by soil chemists and geochemists.

The results of applying the MINTEQA2 model to the reaction mixtures of FGD and coal mine spoil are shown in Table 6. Values of the log of solubility indices (SI) > 0 indicate that the sample solutions were supersaturated with respect to the specified mineral, and precipitation of the solid could occur. Values of log SI < 0 indicate undersaturation with respect to the given solid, generally precluding its precipitation. The 132 days of weathering did not allow complete equilibrium to be achieved and a comparison of predicted versus observed mineral phases was not always in agreement. For example, only the LIMB-amended Fleming spoil (40% rate) and the SPD-amended R & F spoil (40% rate) predicted formation of ettringite, but

Table 5. Unconfined Compressive Strengths of Stabilized Wet Conesville FGD By-Product Material.

Sample Mixture ^a	Water Content	Dry Density ^b	Unconfined Compressive Strength after Days Indicated ^c		
			0	7	60
	%	lb/ft ³	lb/in ²		
Mixture 1: 50/50/0/0/0/0	41.0	74.9	33	55	80
Mixture 2: 50/50/0/0/5/0	43.5	70.5	52	118	372
Mixture 3: 50/50/0/0/5/5	39.2	71.2	47	136	418
Mixture 4: 50/50/0/0/0/5	36.0	78.0	28	171	429
Mixture 5: 75/0/25/0/5/5	54.0	67.4	62	89	237
Mixture 6: 75/0/25/0/0/5	52.5	64.0	61	98	160
Mixture 7: 33/33/17/17/5/5	26.0	87.2	60	154	472
Mixture 8: 33/33/17/17/0/5	32.7	83.0	51	132	365

^aMixture No: Weight ratio of FGD by-product / Fly ash / Boiler slag / Bottom ash / Lime1 / Lime2 where FGD by-product refers to either filter cake or stabilized by-product.

^bTo convert to kg/m³, multiply by 16.0

^cTo convert to Pa, multiply by 6,900.

Table 6. Values of Log Solubility Indices (SI) for Selected Solids after 132 Days of Reaction of Minespoil/FGD By-Product Mixtures.

Sample	Anhydrite	Brucite	Calcite	Dolomite	Ettringite	Gypsum	Lime	Periclase	Portlandite
Fleming Spoil	-3.75	-14.22	-10.58	-21.16	-61.52	-3.54	-10.99	-8.24	-20.05
Flem-LIM(10%)	-0.67	-4.12	-1.08	-3.80	-11.98	-0.46	-18.42	-8.83	-8.30
Flem-LIM(40%)	-0.82	-2.97	0.18	-7.91	4.2	-0.61	-10.65	-7.68	-0.53
Flem-SPD(10%)	-0.06	-3.87	-0.96	-3.37	-18.44	0.15	-18.37	-8.59	-8.24
Flem-SPD(40%)	-1.11	-3.39	0.24	-7.91	-6.53	-0.90	-10.96	-8.11	-0.84
Flem-PFBC(10%)	-2.31	-3.68	-2.09	-4.02	-19.79	-2.10	-19.78	-8.39	-9.66
Flem-PFBC(40%)	-0.14	-4.15	-1.73	-3.73	-12.69	0.07	-19.85	-8.87	-9.72
R&F spoil	-1.69	-6.41	-3.33	-6.79	-22.78	-1.48	-22.24	-11.13	-12.12
R&F-LIM(10%)	-0.80	-1.78	0.03	-2.79	-3.45	-0.59	-14.89	-6.50	-4.77
R&F-LIM(10%)	-0.34	-2.62	0.21	-8.32	-2.07	-0.13	-9.83	-7.34	0.29
R&F-SPD(10%)	-1.36	-1.46	-0.09	-2.17	-8.10	-1.15	-15.44	-6.18	-5.32
R&F-SPD(40%)	-1.84	-2.71	0.20	-8.12	3.08	-1.63	-10.14	-7.43	-0.02
R&F-PFBC(10%)	-2.29	-3.44	-2.18	-3.98	-29.08	-2.08	-19.78	-8.16	-9.66
R&F-PFBC(40%)	-0.03	-2.22	-0.51	-1.85	-16.25	0.18	-17.34	-6.94	-7.22

formation of this mineral was observed in other samples as well. Formation of ettringite is an important reaction because it consumes large amounts of water, results in volume expansion, creates strength, and is involved in controlling solution chemistry at high pH.

Figure 1 provides an illustration of the needle-like structure of ettringite crystals that formed after 132 days of weathering reaction in the Fleming spoil treated with 40% LIMB by-product. In a separate experiment, a synthetic ettringite was prepared and allowed to react in water that had been adjusted to different pH values by adding HCl. The solution chemistries were then analyzed and the data used to create mineral stability diagrams. The mineral stability diagram (Figure 2) indicates that ettringite is stable at high pH (above approximately 10). Below this pH, if concentrations in solution of the different elements that make up ettringite change, the ettringite will begin to break down. In situations where basically pure FGD or FGD in large amounts are used in a restricted volume of space, the dissolution reactions can only take place at the surface of the FGD and the ettringite will remain stable.

For agricultural uses, FGD is applied to soil at much lower rates than when used for construction (engineering) purposes. Formation of ettringite will probably not occur and any ettringite that might form would not remain stable.

Figure 1. Scanning electron microscope photomicrograph of needle-like ettringite crystals in Fleming spoil containing LIMB by-product (40 wt %) after 132 days of reaction.

Figure 2. Mineral stability diagram for the Ca-Al-SO₄-H₂O system. Open circles are experimental data points and the solid line with arrows represents the reaction path predicted using EQ3/6. Estimated Al³⁺ activity values obtained from the literature for flyash (▼), acid mine spoil (■), and laboratory incubations involving flyash (◆) and FGD (▲) are also plotted.

FIELD TRIALS

FGD Stockpile Study

The use of an FGD by-product in construction, land application or other large volume uses will require delivery of large amounts of FGD to the job site in a short period of time. To ensure timely delivery of material, it may be necessary to temporarily stockpile or store material. The aging and weathering of this material during exposed storage may alter the chemical, mineralogical and engineering properties of the FGD. To study these processes a 1,500 ton stockpile of LIMB by-product was constructed at Central Fuel Company, New Philadelphia, OH in July 1991.

The LIMB by-product was conditioned with water at the power plant while being loaded into trucks to an approximate water content of 40 to 50%. The water content of the material that actually was placed in the stockpile was 17% and this decrease is due to hydration of lime (CaO) and anhydrite (CaSO_4) which removes the free water. Dimensions of the stockpile were 20 m by 30 m by 3 m high. Prior to constructing the stockpile, provisions were made to collect any water that percolated through or ran off the surface of the stockpile. Samples of water and LIMB material from the pile were collected over a 30 month period and some of the results are shown in Table 7.

During the time of exposure to climatic elements, the water content of the FGD increased from 17% to about 60% in the top 5 cm of the pile and to about 50% at 30-50 cm depth. Part of this continuing hydration reaction seemed to be due to formation of ettringite which contains 32 molecules of water. This formation was confirmed using x-ray diffraction analyses. Hydration reactions stabilized the surface by forming a crust firm enough to walk on. This crust also prevented movement of airborne particulates even during dry periods. The crust was permeable as little runoff occurred throughout the monitoring period, in spite of some intense rains.

Analyses of runoff water indicated a pH of 7.0 to 7.6. This is due to reaction of CO_2 with the lime and anhydrite to form CaCO_3 . This reaction is quite rapid. Other water quality parameters were measured and indicated concentrations of regulated metals were below drinking water standards. There appears to be limited potential that any adverse impact on air, water or soil

Table 7. Properties of LIMB By-Product after Various Periods of Aging in an Exposed Stockpile.

Sample	cm	Moisture Content	Free CaO	Calcium Carbonate Equivalency	Particle Density	Permeability	Bulk Density ^a
		%	%	% CaCO ₃	g/cm ³	cm/sec	lb/ft ³
<u>3 months</u>							
STO-01	0.5	25			1.24		
	50	33					
STO-02	0-70	10					
	70	12					
<u>6 months</u>							
STO-03	0-15	43					
STO-04	0-15	73					
STO-05	0-5	70	12.4	51			
	15	49	1.2	49			
<u>9 months</u>							
STO-06	150	62			0.70	1.4x10 ⁻⁴	
STO-07	0		1.6	29.6	0.98	4.9x10 ⁻⁶	
	90	47	7.7	34.3		(compacted)	
	150		19.1	50.5			
STO-08	30	19			0.66		
<u>18 months</u>							
STO-09	0-5	62					
	30	102	6.5	22.2	0.6	4.0x10 ⁻⁴	58.6
<u>30 months</u>							
STO-10	0-5	62			0.6		
	30-50	52	2.0	26	0.5		

^aTo convert to kg/m³, multiply by 16.0

quality would occur during short-term stockpiling of LIMB by-product or other similar types of FGD.

FGD Use as a Soil Stabilizer and for Construction Uses

Field projects were conducted to test the use of FGD as a soil stabilizer and to create farm feedlot surfaces that could improve animal production. The humid climate of Ohio often results in muddy farm conditions causing poor animal productivity. There are few economically viable remedies currently available to overcome this problem. In one project, a feedlot pad was constructed by blending dry PFBC material into the top 20 cm of in-place soil and compacting. This procedure created a suitable platform for the placement of an additional 20 cm to 30 cm layer of blended cyclone and bed ash of the PFBC material. Based on laboratory results and the field observations from the PFBC feedlot, two additional 1200 m² pads were constructed for hay bale storage using wet FGD by-product material. To achieve the required densities and strengths, an additional 5% to 10% of lime was added at the job site prior to compaction.

Equipment used to blend water or lime into the PFBC by-product and to compact the moistened material was not ideal. As a result, non-uniformity of the mixed materials occurred as they were placed. The feedlot base was constructed in November of 1992. The laboratory compressive strengths measured on samples of FGD by-product recovered from the feedlots in 1993 showed considerable variability (Table 8). However, strengths of the samples were, in general, sufficient for good pad performance in the feedlot and hay storage area. Further work has been conducted to improve material handling so that the FGD can be applied and compacted at near optimum moisture and density. This has created much more uniform end products with improved performances.

Two field projects were developed using FGD by-products for road repair. The location of these field sites is shown in Figure 3. The FGD materials chosen for both projects was PFBC by-product obtained from American Electric Power's Tidd plant located near Brilliant, OH.

Ohio State Route 541, located near Coshocton, required repair along a 1000 foot portion of the highway. Repair crews began excavating in late autumn and uncovered a spring that was contributing to the slide. After removing poor quality material and redirecting water flow, the replacement of the embankment material commenced. A geotextile filter and a perforated PVC drainage line were placed at the base of the hillside. FGD, which had been stockpiled at the

Table 8. Test Results for the EORDC Feedlot and Hay Bale Test Pad Samples.

Sample No.	Date Sampled	Water Content	Density	Unconfined Compressive Strength ^a	Height to Diameter Ratio of Sample
		%	g/cm ³	lb/in ²	
3A	9/20/93	61.4	1.62	276	2.11
5A	9/20/93	57.1	1.56	277	2.09
2B	10/6/93	52.1	1.65	348	2.14
1C	10/29/93	51.8	1.67	238	1.72
4C	10/29/93	50.9	1.71	192	1.67
6C	10/29/93	53.5	1.57	89	1.98
9C	10/29/93	53.6	1.53	85	1.67
10C	10/29/93	65.8	1.54	58	1.59
7D	11/18/93	58.3	1.60	50	1.17
1G	12/28/93	31.3	1.79	9	2.17
4G	12/28/93	68.9	1.52	75	1.85
5G	12/28/93	76.8	1.40	22	1.64
6G	12/28/93	29.3	1.86	212	1.48
7G	12/28/93	60.1	1.49	30	1.66

^aTo convert to Pa, multiply by 16.0.

Figure 3. Location of road repair field study sites in Coshocton County (State Route 541) and Noble County (State Route 83).

site, was placed in an area 12 m by 30 m to a thickness of about 4 to 5 m. Thickness lifts were not carefully monitored and water content added was thought to exceed the amount considered optimum as determined by laboratory tests. A second layer of FGD was added near the surface and was 1 m thick, 10 m wide and 20 m long and the top of this layer was located 5 m below the road surface. After bringing the surface back to original grade, FGD was used as a road base and the road was used for traffic for several months before final paving occurred in the spring. Before and after embankment configurations are shown in Figure 4.

The second road repair project was on Ohio State Route 83 located in Noble County just south of the village of Cumberland. The failed portion was an embankment 15 m high and 1000 m long. The repair was completed in three stages. The first stage consisted of the excavation of the failed material from the slip and road. Additional material was removed from the upslope slide of the roadway to form a trench 2.5 m deep and fabric drain board was installed against the natural hillside to intercept water before it could reach the FGD. Drain lines were placed in the bottom of the trench to carry the water away. The trench was backfilled with compacted FGD to form a key (Figure 5). When construction of the key was completed, the embankment was divided into four study zones. In two of the zones, the reconstructed embankment was repaired using standard procedures for replacing and recompacting soil. Between these two control sections, a section consisting of a layer of FGD similar to that at State Route 541 was placed. In a fourth section the FGD was mixed with the soil that had been removed from the slide and stockpiled. This fourth section was developed to test whether FGD could be used to effectively improve the mechanical properties of *in-situ* soil. The FGD sections were constructed in lifts of 30 to 60 cm at a water content close to optimum.

Piezometers and slope indicators were installed in the test sections at both the State Route 541 site and the State Route 83 site. Both repairs are performing as expected with no movement being detected at all at State Route 541 and some movement at State Route 83 which appears to be due to inadequate drainage. Water collected to study any adverse environmental impacts of using the FGD materials for road construction, also indicated little difference in quality when comparing pre repair versus post repair samples. Analysis of slope stability before and after repair was also carried out for both sites using a program called PCSTABL. Data input consisted of records available from the Ohio Department of Transportation and typical values of engineering properties of the original embankment materials and of FGD. Figures 4 and 5 show the most critical failure surface calculated for the original and repaired embankment configurations. The calculated factor of safety increased from 0.94 to 58 at State Route 541.

Figure 4. Analyses of minimum safety factors calculated for the State Route 541 field site in Coshocton County for the original embankment (A) and in the failure surface passing through the FGD buttress (in gray) after embankment was repaired (B).

Figure 5. Analyses of a cross section of the embankments at the State Route 83 field site in Noble County reconstructed using soil (A) and FGD (B) materials and showing the slip surfaces with their minimum safety factors.

The areas containing FGD had much greater strengths than in the areas not containing FGD and it would be in these non-FGD areas where any new potential failure surfaces would occur. Similar slope stability analyses for the State Route 83 site showed an increase in the safety factor from 1 to 15 (for the FGD plus soil mixture section) to 27 (for the FGD alone section).

The FGD material used in these projects demonstrate high strength, ease of installation and no measurable change in environment quality of the surrounding area. It is also well suited for use as a soil stabilizer and mixes of soil and FGD can be blended in the field and modifications can be made as repairs proceed.

Use of FGD as an Agricultural Limestone Substitute

Because of the alkalinity contained in many FGD materials, a possible beneficial use is as a limestone substitute to amend acid agricultural soils. A field study was conducted to evaluate a specific FGD by-product (i.e. a 40:60 (wt/wt) mixture of PFBC bed and cyclone ash) applied to three different acid agricultural soils located in eastern Ohio. This by-product was surface applied in the fall of the year at 0, 0.5, 1 and 2 times the lime requirement rate as determined by the state soil testing laboratory and then incorporated to a depth of 10 cm. Separate plots for corn (*Zea mays L.*) and alfalfa (*Medicago sativa L.*) were planted the next spring. Crop yields at harvest were recorded for three consecutive years. Soil samples were also collected from the plots each year to test for changes in pH, soil quality and movement of various chemical constituents.

The FGD material was clearly effective as a liming material as soil pH was rapidly raised to near neutral (i.e., pH 7). Concentrations of Ca, S and Mg increased in the soil and these elements tended to diffuse downward with time. This is a benefit as it helps correct a low soil pH even in layers where the FGD is not applied or mixed. Acidic cations in the soil, such as Al, Mn and Fe, decreased in concentration. With the exception of B, water soluble concentrations of trace elements were unaffected by the FGD application. Concentrations of water-soluble B were increased in the zone of FGD incorporation in all three soils but were well below phytotoxic levels and decreased with time as the B was leached from the soil. Plant available P decreased and this was attributed to the large amount of added Ca and consequent precipitation of relatively insoluble calcium phosphate. This may require farmers to adjust P fertility programs in soils where available P is low at the time the FGD is applied.

Corn grain yield was not affected by the FGD by-product in eight of the nine site years (Figure 6). In the first year (1993) and only on the Coshocton soil, the FGD application caused a small decrease in corn grain yield. This was attributed to drought conditions leading to low amounts of soil water and, therefore, increased soil solution salt concentrations in the FGD treated plots. Alfalfa yields were increased by the FGD in 7 of the 9 site-years (Figure 6). On the Canfield soil where the lowest, and possibly insufficient, rates were applied there were no increases in alfalfa yield in 1993 and 1995. However at the Wooster and Coshocton sites, the alfalfa yields at the recommended rate of FGD application (i.e. the middle rate), were sometimes more than double that of the untreated control. Chemical composition of the alfalfa did not reveal any concerns that would arise if the alfalfa was to be used as an animal feed.

Use of FGD for Mineland Reclamation

A field project demonstrating the beneficial use of FGD for remediation of abandoned surface coal mines was conducted at a site located in Tuscarawas County near Dover, OH. This site, called the Fleming site, was identified by the Division of Reclamation of the Ohio Department of Natural Resources (ODNR) as a site with high priority for reclamation because of excessive erosion, acid mine drainage formation, and offsite damages caused by the erosion and acid mine drainage. The site contained approximately 10 ha (25 acres) of exposed, highly erodible underclay bordered on two sides by about 18 ha (45 acres) of unreclaimed spoil and coal refuse. Little to no vegetation existed on the site at the time the study was initiated. Baseline data was available from the ODNR and we also collected water quality samples prior to any work at the site.

Schematics of the experimental designs developed to study the use of FGD by-products for reclamation of this site are shown in Figures 7 and 8. These field designs permitted measurement of soil quality, plant quality, interstitial soil water quality, and surface and ground water hydrology and quality. The underclay at the site was reclaimed by grading to remove gullies and to create a surface suitable for establishing vegetation and to control water flow. A layer of spoil 1.2 m (4 ft) thick was placed over the underclay before the final reclamation treatments were applied. The six small watersheds (A through F in Figure 7) were separated hydrologically by a berm and had a surface slope that directed water runoff to a collection weir. The underclay for each small watershed was also sloped to the center prior to placement of the spoil and the bottom surface was shaped to direct any leachate to an tile drain at the bottom of the plot. Final reclamation of the surface of two small watersheds was then

Figure 6. Effect of FGD on the yield of alfalfa hay and corn grain in Wooster, Coshocton and Canfield soils (*, the starred means are significantly different from all other means for a particular year and site).

Figure 7. Schematic of the experimental design developed for the Fleming site to study the potential impacts of using FGD for reclamation of abandoned surface coal mine lands. The FGD in the six OSU watershed plots was an AFBC by-product material and the FGD in the USGS designated areas was a PFBC by-product material.

Figure 8. Topographic map showing location of bore holes, lysimeters, wells, and surface geographical surveys at the Fleming abandoned mine site.

accomplished by first mixing limestone into the spoil (112 Mg/ha or 50 tons/acre) followed by placement of 20 cm of a resoil material and then mixing in more limestone (45 Mg/ha or 20 tons/acre). Two other small watersheds were reclaimed using only 280 Mg/ha (125 tons/acre) of FGD from an atmospheric fluidized bed combustion (AFBC) process. This same FGD material was also mixed with yard waste compost (1:1 ratio by volume) and used to reclaim the final two small watersheds. The dry weights in the mixture applied were 280 Mg/ha (125 tons/acre) of FGD and 112 Mg/ha (50 tons/acre) of yard waste. All of the materials were incorporated to a depth of approximately 20 cm (8 in). Areas outside of the six small watersheds were reclaimed using an FGD material from a pressurized fluidized bed combustion (PFBC) process and these areas were used for groundwater studies. Groundwater wells and ceramic lysimeters were placed in strategic areas surrounding the site or within the areas reclaimed with FGD but outside the six small watersheds (see Figure 8).

Complete characterization of the spoil and all materials used during reclamation was conducted. Chemical analyses indicated concentrations of all elements were below that found in the spoil or below levels set by the U.S. Environmental Protection Agency for land application of biosolids. Elements such as As, B and Se that are associated with fly ash and sometimes reported to be a concern, were not a problem in this study. Full dioxin scans were made of all the materials and the results (Table 9) indicated that they were extremely low in dioxin concentrations. The FGD products had dioxin levels similar to the native spoil that had only recently been exposed by grading activity during reclamation and these concentrations were considered equivalent to naturally occurring background levels.

The chemical parameter that probably has the most impact on influencing water quality and plant growth is pH. Figure 9 shows that pH in drainage was approximately 2.5 to 3.5 prior to reclamation and increased to approximately 6 to 7 after reclamation was completed. There was no difference in surface runoff water pH among the various amendments used for reclamation. This increased pH decreased the concentrations of soluble heavy metals in water that drained from the site. It also reflects a soil environment conducive for plants to grow and for plant nutrients to be cycled from one year to the next.

Above ground plant biomass yields for the first season after reclamation was completed are shown in Figure 10. The biomass yields in the topsoil treated plots were more than double those in the plots containing FGD. However ground cover in all plots was more than sufficient to control erosion. Growth in the topsoil plots was primarily restricted to grasses and the

Table 9. Dioxin Concentrations in FGD, Compost, FGD/Compost Mixes and Minespoil Applied to the Fleming Site (7/29/94).

Sample	Dioxin Toxicity Equivalents ^a
	parts per trillion
PFBC ^b	0.53
AFBC ^c	0.48
Compost ^d	4.33
PFBC/Compost	2.83
PFBC/Compost	3.08
Minespoil ^e	0.57

^aCalculated based upon a full scan of various dioxin congeners according to a worksheet procedure prescribed by the Ohio Environmental Protection Agency (Columbus, OH).

^bPFBC, pressurized fluidized bed combustion FGD by-product obtained from the American Electric Power plant (Brilliant, OH).

^cAFBC, atmospheric fluidized bed combustion FGD by-product obtained from the General Motors facility (Pontiac, MI).

^dCompost material was obtained from Earth-N-Wood (North Canton, OH).

^eRepresentative minespoil was obtained from the surface of the Fleming site located near Dover, OH.

Figure 9. pH of surface water runoff from Fleming spoil (OSU watershed plots) reclaimed with topsoil, FGD, and FGD+compost and in a pond collecting water from other areas at the Fleming site reclaimed with FGD.

Figure 10. Vegetative biomass production in 1995 on Fleming minespoil reclaimed with topsoil, FGD and FGD+compost. This harvest data was obtained from the OSU watershed plots.

presence of legumes in the reestablished vegetation was mostly lacking. This may impact long term sustainability as legumes provide a natural input of N into an ecosystem.

Interstitial and groundwater quality were also monitored at the Fleming site in the areas treated with FGD (created by the PFBC process) as described previously. Interstitial water, or water in the soil matrix itself was monitored during three sampling rounds up to 16 months after reclamation was completed. Ceramic lysimeters were installed at various depths within soil profiles in areas reclaimed with FGD or topsoil material. During the initial sampling, only 9 of 35 lysimeters yielded enough interstitial water for analyses. This was due to the soil profile, reformed during reclamation, needing time to become wetted up. Subsequent samplings yielded a much greater number of samples for analyses and indicated pH of the interstitial water ranged from 4.3 to 7.6 with the median pH being approximately 6.2 (Round 2) and 6.9 (Round 3).

Interstitial water samples were the most concentrated waters found at the Fleming site. Specific conductance in the FGD treated areas decreased from Round 2 (median value, 9,340 $\mu\text{S}/\text{cm}$) to Round 3 (median value, 7,440 $\mu\text{S}/\text{cm}$). Specific conductance in interstitial waters from the topsoil area was much lower and was 1,445 $\mu\text{S}/\text{cm}$ during Round 3. Other changes in interstitial water quality collected from the FGD treated areas were also noted. In particular, Mg and SO_4^{2-} concentrations generally increased between Rounds 1 and 2 and then decreased. Calcium concentrations tended to decrease during all sampling rounds. Dilution of the interstitial waters during recharge events is probable and would yield the declining concentrations observed for several constituents. A reliable indicator of temporal changes is the use of element ratios, which if both elements are conserved, are unaffected by dilution. Magnesium to calcium (Mg:Ca) mole ratios increased between rounds 1 and 2 and then remained fairly constant (Figure 11). This pattern would indicate that chemical processes controlling interstitial water chemistry did not vary significantly between rounds 2 and 3 despite the significant changes in calcium and magnesium concentrations observed between the two rounds. The Mg:Ca mole ratios were also higher in the FGD treated areas than in the topsoil treated area.

Trace elements found at elevated concentrations in the interstitial water samples collected in the FGD treated area included B, Co and Zn. However, only B had concentrations that were consistently higher in the FGD treated versus topsoil treated areas for all three sampling rounds. In the treated areas, concentrations of B were highest in round 1 (850 $\mu\text{g}/\text{L}$ in the

Figure 11. Plot of magnesium:calcium (Mg:Ca) mole ratio versus dissolved sulfate for all water samples.

treated area versus 200 µg/L in the topsoil area). During round 3 the values for the treated and topsoil areas were 448 and 45 µg/L, respectively. Other trace elements of environmental concern including As, Cr, Hg, Pb and Se were detected only at concentrations near the reporting limits of the analytical equipment.

Data collected to date show no evidence that FGD by-product leachate has affected the quality of ground water at the study site. Water quality data from the interstitial waters may be used to assess the potential effects of FGD on ground water quality, but to fully evaluate whether there will ever be any effects on ground water quality would require many additional years of post reclamation monitoring. The likelihood of any negative impact on ground water quality by FGD application is thought to be extremely low because (1) the small area actually treated with FGD compared to the much larger areas of untreated areas which contribute to groundwater recharge (2), the natural attenuation processes that occur as elements are cycled among plants, soils and water, and (3) the observations that surface water, which is the source of ground water recharge, is actually improved by FGD treatment.

The chemistry of the FGD and of the FGD-compost mixtures was found to be ideal for use in reclamation. The high alkalinity content improves soil pH creating an environment that is acceptable for plant growth. The high gypsum content helps move calcium down into the soil profile so that areas not directly in contact with the applied FGD can also be improved. One of the problems with traditional resoil reclamation technologies is that the surface soil layer is very thin. If any erosion occurs, the rooting depth becomes too shallow to maintain plant growth. FGD helps overcome this problem by providing more soluble basic cations that can move into the underlying spoil material, thus increasing plant rooting depth. In addition, use of FGD avoids the problem of having to disturb one area of land to reclaim another. Surface water quality was substantially improved from what existed prior to reclamation. Changes in interstitial water quality were observed but these seemed to be rapidly reverting back to baseline levels as water percolated through the soil. There was no change in ground water quality caused by FGD application during this study.

Monitoring at the Fleming site will continue for at least three more years. Soil quality, plant quality, surface water quality and groundwater quality will all be measured to determine the longer term impacts of using FGD to reclaim acid and toxic mine spoil.

ECONOMIC CONSIDERATIONS

Economic studies were conducted to develop conceptual models and statistical estimates of procedures related to FGD utilization. Hedonic pricing methods were used to estimate impacts of (1) FGD disposal in landfills on private property values and (2) FGD use for reclamation of surface coal mines areas. A linear optimization model was applied to identify the least cost disposal/use options for FGD. The application of the linear optimization model included analyses of the social costs/benefits associated with the FGD by-product options for disposal and use.

When FGD is created in excess of amounts that can be recycled beneficially, the excess must be landfilled. Landfills are widely viewed as environmental disamenities and, as such, will result in decreased levels of perceived quality to nearby human populations. If sufficient beneficial reuses of FGD are developed, the negative impacts of landfills could be mitigated as these reuses would reduce the flow of FGD into landfills. Similarly, there is a quantifiable social benefit if FGD is used to reclaim surface coal mines, reducing the negative environmental impacts of acid mine drainage and sediment movement.

In order to implement the model, four well defined areas around landfills in Franklin County, OH were chosen for analyses (Figure 12). A full year of 1990 real estate transactions data were collected and subsequently supplemented with 1990 census group micro data and household level survey data. The full data set captures the marginal effect of landfills on nearby real estate markets. Finally, a two-stage econometric model was used to estimate empirical compensating variations. The results obtained for these four landfills were then assumed to apply to FGD landfills. Findings of this study indicate that there are three primary factors that affect the economic impacts of a landfill: (1) the spatial effect of proximity of the landfill—with real estate values increasing as distance from the landfill increases, (2) the landfill's life expectancy, and (3) the time since the landfill has closed. Results showed that even after closing, the negative impacts of the landfill can persist for some time (Table 10). Applying all of these results to a FGD landfill provided an estimate of welfare cost of \$1.42/ton for FGD disposal. This indicates that for every ton of FGD that is used, there is at least a \$1.42 economic benefit to society.

Figure 12. Map of Franklin County, OH landfill study sites.

Table 10. Landfill Life Expectancy and Compensating Variation Measures for Landfills in Franklin County, OH.

Landfill Site	Life Expectancy (Years)	Compensating Variation/Month	Compensating Variation/Year
Grove City	20	\$203.61	\$2,443.32
Gahanna	2	\$166.02	\$1,992.24
Obetz	-6	\$69.70	\$836.40
Alum Creek	-11	\$25.70	\$320.40

A least cost disposal model for the movement of FGD by-product to various geographic locations throughout Ohio for its use as a soil amendment for highway construction, coal surface mine reclamation, and landfilling was also developed. In doing so, total disposal costs and quantities were derived as well as shadow prices identified for each county (demand node).

This analysis compared several scenarios for future FGD by-product distribution and use. Others may be plausible and easily analyzed by the model. Under the most realistic scenario, the linear transportation model estimates that it would cost \$70.1 million annually to dispose of 3.45 million Mg (3.8 million tons) if the full social costs of landfilling were considered. This contrasts with the costs if no alternatives for recycling existed in which case the social cost alone is \$4.7 million per annum, and full costs of landfilling are \$115.6 million per annum (\$26.88/Mg or \$29.64/ton on average including transportation to the landfill and social costs). When the social costs of landfilling are not considered, the linear model predicts least cost disposal amounts equal to \$68.0 million per annum. Thus, even in this scenario where significant alternative disposal means are used, the social cost from landfilling will amount to more than \$2 million per year.

This analysis suggests that landfilling would remain the final option for disposing of approximately 36 percent of the total FGD by-product produced. Two other potential end use alternatives currently identified for FGD by-product (i.e. highway construction and repair and reclamation of surface coal mines) could potentially account for about 17 and 47 percent,

respectively. On average, alternative uses of FGD by-product represent a savings of \$10.58/Mg (\$11.67/ton) which is the difference between the cost of landfilling (\$26.88/Mg or \$29.64/ton) and the average cost associated with alternative uses (\$16.30/Mg or \$17.97/ton).

This study demonstrates that even if alternative uses are identified, a significant quantity of FGD would still be landfilled. This provides an enormous incentive to supply FGD for surface mine reclamation and highway repair, and to find other potential uses for FGD.

LIST OF PHASE REPORTS

Stehouwer, R., W. Dick, J. Bigham, R. Forster, F. Hitzhusen, E. McCoy, S. Traina, W. Wolfe and R. Haefner. 1995. Land application uses for dry flue gas desulfurization by-products. EPRI Report No. TR-105264, Electric Power Research Institute, Palo Alto, CA.

Stehouwer, R., W. Dick, J. Bigham, R. Forster, F. Hitzhusen, E. McCoy, S. Traina, W. Wolfe, R. Haefner and G. Rowe. 1998. Land application uses for dry flue gas desulfurization by-products: Phase 2. EPRI Report No. TR-109652, Electric Power Research Institute, Palo Alto, CA.

Dick, W., J. Bigham, R. Forster, F. Hitzhusen, R. Lal, R. Stehouwer, S. Traina, W. Wolfe, R. Haefner and G. Rowe. 1999. Land application uses for dry flue gas desulfurization by-products: Phase 3. Report submitted to Dravo Lime Company, Pittsburgh, PA.