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POWER-PLANT FLY-ASH UTILIZATION--A CHEMICAL-PROCESSING PERSPECTIVE*

by

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Abstract

The disposal of large amounts of coal fly ash is an environmental problem of increasing magnitude. The two principal reasons for environmental concern are the entry of heavy metals from fly ash into the soil and water supplies, and radiation from the naturally occurring radionuclides in fly ash.

Currently, about 50 million tons per year of coal fly ash are being produced in the United States, and it is estimated that the increased consumption of coal will raise fly ash production to approximately 60 and 150 million tons per year by 1985 and 2000, respectively. Only about 17 percent of the fly ash produced annually is presently being used and this largely for construction purposes.

The 1976 Resource Conservation and Recovery Act (RCRA) deals with the management of solid and hazardous wastes, and encourages energy and resource recovery. Recent research has indicated that solid wastes from coal combustion, including fly ash, could be classified as hazardous under present EPA definitions. The seriousness of this possibility has been recognized and new rules for coal ash waste disposal are being considered.

Ames Laboratory research on fly ash utilization as an alternative to disposal includes extraction of metals from the ash and discovery of uses for the process residues. Recovery of alumina and iron oxides by physical and chemical processing would permit large scale utilization of fly ash and help reduce dependency on imports.

One of the processes investigated uses a lime-soda sinter method to form soluble aluminate compounds from mixtures of fly ash, limestone, and soda ash. The aluminates are extracted, treated to remove silicates and precipitated; the precipitate is calcined to metallurgical grade alumina. The extract residue shows promise as a raw material for the production of Portland cement. Process economics are presented, and the effects of alumina and silica contents of the fly ash, sintering temperatures and time, and sales credits for by-products are discussed.

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DISCLAIMER

Introduction

By the year 2000, according to one EPRI estimate (EPRI Journal, 1980) the United States will require about three times the coal produced in 1978--or about two billion tons annually. To satisfy this demand, coal production will have to increase an average rate of 4.7% a year. While this growth rate may not appear very large, production, constrained by demand, has grown by only 1.5% a year over the past 20 years. To meet this production goal, the nation must successfully meet challenges in coal exploration, mining, labor, transportation, and solid waste disposal.

The disposal of large volumes of coal fly ash, generated when pulverized coal is combusted, is developing into a major environmental problem. The fly ash consists of finely divided particules of inorganic oxides that are either entrained in the flue gas leaving the boiler or are produced by condensation as the gas cools. Disposal by venting, burial, or ponding allows toxic elements and natural radionuclides from the ash to enter the air, water, and soil.

Although the precise rate at which coal burning power plants will be placed into operation is somewhat difficult to predict, there seems to be no doubt that the increase in coal utilization for this purpose will be dramatic. The levels of present and projected coal usage and ash production for utility power generation are shown on Figure 1 (Ash at Work, 1979). The National Energy Plan of 1977 outlined goals for coal utilization for both industrial and utility power generation. These goals were used in Figure 1 to predict utility coal consumption and ash production to 1990. The data point included for estimated steam coal production in 1985 (Coal Age, 1979) suggests that these coal consumption projections are reasonable.

As shown in Figure 1, about 45 million tons of coal fly ash were produced in 1978 and it is estimated that the increased consumption of coal will raise fly ash production to approximately 60 and 150 million tons per year by 1985 and 2000, respectively. Only about 17 percent of the fly ash produced annually in the United States is presently being used and this largely for construction purposes. Today 40 to 45 million tons of fly ash per year are being transported to disposal sites. A graphic representation of the fly ash generated and used in 1978 is shown in Figure 2. Disposal of the unused fly ash is estimated to have cost utilities about $200 million.

A number of new coal-fired power stations are being constructed in areas where other fossil fuels or nuclear power might have provided the electrical energy. Table 1 contains information about 259 new coal-fired power stations that are expected to come on-line by 1986 (Ash at Work, 1977). Many of these stations will be fueled with low-sulfur western coals transported by rail from Wyoming and Montana and are in areas where coal has not previously been used adding to the waste disposal problems. As these new power stations alone begin operation, total ash production will increase to about 100Tg per year.

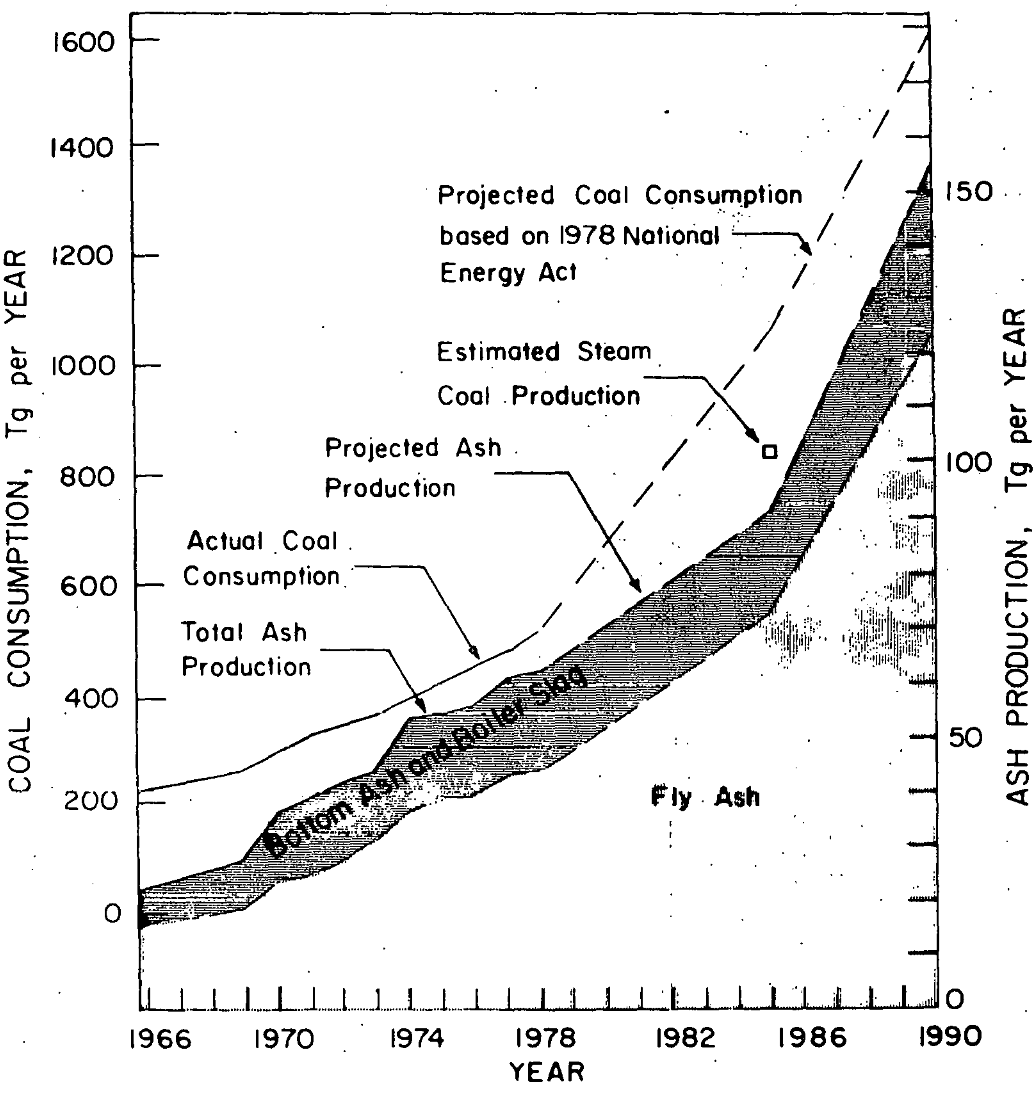

Figure 1. Coal Consumption and Ash Production by U.S. Electric Utilities.

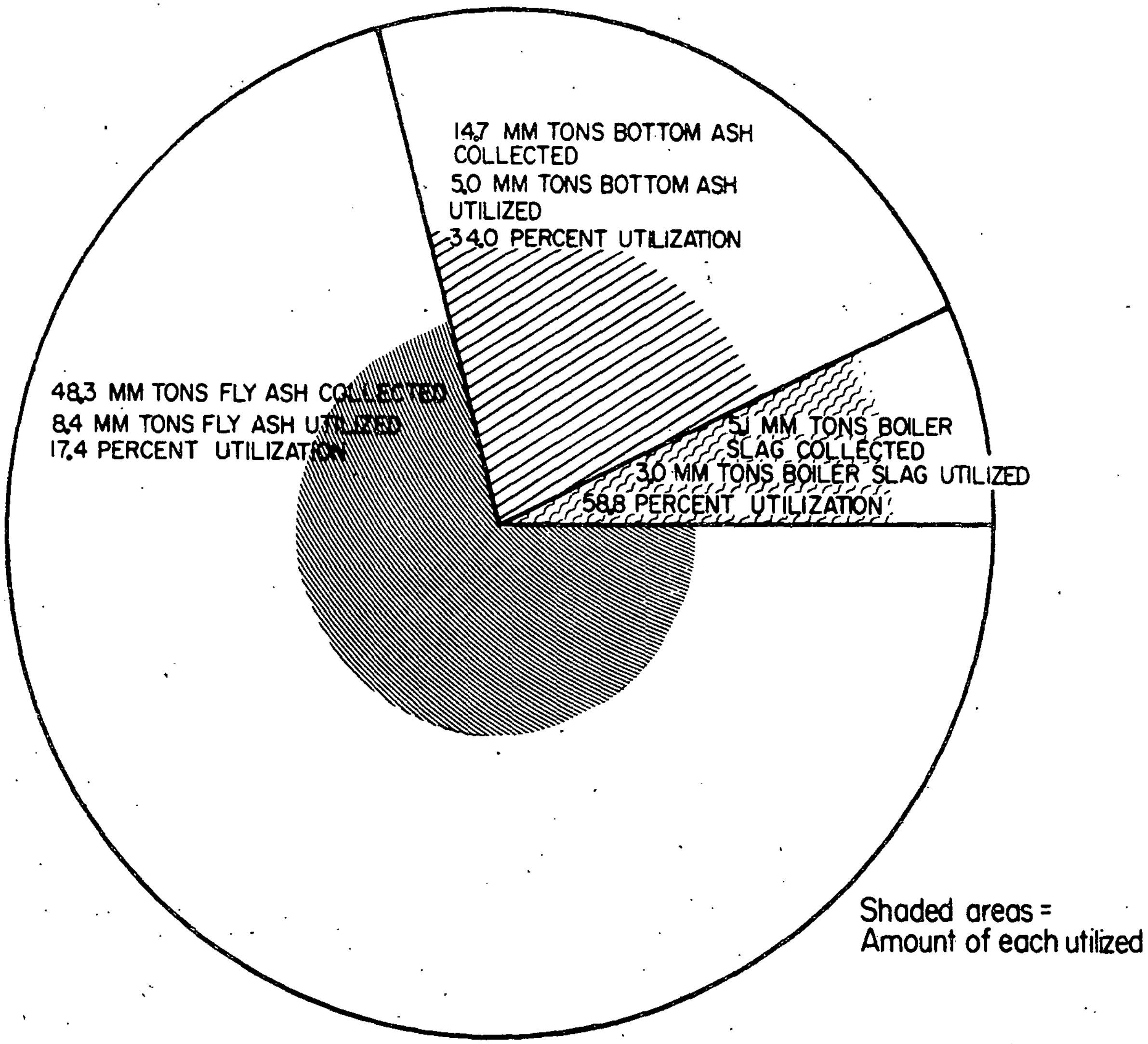

Figure 2. Coal Combustion Solid Wastes Produced and Utilized in the U.S. During 1977, Million (MM) tons.

Table 1. New United States Coal Fired Power Plants Planned for 1977-1986 (Ash at Work, 1977).

Region	States	Units	Megawatts
New England	CN, ME, MA, NH, RI, VT	1	600
Middle Atlantic	NY, PA, NJ	7	5,500
East North Central	IL, IN, MI, OH, WI	50	22,124
West North Central	IA, KS, MN, MO, NE, ND, SD	40	18,727
South Atlantic	DE, DC, FL, GA, MD, NC, SC VA, WV	31	18,444
East South Central	AL, KY, MS, TN	30	14,940
West South Central	AR, LA, OK, TX	59	32,398
Mountain	AZ, CO, MN, NV, NM, UT, WY	36	13,952
Pacific	CA, OR, WA	5	2,630
Total		259	129,315

Disposal of coal fly ash presents some potential environmental hazards which, depending upon pending RCRA regulations, may greatly increase ash disposal costs. The wastes may have to be contained in clay-lined pits to minimize ground water contamination due to leaching of heavy metals and the number of available disposal sites could thus be even further reduced. Overall the cost of fly ash disposal could increase to as much as $20 to $50 per ton (EPRI Journal, 1980).

As an alternative to disposal, coal ash can be processed as a resource to recover minerals of value to the U.S. economy. Coal fly ash is an already mined, crushed, and readily available source of several metal oxides. The chemical contents of fly ashes from U.S. bituminous, subbituminous, and lignite coals are given in Figure 3 (Roy et al., 1979). The average values for silica and alumina in the ashes are quite constant. Differences are found in the lower lime content of bituminous coal ashes and the lower iron oxide content of subbituminous coal and lignite ashes. The 20 weight percent alumina is equivalent to about 10 weight percent aluminum.

A metal of much higher value than aluminum and found in most fly ashes at a level of about one weight percent as the oxide is titanium. Bituminous coal fly ashes also contain an average of about 18 percent iron expressed as Fe_2O_3. The iron occurs predominently in an iron-rich fraction, about two thirds of which can be recovered by magnetic separation. Table 2 gives information about the potential of coal fly ash an an aluminum, titanium, an iron resource (Bur. of Mines, 1980). Large

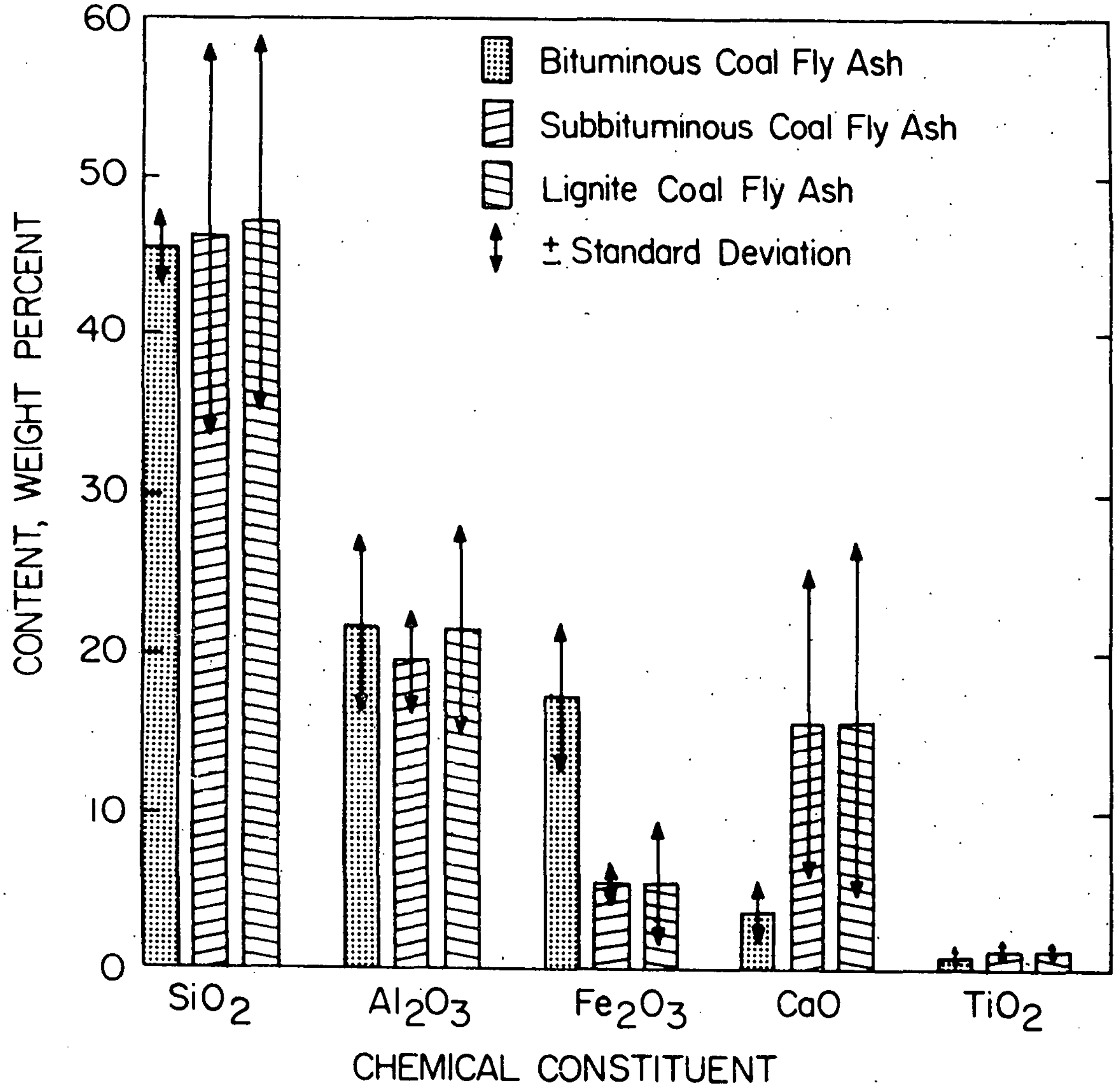

Figure 3. Chemical Compositions of U.S. Power Station Fly Ashes.

scale processing of coal fly ash can provide significant percentages of these metals independent of imports, thus utilizing coal ash in a beneficial manner and improving our balance of payments. Processing of the fly ash collected at the large, greater than 500MWe, power stations could provide 80 percent of our primary aluminum and about 50 percent of our titanium needs. Only about 5 percent of our iron ore requirement can be met from this fly ash but the iron-rich fraction has other potential uses such as in heavy media for coal washing and ore beneficiation.

Table 2. Percent of National Demand for Aluminum, Titanium Oxide and Iron Ore Recoverable from Power Station Fly Ash (Bur. of Mines, 1980)

Material	Demand, 1979	Equivalent Material Recoverable from Fly Ash[1]		Imports	
	Tg	Tg	% of Demand	Tg as Ore (Ore Type)	% of Demand Metal
Aluminum, primary	4.60	3.60	80	11-14 (Bauxite)	93
Titanium	0.78	0.36	47	1.0 (Illmenite)	46
Oxide				0.32 (Rutile)	100
Iron Ore	105.00	5.50[2]	5	30 (Iron Ore)	28

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[1] Assumes 80 percent recovery from the fly ash

[2] Based on $51.5\%_w$ iron content.

Formation of Fly Ash During Combustion

Combustion releases the mineral constituents of coal and many of the elements are toxic. Two types of element distributions result from coal combustion--elements not volatilized in the combustion and elements volatilized. The elements not volatilized in the combustion zone form a melt of rather uniform composition that makes up the matrix of both fly ash and bottom ash. Elements which are not volatile show little partitioning between the fly ash and the bottom ash. The volatile elements are preferentially concentrated by condensation or adsorption on the surfaces of the smallest fly ash particles as the flue gas cools.

Trace elements in coal are present as contaminants in aluminosilicates in the form of inorganic sulfides or organic complexes. On combustion, the aluminosilicates are not decomposed, rather they melt and coalesce to form slags and ash. During the initial stages of combustion, a reducing environment probably exists in coal particles and the chemical bonding between metal elements and sulfur in sulfide mineral inclusions or between the elements and the organic matrix is broken leading to the formation of volatile species. The elements thus volatilized or dispersed in the flue gas stream can then be oxidized to form less volatile species which condense or adsorb on ash particles as the temperature of the flue gas drops.

It has been found that the concentration of toxic trace elements associated with fly ash particles increases as the particle size decreases in the diameter range 1 to 10 μm. Figure 4 shows the concentration of toxic metals as a function of ash particle diameter. Preferential condensation or adsorption onto these particles gives trace element concentrations enhanced from 100 to 1000 times over the concentrations in crustal rock and earth. Concentrations are not a function of size for submicron particles because these particles appear to result at least in part from the bursting of larger particles due to gas evolution (Smith, 1979).

The total quantities of trace elements released as a result of coal combustion are large, being roughly comparable to the amounts annually mobilized by natural processes of weathering of crustal rocks. For most elements, about 5 percent of the amount in the coal is discharged to the atmosphere but selective volatility increases the percentages of As, Hg, Cd, Sn, Sb, Pb, Zn, Tl, Ag, and Bi released. The remainder of the elements are found with the ash.

Environmental Regulations and Fly Ash Disposal

In May 1980 the U.S. Environmental Protection Agency (EPA) issued promulgations under the auspices of the Resource Conservation and Recovery Act (RCRA) which temporarily exempted coal wastes from classification as hazardous wastes. Then in October 1980 Congress passed amendments to RCRA, one of which stated that the EPA was not to regulate coal wastes as hazardous until the Agency performed comprehensive studies demonstrating the hazards to environment and health.

The EPA now has a research program that deals with various types of coal wastes, modes of disposal, and types of geohydrological soil structures. Under this program, 12 existing ash disposal sites at least two years old have been selected throughout the nation. Wells will be drilled, and the ground and surface waters, and soils at each site will be monitored for toxic element dissolution or assimulation. Data from these studies are expected to be complete in 1982.

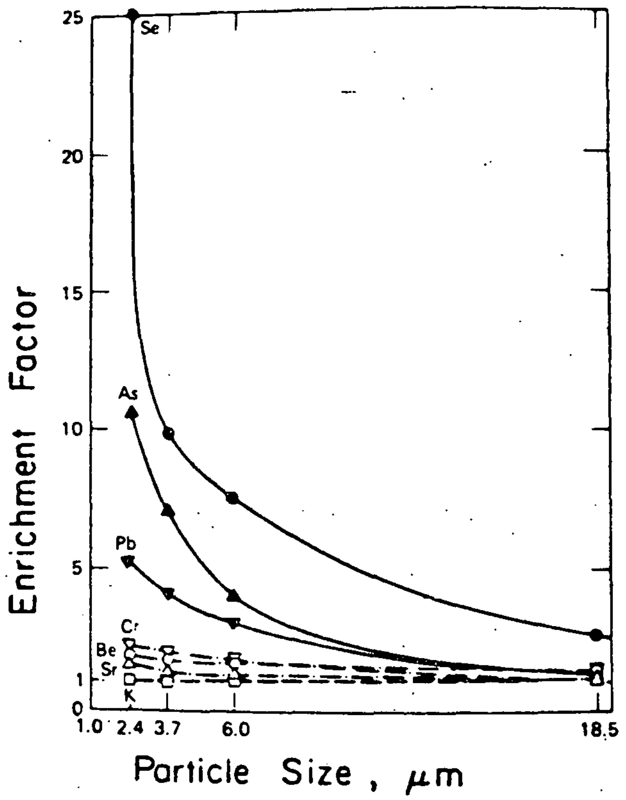

Figure 4. Enrichment of volatile metal elements as a function of particle size for ash particles collected by an electrostatic precipitator. (Coles, 1979)

Although coal ash is not now classified as a hazardous waste, coal wastes are covered under subtitle D of RCRA for nonhazardous wastes (September 13, 1979 Federal Register). Subtitle D covers municipal wastes and most industrial wastes, and identifies the permitting for siting waste disposal sites as a state function. Although there are federal siting criteria which can be used, each state can develop its own regulations. A suit can be brought against the owner of a nonhazardous waste disposal site if there is environmental degradation at the site boundary.

To classify a material as hazardous, it must be subjected to acid leaching in the laboratory and produce concentrations in the leachate that are prejudged to be harmful to the environment if normally disposed of. Nonhazardous materials can be disposed of but the concentrations in waters at the disposal site boundary must be within state and/or federal criteria.

Upon completion of the study of potential environmental degradation from coal waste disposal, EPA will recommend whether coal wastes should be declared hazardous. Even if the wastes continue to be classified as nonhazardous, EPA will issue coal waste disposal and management guidelines based on the research results (Heffelfinger, 1980).

Chemical Processing of Fly Ash by Calcination

Coal ash mineralogy is determined by the inorganic materials in the coal which is burned. Inorganic minerals in the coal structure and in the clays and shales mined with the coal are released during combustion and form fly ash particles through a combination of volatilization and coalescence, and agglomeration. Because of the random nature of the formation process, the particles vary in size, shape, mineralogy, chemical composition, surface characteristics, and internal structure. The properties are both a function of the nature of the coal burned and the manner in which it is fired.

Composition data for the major constituents in ashes from commercially produced U.S. coals are available (Abernathy, et al, 1969). Ash constituents are reported as normal oxides, but are present in the ash as a mixture of silicates, oxides, carbonates, and sulfates, with traces of other minerals as well. Major constituents in fly ashes have already been given in Figure 3. Of particular importance to this work is the alumina content of approximately 20 weight percent.

Recovery of minerals from fly ash is hindered by the nature of the ash. The vitreous and fused particles of the ash consist of metal silicates which are resistant to chemical processing. For example, neither caustic nor acid digestion will attack the structure to release significant amounts of the metal oxides except under the most severe conditions. Consequently, the work at the Ames Laboratory has focused on a high-temperature sinter-leach process to break the metal-silica bonds and recover the alumina from the clinker.

The sinter treatment of silicate compounds is not new--Sèailles patented most of the sinter, extraction, and purification steps during the years 1925 to 1950 (Sèailles, 1947). Kammermeyer used a similar process for the extraction of alumina from kaolin clay (Kammermeyer, 1941). The process developed by Sèailles has been applied in Poland and Hungary to the recovery of alumina and the production of cement from the ash residue. The work included a pilot plant study carried out to investigate several non-bauxite raw materials including fly ash (Gulyas and Vamos, 1976). This process, as partially described in several papers, did not give high alumina recoveries from the U.S. fly ashes tested. Consequently, our research has been conducted to develop improved process conditions for the U.S. coal fly ashes and has led to a high-yielding, lime-soda sinter process (Murtha and Burnet, 1979). The processing sequence involved is shown in Figure 5.

As noted previously, fly ashes from bituminous coals contain a significant amount of iron, much of which can be removed magnetically as an iron-rich fraction. Once this is done, the nonmagnetic fly ash (or low-iron ash from subbituminous coals or lignite) is combined with pulverized limestone and a concentrated soda ash solution and pelletized and sintered. In the sintering step, soluble sodium and calcium aluminates

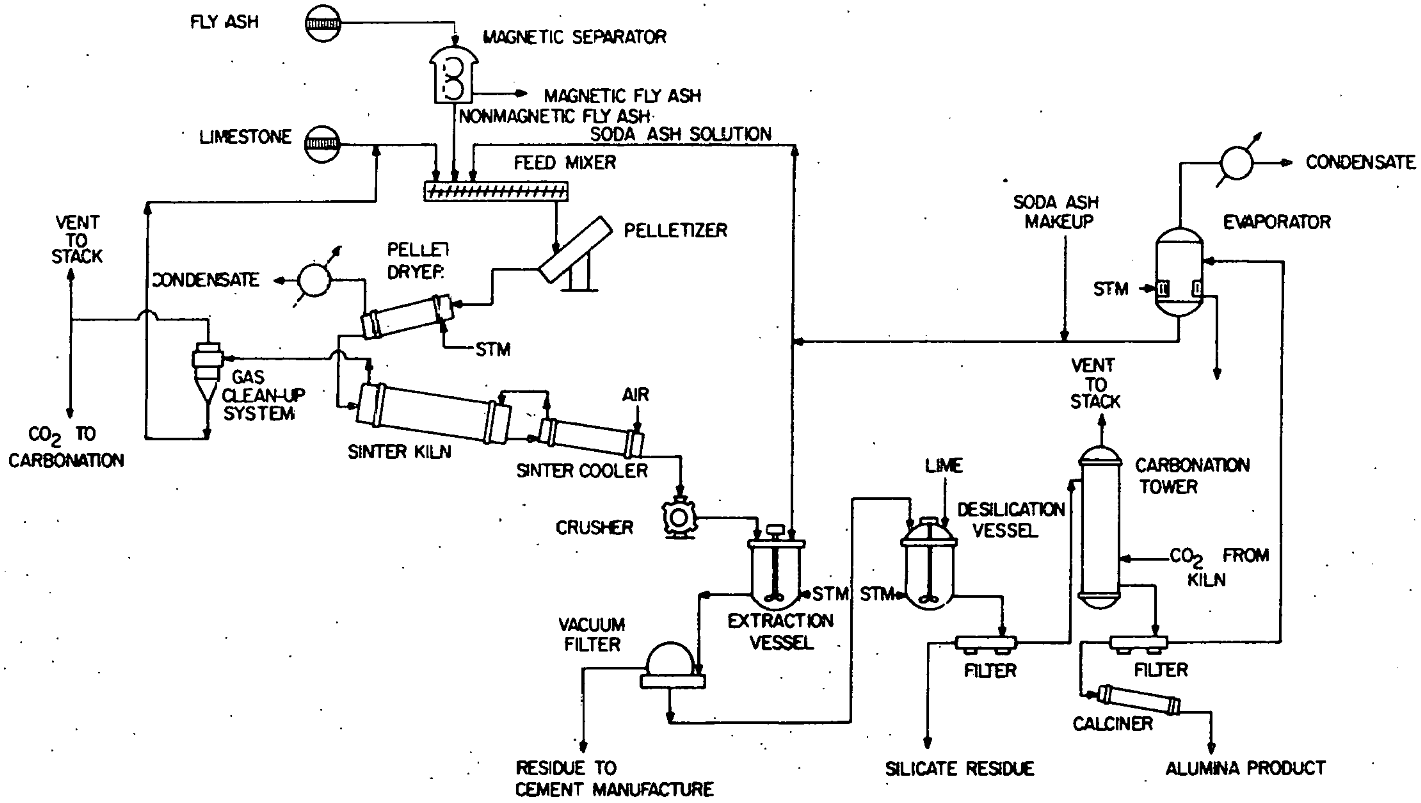

Figure 5. Lime-Soda Sinter Process Flowplan for Extraction of Alumina From Coal Fly Ash.

and insoluble calcium silicate compounds form. The sintered material is cooled and crushed, and then leached with dilute soda ash solution. The aluminate compounds dissolve along with a small amount of silicate which is next precipitated by reaction with lime at high temperature under pressure. Finally, aluminum tri-hydroxide is precipitated by pH reduction brought about by sparging with carbon dioxide. Metallurgical grade alumina is obtained by calcining the precipitate.

The process variables which effect the lime-soda sinter process are the composition of the mixture sintered, the sintering temperature, and the composition of the leach solution. The composition of the sinter mixture determines the nature and amount of soluble and insoluble compounds formed during sintering. With optimal mixture compositions, high percentages of aluminates and minimum amounts of silicates are solubilized. Table 3 gives alumina recoveries as a function of sinter composition and temperature for several different fly ashes and shows the significant effect of small sinter mixture composition changes.

The solution used for leaching sintered material also influences compound dissolution because the solubilities of calcium and sodium aluminates, and calcium silicates are a function of solution pH. An extraction solution containing about 3 weight percent soda ash is of proper pH for high aluminate solubility and low silicate dissolution. The extraction results shown in Table 3 represent typical alumina recoveries from the fly ashes of most of the large coal producing regions of the United States.

Economics of the Lime-Soda Sinter Process

The equipment used in the lime-soda sinter process consists of size reduction equipment, mixers and blenders, kilns, filters, and pressure vessels. These items can be readily purchased and require no special materials of construction. The major equipment cost is for the sintering kilns which are refractory-lined, pulverized coal-fueled kilns not unlike the type used for the manufacture of cement. A large part of the process operating cost is the fuel for these kilns. Optimization of the process includes maximizing kiln throughput, minimizing kiln operating temperature, and minimizing the amount of leach solution. For a given plant capacity, increased throughput will reduce kiln size, while lower kiln temperature will reduce equipment cost, operating cost, and kiln maintenance expense. A minimum volume of liquid in the extraction circuit will reduce equipment costs, increase concentration of the extracted filtrate, and lower the evaporative load on the soda ash recycle circuit. Higher dissolved aluminate and silicate contents in the extracted filtrate also enhances desilication.

Tables 4 and 5 provide an engineering capital cost estimate and an operating cost estimate respectively for a plant capable of processing the fly ash from a 1000 MWe coal-fueled power station. A bituminous coal fly ash containing 20 weight percent alumina is assumed, as is an annual fly ash production rate of 275,000 Mg from the burning of over 4,000,000 Mg of pulverized coal. An alumina recovery of 80 percent

Table 3. Effect of Sinter Composition and Temperature on the Recovery of Alumina from Various Fly Ashes

Fly Ash Type (Wt. % Al_2O_3, CaO, SiO_2)	Sinter Mixture, Molar Ratios $\frac{CaO}{SiO_2}$ and $\frac{Na_2O}{Al_2O_3}$	Percent Alumina Recovery at Sintering Temperatures		
		1100°C	1200°C	1300°C
Bituminous (a)	2.0 - 1.2	80.8	91.2	84.5
(20.6, 5.5, 48.0)	2.2 - 1.2	98.3	91.8	99.8
Bituminous (b)	2.2 - 1.2	83.6	79.7	85.4
(28.3, 1.6, 52.1)	2.0 - 1.4	88.0	91.3	91.9
Bituminous (c)	2.2 - 1.2	99.8	99.7	91.9
(30.4, 0.6, 56.2)	2.3 - 1.1	73.3	87.6	80.0
Subbituminous (d)	2.2 - 0.8	66.0	58.7	70.8
(19.7, 28.8, 30.2)	2.2 - 1.2	92.9	88.4	
Subbituminous (e)	2.2 - 1.2	91.5	82.4	85.7
(31.8, 1.9, 55.7)	2.5 - 1.0	85.5	79.7	
Lignite (f)	2.2 - 1.2	89.5	93.4	91.6
(19.1, 10.0, 59.6)	2.5 - 1.0	79.4	71.9	
Lignite (g)	2.4 - 1.0	65.6	55.4	
(13.6, 25.0, 25.5)	2.3 - 1.4	80.5	81.6	

(a) Nonmagnetic fraction of fly ash from Lakeside Power Plant, Milwaukee, WI, Illinois-Kentucky coal.

(b) Nonmagnetic fraction of fly ash from TVA Kingston Steam Plant, Kentucky coal.

(c) Whole fly ash from Kanawha Power Station, Glascow, WV, West Virginia coal.

(d) Whole fly ash from Commanche Power Station, Pueblo, CO, Wyoming coal.

(e) Whole fly ash from Mexican-Texas coal.

(f) Whole fly ash from Monticello Power Station, Mt. Pleasant, TX, Texas coal.

(g) Whole fly ash from Hoot Lake Power Station, Fergus Falls, MN, North Dakota coal.

Table 4. Total Estimated Capital Requirements For a Lime-Soda Sinter Process Facility For a 1000 MWe Power Station[1]

Plant Section	$ Millions
Raw material preparation	1.75
Sintering	10.15
Leaching	0.70
Desilication	1.40
Carbonation and Calcination	1.93
Soda ash recovery	0.87
Flue gas (CO_2) processing	0.70
Total installed equipment cost[2]	17.50
Steam plant	1.00
Subtotal	18.50
Plant facilities,[3] 10% of Subtotal	1.85
Plant utilities,[4] 12% of Subtotal	2.22
Total construction cost	22.57
Engineering and construction, 10 percent of total construction cost	2.25
Total direct cost	24.82
Contractor's fee, 5 percent of total direct cost	1.24
Contingency, 15 percent of total direct cost	3.72
Total plant cost	29.78
Interest during construction period	3.00
Fixed capital cost	32.78
Working capital	4.00
Total capital cost	36.78

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[1] Station produces approximately 275,000 Mg per year of fly ash.

[2] Includes delivered equipment cost plus all foundations and structures, instrumentation, electrical, piping, insulation, painting and miscellaneous expenses.

[3] Includes buildings, laboratories, shops, roads, but not land.

[4] Includes steam, water, and power distribution, cooling towers, and fire protection equipment.

Table 5. Estimated Production Cost for a Lime-Soda Sinter Process Facility[1] for a 1000 MWe Power Station

	Mg per Year	Production Cost $ per Mg Alumina[2]		
Direct Cost:				
Raw Materials:				
Limestone, $6.60/Mg	460,000	66		
Coal fly ash, $6.60/Mg	275,000	39		(--)[3]
Soda ash, $82/Mg	8,200	14		
Coal, $33/Mg	109,000	78		
Total		197		(158)[3]
Utilities:				
Electric power, 4¢/Kwhr		24		
Steam, recovered at 55¢/Mg		8		
Water		5		
Total		37		
Direct Labor:				
Labor, $20 K/man-yr		13		
Supervision, 15 percent of labor		2		
Total		15		
Plant Maintenance, 5 percent of installed equipment cost		19		
Operating supplies, 15 percent of plant maintenance		3		
Total Direct Cost			271	(232)[3]
Indirect Cost, 50 percent of direct labor and maintenance			17	
Fixed Cost:				
Taxes and insurance, 2 percent of total plant cost		13		
Depreciation, 5 percent of fixed capital cost		36		
Total Fixed Cost			49	
Total Operating Cost			337	(298)[3]

[1] Process facility produces 45,500 Mg alumina per year.

[2] Operating year of 350 days and recovery of 80 percent of the alumina in the ash from the coal used to fuel the kiln in addition to 80 percent of the alumina in the fly ash.

[3] Costs if fly ash is provided at no cost.

results in production of 45,500 Mg of metallurgical grade alumina each year, including that from the coal used to direct fire the sintering kiln.

Table 5 shows a substantial cost for the limestone and coal used to produce a Mg of alumina. Other than operation at the lowest permissible kiln sintering temperature to reduce coal costs, these factors can only be decreased by procuring the materials at a lower price. This possibility exists for the limestone. Limestone of the type used in road construction or for concrete is crushed to about one inch size. Fines are removed to minimize dusting during transportation from the quarry. Some of the fines are sold as agricultural lime but the majority simply accumulates at the quarry and is available in significant quantities and at a low cost. Lime-soda sinter limestone costs could be reduced by locating the process facility near the quarry, which would permit use of the less expensive fines and reduces transportation charges.

Other low value raw materials usable in the lime-soda process include cement kiln dust as a source of lime and alkali, and potash or trona as a substitute for sodium carbonate. Some potential raw materials are available at a low cost because they contain silica, but this is not a problem when they are used in the lime-soda sinter process. The use of these low value materials could decrease costs by as much as $100 per Mg of alumina recovered, and in some cases would be a means of disposing of objectionable solid wastes. After the sintering and extraction steps, the sinter residues would still be a possible raw material for production of Portland cement. Any alkalis, chlorides, and sulfates present would be either dissolved during the extraction step of the lime-sinter process or removed in the kiln gasses.

The data of Table 6 show the effects of changes in items such as raw material cost, kiln operating temperature, and the use of high-calcium western coal fly ashes on the production cost of the recovered alumina. Even substantial assumed changes in these items fails to bring about changes in the unit production cost needed to give an attractive return on investment for the alumina plant alone. When simultaneously the sintering temperature is reduced, fly ash is available at no cost, high-calcium western coal fly ash is used, and the plant capital cost is reduced by 50 percent (Case 14, Table 6), the cost of alumina production still exceeds the current calcinated bulk alumina price of $193 per ton ($212 per Mg) (Chemical Marketing Reporter, 1980).

Earlier cost estimates by this Laboratory and by others (Peters and Johnson, 1974; Katell, 1977; TRW, 1978; Canon et al, 1979) have consistently shown a return on investment for the alumina plant alone. The reason this is not true today can be found in the remarkably constant price for alumina over the past two years. While inflation and increased energy costs have driven many of the production costs up, the unit selling price for alumina has not kept pace. This is thought to be due to a combination of factors including a soft world bauxite market, an overcapacity in aluminum metal production facilities, and reduced demand for primary aluminum metal because of recycling.

Table 6. Effect of Changes in Raw Material Costs, Capital Cost, Type of ash, and Sintering Temperature on the Production Cost of Alumina.

Case No.	Raw Material Cost $ per Mg[1] Limestone	Fly Ash	Soda Ash	Coal	Total Capital Cost	Production Cost $ per Mg Alumina
			Effect of Changes in Raw Material Cost			
1	11.00	6.60	82	33	36.8	381
2	6.60	6.60	82	33	36.8	337
3	6.60	--	82	33	36.8	298
			Effect of Changes in Plant Cost Estimate			
4	6.60	6.60	82	33	36.8 x 0.5	296
5	6.60	--	82	33	36.8 x 0.5	257
6	6.60	6.60	82	33	36.8 x 1.5	375
7	6.60	--	82	33	36.8 x 1.5	335
			Effect of Changes in Sinter Temperature			
8	6.60	6.60	82	33	36.8	337
9	6.60	6.60	82	33	36.8	323
10	6.60	--	82	33	36.8	286
			Effect of Using High-Calcium Fly Ash			
11	11.00	6.60	82	33	36.8	330
12	6.60	6.60	82	33	36.8	300
13	6.60	--	82	33	36.8	260
			Minimum Cost Case			
14	6.60	--	82	33	36.8 x 0.5	220

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[1] The sintering temperature for cases 1-8 is 1200°C and for cases 9-14 it is 1100°C.

In order to show a profit it is now necessary to combine the alumina plant with a facility to manufacture Portland cement from the residue remaining after the crushed sinter is extracted to remove the aluminates. The incorporation of a cement facility with the lime-soda process is more than an economic consideration. The tandem plant is attractive for other reasons. Cement production from the residue permits total utilization of the fly ash, and also the rather large amount of limestone consumed in the lime-soda sinter can be put to use. In one sense, the lime-soda sinter facility becomes a pretreatment step producing calcium silicates for cement production. Part of the energy normally provided in the cement kiln has been supplied in the lime-soda sinter kiln with formation of the calcium silicates. Addition of a relatively small amount of limestone to the sinter residue (about 1 Mg of limestone per 4 Mg of sinter residue) would result in production of Portland cement at a higher throughput for a given kiln size because of the reduced energy requirements and the reduced amount of feed material (Grzymek, 1974).

The Economics of Cement Production from Sinter Residues

The cost estimate for a cement facility to use the extracted sinter residue of the lime-soda sinter process is presented in Table 7. Processing the sinter residue with additional limestone can produce over 500,000 Mg of Portland cement as another product of fly ash utilization.

The combination of the lime-soda sinter process with cement production results in a profitable operation, while at the same time disposing totally of the waste coal ash. Table 8 is a discounted cash flow sheet for the combined alumina-cement production facility. Even with the conservative basis for estimating used, the discounted cash flow rate of return is an acceptable 14.4 percent.

Bases for Cost Estimates Used

The lime-soda sinter process equipment costs are based on U.S. Bureau of Mines equipment designs developed to recover alumina from clay and anorthosite (Peters et al, 1967). Equipment capacities of individual units and the similarity in operating conditions make possible the almost direct application of some of the equipment in the lime-soda sinter process. Costs were calculated using a capacity ratio raised to the 0.9 power. The Marshall and Swift (formerly Marshall and Stevens) installed equipment cost indexes was used to update estimates.

The capacity of the cement plant is nearly equal to that of a plant designed by Katell, 1977. The cement plant cost was therefore determined by simply updating this earlier estimate using the Marshall and Swift indexes.

Table 7. Estimated Production Cost for Portland Cement from Lime-Soda Sinter Process Residue[1]

	Mg per Year	Production Cost $ per Mg Cement[1]	
Direct Costs			
Limestone, $6.60/Mg	114,000	1.35	
Sinter residue, no cost	455,000	--	(0.90)[2]
Gypsum, $22/Mg	27,000	1.09	
Coal, $33/Mg	243,000	14.56	
Electric power, 4¢/Kwhr		1.20	
Water, 10¢/m^3		0.10	
Operating labor		1.85	
Supervision and benefits		1.85	
Maintenance and supplies		2.65	
Total Direct Costs		21.80	(22.70)[2]
Indirect Costs			
Depreciation, 20-year life		3.25	
Interest, 7 percent for 20 percent debt		0.90	
Insurance and local taxes		1.85	
Overhead		1.85	
Total Indirect Costs		7.85	
Total Production Cost		29.65	(30.55)[2]

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[1] Wet process plant, 350 day operating year, producing 550,000 Mg cement per year, installed capital cost $36 million

[2] Sinter residue is purchased at $1.10 per Mg.

Table 8. Discounted Cash Flow for the Production of Alumina and Cement from Fly Ash for a 1000 MWe Power Station.

	$ per Year
Total Sales	
Alumina at $209 per Mg (45,500 Mg per Year)	$ 9,510,000
Cement at $66 per Mg (550,000 Mg per Year)	36,300,000
	45,810,000
Production Cost	
Alumina, $337 per Mg[1]	15,335,000
Cement, $30 per Mg[1]	16,500,000
	31,835,000
Profit before taxes	13,975,000
Federal income tax, 50 percent	6,987,000
Net profit after taxes	6,988,000
Depreciation, 5 percent of fixed capital cost	3,640,000
Cash flow	10,628,000

$$\text{Payout time}^2 = \frac{\$68,780,000}{\$10,628,000} = 6.5 \text{ years}$$

Discounted cash flow rate of return (20-year life of plant) = 14.4 percent

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[1] Limestone and fly ash purchased at $6.60 per Mg, sinter residue provided at no cost.

[2] Payout time= Total capital cost/Cash flow

Summary

The combustion of increasing amounts of pulverized coal, principally by utilities, can be expected to add to already serious fly ash disposal problems. The 1976 Resource Conservation and Recovery Act (RCRA) has resulted in research sponsored by EPA that could lead to more restrictive rules for coal ash disposal.

Work at the Ames Laboratory on fly ash utilization as an alternative to disposal has resulted in a sintering process that shows promise of consuming large amounts of solid wastes economically to provide materials important to our national economy. An estimate for a processing facility to produce alumina and cement from the fly ash of a 1000 MWe coal-fueled power station shows a DCF rate of return of 14.4 percent when the plant life is assumed to be 20 years. The capital cost for both parts of the facility totals $68.8 million. Use of an average quality fly ash and a recovery of 80 percent of the contained alumina were assumed.

The operating cost estimate calls for purchase of both the limestone and fly ash. The return on investment is more attractive when credit is taken for fly ash disposal, and the limestone is replaced by quarry fines or cement kiln dust.

Literature Cited

Abernathy, R. F., M. J. Peterson, and J. F. Gibson, "Major Ash Constituents in U.S. Coals," U. S. Bur. of Mines R. I. 7240 (1969).

Ash at Work, Vol. IX, No. 6 (1977).

Ash at Work, Vol. XI, No. 2 (1979).

Canon, R. M., F. G. Seeley, and J. S. Watson, "Engineering Analysis and Comparison of New Processes for the Recovery of Resource Materials from Coal Ash," Proc. 5th International Ash Utilization Symposium, U.S.D.O.E. METC/SP-79/10 (Pt. 1), 56, Atlanta, GA, February (1979).

Chemical Engineering Reporter, March 17 (1980).

Coles, D. G. et al, "Chemical Studies of Stack Fly Ash from a Coal-Fired Power Plant," Environ. Sci. Tech., 13, 455-459 (1979).

Grzymek, J., "Alumina-from-Clay Plant Gives Cement Bonus," Process Engineering, 43, February (1974).

Gulyas, Imre and Gyorgy Vamos, "Problems of the Production of Alumina and Cement Based on Low-Grade Aluminum Carriers, and the Optimum Solution of the Problems," Hungarian Heavy Industries, Third Quarter, Vol. 27, 36 (1976).

Heffelfinger, J., Private communication, U. S. Environ. Prot. Agency, Div. Haz. Matls., Washington, D.C., October 28 (1980).

Kammermeyer, Karl and Alfred H. White, "The Extraction of Alumina from Kaolin and Other Silicates," Proc. AIChE, 683 (1941).

Katell, Sidney, "The Potential Economics of the Recovery of Trace Elements in Coal Refuse," Proc. 3rd Kentucky Coal Refuse Disposal and Utilization Seminar, 89, May 11-12, Lexington, KY (1977).

Mineral Commodity Summaries 1980, U. S. Bur. of Mines, U. S. Dept. of the Interior (1980).

Murtha, M. J. and G. Burnet, "New Developments in the Lime-Soda Sinter Process for Recovery of Alumina from Fly Ash," Proc. 5th International Ash Utilization Symposium, U.S.D.O.E. METC/SP-79/10 (Pt. 1), 68, Atlanta, GA, February (1979).

"New Strategy for an Old Game," EPRI Journal, 6, October (1980).

"Oil Seeks Top Role in Coal Game," Coal Age, 64, October (1979).

Peters, Frank A., Paul W. Johnson, John J. Henn, and Ralph C. Kirby, "Methods for Producing Alumina from Clay," U. S. Bur. of Mines R.I. 6927 (1967).

Peters, Frank A. and Paul W. Johnson, "Revised and Updated Cost Estimates for Producing Alumina from Domestic Raw Materials," U. S. Bur. of Mines I.C. 8648 (1974).

Roy, N. K., M. J. Murtha, and G. Burnet, "Recovery of Iron Oxide from Power Plant Fly Ash by Magnetic Separation," Industrial Applications of Magnetic Separations, IEEE Publication No. 78CH1447-2 MAG, 32 (1979).

Sèailles, J. C., "The Manufacture of Cement and Other Products," Cement and Lime Manufacture, 20, 1 (1947).

Smith, R. D., J. A. Campbell and K. K. Nielson, "Concentration Dependence Upon Particle Size of Volatized Elements in Fly Ash," Environ. Sci. Tech., 13, 553-558 (1979).

"The Continuing Disposal of Coal Ash," EPRI Journal, 18, March (1980).

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