1 of 1

Multiple-Use Marketing of Lignite

Topical Report

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TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	iii
EXECUTIVE SUMMARY	ES-1
1.0 INTRODUCTION	1
2.0 INFORMATION COLLECTION	2
2.1 Knife River Coal Mining Company	2
2.2 J.R. Simplot Company	2
2.3 Grand Forks City Water Department	2
2.4 Grand Forks City Wastewater Treatment	3
2.5 Grand Forks City Landfill	3
2.6 American Crystal Sugar Company	3
2.7 University of North Dakota Plant Services	4
2.8 Concrete Company	4
2.9 Equipment Vendors	5
3.0 EXPERIMENTAL	6
3.1 Raw Materials	6
3.1.1 Coal	6
3.1.2 Calcium	6
3.1.3 Wastewater Treatment	6
3.1.4 Briquette Production	10
4.0 MULTIPLE-USE MARKETING	10
4.1 Potential Markets	10
4.2 Product Quality	11
4.3 Processing Economics	11
4.3.1 Raw Materials	11
4.3.2 Wastewater Treatment	12
4.3.3 Briquette Production	12
4.3.4 On-Site Cogeneration	12
4.3.5 Ash in Concrete	14
4.3.6 Coal Feed Cost and Product Value	15
5.0 CONCLUSION	16
6.0 REFERENCES	16
Appendix A: Multiple-Use Marketing (MUM) – Potato Wastewater Cleanup	A-1
Appendix B: Multiple-Use Marketing of Lignite	B-1
Appendix C: Library Search Information	C-1

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Sample Collection and Analysis	7
2	Knife River Coal Analysis Data	8
3	Ash Analysis of Calcium Sources	9
4	Comparison of Feed Coal Costs to Market Value	15

EXECUTIVE SUMMARY

Marketing of lignite faces difficulties due to moisture and sulfur contents, as well as the sodium content, of the ash. The purpose of this Energy & Environmental Research Center (EERC) study is to determine the economic viability of multiple-use marketing of lignite as a method to increase the use of North Dakota lignite by recapturing lost niche markets. Multiple-use marketing means using lignite and sulfur-capturing additives to clean agricultural wastewater followed by either direct steam and power generation or briquetting to produce a higher-Btu compliance fuel. Cooperative ownership of the resulting business by a coal company and an agriculture processing company helps ensure that lignite remains the coal of choice, especially when the "good" attributes of lignites are maximized, while the agricultural company obtains cleaner wastewater and a long-term supply of coal at a set price.

The economic viabilities of the following scenarios were investigated: 1) Agri-processing wastewater treatment using lignite and an additive followed by 2) the production of compliance fuel for resale or on-site cogeneration of steam and electricity.

Information has been collected, and preliminary experimental work has been performed. A number of companies and government entities have been contacted for information and all have been very helpful in assembling and providing information for use in this study.

The preliminary laboratory tests indicated that treating potato-processing plant wastewater with lignite and lime sludge does result in clarification and decreased tendencies to produce odor. The resulting mixture of lignite, lime sludge, and starches can be successfully briquetted after partial drying. However after scaleup, it was found that the pilot-size centrifuge would not remove coal fines nor clarify the wastewater.

In separate testing, starchy material was precipitated from wastewater using iron, concentrated, mixed with coal, and briquetted. However, since coal did not replace iron in the precipitation step, the economic viability of multiple uses of coal disappears. The use of coal to produce steam is viable and cost effective but initial capital costs are higher, making the payoff up to 15 years after initiating operation. The question remains; how do we convince the end user to take advantage of low-cost coal for energy production? It seems turnkey systems (coal for x years at \$ x , steam plant installed at \$ x , etc.) in the range of 40,000 – 100,000 lb of steam are needed to provide a more attractive package to the end user.

MULTIPLE-USE MARKETING OF LIGNITE

1.0 INTRODUCTION

The interest of the state of North Dakota in determining the opportunities for lignites is indicated by marketing and upgrading studies underway (1-4). However, a cursory examination of upgrading costs suggests that North Dakota lignites face an uphill battle if the end product is limited to a cheap fuel.

The concept of multiple-use marketing involves the integrated use of the good properties of lignite (i.e., ionic nature, high water content) as a bulk-treatment agent for agricultural wastewater. The addition of waste calcium aids water treatment by increasing pH, increasing the coal quality (by replacing sodium in the lignite), and decreasing emissions during combustion by retaining sulfur in the ash. Although adding calcium increases the ash content of the product fuel, the final ash can also represent a potential value-added product. Steps to be evaluated for economic projections are as follows:

1. Costs of coal, receiving and storage
2. Crushing of coal
3. Receiving of calcium sludge
4. Contact of wastewater, coal, and sludge
5. Recovery of solids and cleaned water
6. Partial drying of solids

and (Market Scenario 1)

7. Briquetting of solids
8. Marketing of compliance fuel
9. Production and marketing of a cement replacement

or (Market Scenario 2)

7. Utilization of the fuel in an on-site cogeneration unit
8. Production and marketing of a cement replacement

Information from a potential market has been collected (5-9), as well as vendor information, to provide a better evaluation of the actual costs and values of each step. Combustion information indicates that a fluid-bed configuration would give high-sulfur retention and low-NO_x production (10). A unique aspect that required some experimentation was the treatment of wastewater with combined lignite and calcium.

The best economic scenario is expected where steps are fully integrated by utilizing waste heat from electricity and steam production and from agricultural processing to reduce the moisture content of the lignite. The drier lignite then becomes an inexpensive fuel source for producing steam and electricity.

2.0 INFORMATION COLLECTION

2.1 Knife River Coal Mining Company

The Knife River Coal Mining Company (part of MDU Resources Group Inc.) operates the Beulah mine with an approximate production level of 2.4 million tons per year (MM t/yr) (2). Additional sales of 200,000 t/yr would represent an increase of about 10% in production and add 12 jobs (due only to increased coal production) and \$154,000 in additional coal severance tax receipts (11). At a coal value of \$10/t, the company would have an increase of \$2,000,000 in gross income. Two 50-gal drums of raw coal have been provided and crushed to 100% minus ¼ inch for use in the testing.

2.2 J.R. Simplot Company

The J.R. Simplot Company presently uses 0.7 to 1 MM gal/day of water (about 20% of the city water supply) to process potatoes. After use in the processing of potatoes, this water (less evaporative and other losses) is partially treated and discharged to the city for further treatment. The cost of feed water has increased from \$0.28 to \$1.52/M gal over the years. Wastewater costs are presently about \$0.75/M gal for water containing around 2000 mg/L of suspended solids at a pH of 7-7.5. Wastewater treatment at the plant consists of aeration and settling ponds to reduce BOD and suspended solids prior to discharge to the city.

Another potential source of starchy material is the various plant waste solids and primary clarifier sludge that are collected and disposed of as cattle feed (about nine 5000-gal truckloads/day). This material has a pH of 3.5 and is 85% water. The haulage fee is subsidized.

Steam for the plant is supplied by natural gas- or oil-fired boilers. Electricity is purchased. Space is available for additional water treatment facilities, and a rail spur line is also present.

Open access was provided to collect fresh samples of wastewater for use in experiments. A literature search was performed, and articles were reviewed concerning potato wastewater treatment; pertinent articles are listed in Appendix C.

2.3 Grand Forks City Water Department

One part of this work was to investigate the use of lignite as a water treatment additive to remove organics while softening the water. After further evaluation, this effort was tabled. The treatment plant operates in a fixed manner and very successfully produces 5 million gal of drinking water a day that has to meet strict specifications. The testing and integration of lignite into the processing would require more funding than is available in this contract. Also, even if the small tests were successful, it would be necessary to build and operate a demonstration unit prior to any use in a city's drinking supply. It could easily require five or more years to do the testing and certification.

The city of Grand Forks purchases and uses 4,358,000 lb/yr of dry lime in the treatment of water, which is recovered as a sludge that is presently landfilled. After use in the treatment of water, the sludge is recovered by settling and filtration, loaded on a

truck, and transported to the landfill (by the J.R. Simplot Company drivers) where it is used as ground cover. In 1992, 19,000 tons of landfill (LF) sludge (25%–29% solids) was transported by one driver (\$32,000/year with benefits) in one of two dedicated 13-ton trucks (\$60,000 each). Truck maintenance is increased due to flat tires caused by the landfill. Since it is a city landfill, no tipping fee is required. However within ten years, a regional landfill may be established. A \$10/t tipping fee would add \$190,000 to the cost of disposing this material.

The LF sludge has been analyzed by the city for trace metals and is still acceptable as a landfill material. Alternate plans for its ultimate use would need approval by appropriate state agencies.

Samples of the LF sludge and a more calcium-rich stream (softening basin [SB] sludge) were obtained for analysis and use in testing.

2.4 Grand Forks City Wastewater Treatment

The cost of discharging wastewater to the city treatment system is covered by permit fees for individual companies and determined by city ordinance (5, 6, and 9). A surcharge is in effect for water containing total suspended solids over 350 ppm and a biological oxygen demand (BOD) value over 300. Penalties are assessed if maximum values are exceeded. The acceptable water pH is from 5.5 to 9.5. Although no value is specified for water sodium content, it does affect the bacteria and, therefore, is of concern.

The city lagoon is 33–34 years old. Improvements in, and replacement of, equipment is being planned or is in progress. The lagoon is scheduled to be cleaned in 1995 by removing the sludge. At present sludge can be landfilled. Blowers are used to aerate the lagoon at an electricity cost of \$10,000 to 12,000 per month. Receiving a "cleaner" wastewater would mean fewer blowers would be needed.

2.5 Grand Forks City Landfill

The Grand Forks city landfill is projected to have an eight- to ten-year lifetime and is currently serving as the regional landfill. A consultant is presently reviewing landfill needs of the future. Coal ash is accepted at a purchase price of a few cents/t. It is spread out, dried, and subsequently used as a daily cover material. This sludge is considered hard to handle, and landfill operators would gladly forego working with it. City water treatment sludge is accepted at no cost. The present tipping fees for any industry are \$13/t for the city of Grand Forks and \$19/t for other locations. As long as the city of Grand Forks is responsible for the landfill, no change is expected in the landfill operation. However, if a regional authority were established, the city may be subjected to tipping fees.

2.6 American Crystal Sugar Company

The American Crystal Sugar Company (ACSC) has a number of plants in the Red River Valley. One is located in East Grand Forks, Minnesota, and has been contacted for information concerning their plant. This plant uses 167,000 t of coal to produce steam or to dry beet pulp over a 220-day campaign in the processing of sugar beets. In addition, about 3530 t of coke (costing about \$150/t) was used in 122 days of this campaign. The

coal source was North Dakota lignite until about 1986 when sulfur emissions were considered a problem. The present source of coal is Colstrip, Montana. That coal costs \$34.80/t delivered, and was last analyzed at 9301 Btu/lb, 25.22 wt% moisture, 4.32 wt% ash, and 0.34 wt% sulfur. The coal is delivered in unit trains of 97 to 123 cars and is unloaded indoors. The stockpile is packed by a bulldozer to limit water contact and control spontaneous combustion. The sulfur emissions are well in compliance at about 0.4 lb SO₂/MM Btu. The coal is fired in a Babcock & Wilcox spreader-stoker boiler.

This plant uses 100,000 tons of a limerock feed each year. This material is calcined with coke before being used in the cleaning of sugar water. The material is subsequently removed using a filter, reslurried, and pumped to an on-site lagoon where it is allowed to dry. Over 400 acre-feet of dry material and 400 acre-feet of wet material are available. In the past, truckloads of the dry material had been given to farmers as a soil additive. Using a front-end loader, this dry powder can be readily loaded to dump trucks and transported. More recently, the Minnesota Pollution Control Agency (MPCA) has put restrictions on the shipment of this material. The company has a consultant looking at disposal methods. Samples of the waste-lime sludge material from the filter were obtained for analysis and used in testing.

2.7 University of North Dakota Plant Services

The University of North Dakota (UND) operates a steam plant that consumes up to 70,000 tons of coal per year. In December of 1992, 110,663 units of steam were produced (1 unit equals 1000 psi of steam). At present, only 37,000 tons of coal are used and the balance of energy is supplied by natural gas to reduce sulfur emissions. The present coal from Montana costs \$25.90/t delivered at 8784 Btu/lb and less than 0.77 wt% sulfur. The delivered price is adjusted if the heating value is not within 125 Btu/lb of the contract value. Average values for ash and sulfur contents are 6.6 wt% and 0.45 wt%, respectively. A 160-ft stack is under construction to enable the use of more coal. Ash is removed at a contracted cost of \$4.00/t. The contractor trucks the ash to the city landfill where it is purchased for the contract price of a few cents/t and is used as a road amenity (over ice and snow).

Fugitive coal dust and spontaneous combustion are concerns since coal is stockpiled for up to two years. Another concern is the effect of higher-Btu coals on furnace grates. Any test projects at the university plant would need proper permitting by state agencies.

2.8 Concrete Company

A local concrete company was contacted concerning their use of fly ash in the cement. They generally use 20% fly ash as a cement replacement. For a five-bag mix of cement per yard of concrete, they would use 376 lb of cement and 94 lb of fly ash. They use approximately 150 t/yr, Class C or F, at a delivered cost of about \$33/t.

The rights to fly ash are presumably sold by bid for five-year contracts by a utility. One contract holder is Contech Admixtures, Inc. (800-989-0665), out of Minneapolis, Minnesota. A local distributor indicated that they purchase thousands of tons of fly ash and provided a sample and an analysis sheet. The analysis had been performed at the EERC By-Products Utilization Laboratory.

2.9 Equipment Vendors

A number of vendors who market commercial-size equipment in the areas of coal crushing, solids removal from water, coal drying, and briquetting have provided estimated costs of equipment to produce approximately 20 t/hr of product. The information listed below includes estimated equipment costs and operational requirements.

Coal Crushing

- a. Gundlach Model 30-1C3R Cage-Paktor: \$30,000 F.O.B. Illinois requires 60-hp motor, with 75 hp could operate at 30 t/hr estimate 6 cents/t for parts and 100 hr/yr for maintenance
- b. Alternate double roll crusher, would need to run a test.

Coal/Wastewater Slurry Centrifuging

- a. Screen Bowl Centrifuge: \$250,000 new, \$150,000 refurbished, 35 wt% solids feed at 75,000 to 90,000 lb/hr to 55 wt% solids product screen of +1/8" material
150-200 hp, 4-6 cents/t for parts, 200 hr/yr maintenance.

Coal Product Drying

- a. PESCO fluid-bed dryer: \$313,350
feed 45,000-55,000 lb/hr, product at 65%-70% solids
assumes on-site FBC delivering 250°F drying gas
requires at least 1 operator

Dust Collection Baghouse: \$350,000
bags once per year at \$45,000 plus 165 hours labor
about a 450-hp system

- b. Aeroglide Rotary Drier: \$438,300 F.O.B. Raleigh, NC
feed minus 1/4 inch, 70% minus 60-mesh
45,500 lb/hr (7,000 lb of evaporation to 35% moisture)
40-hp drum, 150-hp fan
little operator time, internal repairs in 3-5 years
- c. Conveyor Drier: would require initial removal of fines

The above listing indicates that the cost of crushing coal is modest compared to that of drying, especially if fines require the use of a baghouse. The best overall cost estimate for site preparation and handling is \$15,000,000 for feeding two 170,000-lb steam fluidized-bed steam units; this estimate would be a \$15,000,000 addition to the cost estimate based on the "Iowa installation" (11,12). References to the above pricing are available from the Principal Investigator.

3.0 EXPERIMENTAL

3.1 Raw Materials

3.1.1 Coal

Knife River Coal Mining Company has provided two 50-gal drums of raw coal from its Beulah mine for this study. The coal was crushed to 100% minus $\frac{1}{4}$ inch. Sieve analysis data indicate the crushed product is essentially 100% minus 10 mesh (see Table 1). Proximate, ultimate, heating value, and ash analysis data for the crushed coal (considered "as received" [AR]) are provided in Table 2.

A value of 2.08 lb of SO_2 /MM Btu can be calculated from the sulfur content of the coal. However, the actual sulfur emissions are related to the firing temperature of the furnace. In an ASTM ash analysis performed at 750°C , 75% of the calcium in the coal captures sulfur, trapping it in the ash and reducing the predicted emissions of sulfur dioxide to 0.71 lb of SO_2 /MM Btu. At hotter combustion temperatures, less sulfur is captured by the alkali constituents in the ash, increasing the emission of sulfur dioxide. Two methods of reducing the sulfur dioxide emission include reducing the combustion temperature and/or adding calcium to the coal. Fluidized-bed combustion appears to be the optimum combustion system for reducing both SO_x and NO_x emissions.

3.1.2 Calcium

In the proposed multiple-use concept, calcium-waste materials can help clean potato-processing wastewater and add calcium to the resultant coal product to aid in sulfur capture. The addition of calcium will also influence a potential use of the combustion ash as a cement replacement.

Three samples of calcium-containing sludge were obtained from local producers for analysis (Table 3, see bottom of table for abbreviations). All three samples have very similar chemical compositions. The waste-lime sludge contains the highest amount of dry solids and calcium. However, the LF sludge was selected for use in the testing over the waste-lime sludge for economic reasons (discussed later). The SB sludge was eliminated since it is from an intermediate step in water treatment, and removing the sludge could affect the downstream processing.

3.1.3 Wastewater Treatment

Fresh potato wastewater has been mixed with various amounts of coal and SF sludge to determine (based on clarity and odor) the best proportions. The amounts are consistent with 1) estimated amounts of suspended solids in the wastewater needed to briquette the coal and 2) estimated amounts of calcium needed in the final coal product to capture sulfur during combustion.

The results of lab-scale and larger-scale feasibility testing are discussed in Appendices A and B, respectively. In the laboratory it was possible to successfully mix coal and waste lime sludge with the wastewater, to centrifuge out solids, and to produce pellets using a hand press. When the lab methods were taken to the pilot-size centrifuge it was found that this unit would not remove the coal fines. A number of variations of

TABLE 1

Sample Collection and Analysis

A. Coal, Beulah Lignite**I.D. Abbreviation****MUM-2**

Dry Sieve	See below
Proximate-Ultimate	See Table 2
Heating Value	See Table 2
Ash-XRF	See Table 2
Ash Fusion (reducing)	See Table 2

Received 2 drums from Knife River. Pulverized to 100% -0.25".

COAL SIEVE ANALYSIS

<u>Sieve Size</u>			<u>Coal Retained, %</u>	<u>Cube^a m²/100 g</u>	<u>Surface Area</u>	
					<u>Area Contribution</u>	
<u>Mesh</u>	<u>mm</u>	<u>in.</u>			<u>m²</u>	<u>%</u>
5	4	0.1575	0.00	11	0.0	0.00
10	2	0.0787	4.26	21	0.9	0.41
16	1.19	0.0469	22.25	36	8.0	3.59
35	0.500	0.0197	31.58	86	27.1	12.13
60	0.250	0.0098	15.46	171	26.5	11.87
100	0.150	0.0059	7.00	286	20.0	8.96
140	0.105	0.0041	3.93	408	16.0	7.19
200	0.074	0.0029	3.20	579	18.5	8.30
270	0.053	0.0021	2.06	809	16.7	7.46
325	0.044	0.0017	0.33	974	3.2	1.44
Pan	--	--	8.86	974	86.3	38.66
Total			98.93		223.2	100.01

B. Calcium Sources**I.D. Abbreviation****ACSC-Sludge^b****LF-Sludge^c****SB-Sludge^d**

Dry Solids, 110°C	56.50%	27.70%	13.10%
Dry Ash, 750°C	53.24%	56.81%	56.51%
Ash-XRF (see Table 3)			
Ash Fusion, °F (reducing)			
Initial	2726	> 2800	> 2800
Softening	2729		
Hemi.	2730		
Fluid	2735		

^a Values calculated assuming cubic-shaped coal particles.

^b Waste sludge sample obtained from American Crystal Sugar Company, 1-6-92.

^c Landfill sludge sample obtained from the Grand Forks Water Department, 1-7-92.

^d Softening basin sludge sample obtained from the Grand Forks Water Department., 1-7-92.

TABLE 2

Knife River Coal Analysis Data (1-13-93; Lab Number 93-0011)

Proximate Analysis, wt%	As Determined	As Received	Moisture-Free	Moisture- and Ash-Free		
Air Dry Loss	19.43					
Moisture	19.96	35.51	--			
Volatile Matter	37.05	29.85	46.29	51.19		
Fixed Carbon	35.33	28.47	44.14	48.81		
Ash	7.66	6.17	9.57	--		
Total	100.00	100.00	100.00	100.00		
Ultimate Analysis, wt%	As Determined	As Received	mf	maf		
Moisture	-- ^a	35.51	--	--		
Carbon	41.67	41.67	64.61	71.45		
Hydrogen	6.48	2.53	3.93	4.35		
Nitrogen	0.50	0.50	0.77	0.85		
Oxygen (dif)	44.45	12.88	19.98	22.09		
Sulfur	0.74	0.74	1.14	1.26		
Ash	6.17	6.17	9.57	--		
Total	100.00	100.00	100.00	100.00		
Heating Value, Btu/lb	8878	7072	10,967	12,128		
lb-SO ₂ /MM Btu	2.08					
	Elemental		As Oxides, wt% of Ash			
Ash Analysis	wt% (from norm.)	Moles/ 100 g ash	Oxide	As-Deter.	Normal	SO ₃ -Free
Silicon	11.844	0.422	SiO ₂	26.69	25.34	31.49
Aluminum	6.245	0.231	Al ₂ O ₃	12.43	11.80	14.67
Iron	4.668	0.084	Fe ₂ O ₃	7.03	6.67	8.29
Titanium	0.250	0.005	TiO ₂	0.44	0.42	0.52
Phosphorous	0.447	0.014	P ₂ O ₅	1.08	1.03	1.27
Calcium	13.047	0.326	CaO	19.23	18.26	22.69
Magnesium	5.718	0.235	MgO	9.99	9.48	11.79
Sodium	5.345	0.233	Na ₂ O	7.59	7.21	8.96
Potassium	0.213	0.005	K ₂ O	0.27	0.26	0.32
Sulfur	7.827	0.244	SO ₃	20.59	19.55	
Total				105.34	100.00	100.00
Molar Ca/S Ratio		0.87				
Sulfur Retention, %		65.71	0.71 lbs-SO ₂ /MM Btu			
Ash Fusion	Initial Temp.		2063 °F		Hemi.	2128 °F
Reducing Atm.	Softening		2073 °F		Fluid	2447 °F

^a Hydrogen and oxygen from water included as elements.

TABLE 3

Ash Analysis of Calcium Sources

LANDFILL SLUDGE (93-0013)						
Ash Analysis (wt%)	Elemental		As Oxides, wt% of Ash			
	(From Norm.)	Moles/ 100 g Ash	Oxide	Deter.	Normal	SO ₃ - Free
Silicon	1.303	0.046	SiO ₂	2.75	2.79	2.84
Aluminum	0.703	0.026	Al ₂ O ₃	1.31	1.33	1.35
Iron	0.163	0.003	Fe ₂ O ₃	0.23	0.23	0.24
Titanium	0.000	0.000	TiO ₂	0.00	0.00	0.00
Phosphorous	0.000	0.000	P ₂ O ₅	0.00	0.00	0.00
Calcium	57.837	1.443	CaO	79.85	80.93	82.46
Magnesium	7.510	0.309	MgO	12.29	12.46	12.69
Sodium	0.113	0.005	Na ₂ O	0.15	0.15	0.15
Potassium	0.210	0.005	K ₂ O	0.25	0.25	0.26
Sulfur	0.747	0.023	SO ₃	1.84	1.86	
Total				98.67	100.00	100.00
SOFTENING BASIN SLUDGE (93-0014)						
Ash Analysis (wt%)	Elemental		As Oxides, wt% of Ash			
	(From Norm.)	Moles/ 100 g Ash	Oxide	Deter.	Normal	SO ₃ - Free
Silicon	1.321	0.047	SiO ₂	2.82	2.83	2.91
Aluminum	0.355	0.013	Al ₂ O ₃	0.67	0.67	0.69
Iron	0.161	0.003	Fe ₂ O ₃	0.23	0.23	0.24
Titanium	0.000	0.000	TiO ₂	0.00	0.00	0.00
Phosphorous	0.000	0.000	P ₂ O ₅	0.00	0.00	0.00
Calcium	56.935	1.421	CaO	79.48	79.66	82.04
Magnesium	8.044	0.331	MgO	13.31	13.34	13.74
Sodium	0.097	0.004	Na ₂ O	0.13	0.13	0.13
Potassium	0.200	0.005	K ₂ O	0.24	0.24	0.25
Sulfur	1.160	0.036	SO ₃	2.89	2.90	
Total				99.77	100.00	100.00
ACS LIME SLUDGE (93-0012)						
Ash Analysis (wt%)	Elemental		As Oxides, wt% of Ash			
	(From Norm.)	Moles/ 100 g Ash	Oxide	Deter.	Normal	SO ₃ - Free
Silicon	1.768	0.063	SiO ₂	3.57	3.78	3.85
Aluminum	0.303	0.011	Al ₂ O ₃	0.54	0.57	0.58
Iron	0.267	0.005	Fe ₂ O ₃	0.36	0.38	0.39
Titanium	0.000	0.000	TiO ₂	0.00	0.00	0.00
Phosphorous	0.948	0.031	P ₂ O ₅	2.05	2.17	2.21
Calcium	62.249	1.553	CaO	82.23	87.10	88.72
Magnesium	2.223	0.091	MgO	3.48	3.69	3.75
Sodium	0.086	0.004	Na ₂ O	0.11	0.12	0.12
Potassium	0.299	0.008	K ₂ O	0.34	0.36	0.37
Sulfur	0.734	0.023	SO ₃	1.73	1.83	
Total				94.41	100.00	99.99

sized coal was tried. In these sizing tests it was determined that once the coal was sized, the over -60-mesh material resisted further size degradation in tumbling tests. Also, when drying over -60 mesh coal that had been in contact with wastewater the residual dust was nonelectrostatic, i.e., it did not stick to container walls but separated easily from the coal. The addition of the lime sludge or coal controlled the pH, resulting in a wastewater that did not develop odors over extended periods of time. However, in general the presence of coal particles or fines did not significantly reduce the suspended-solids content of the wastewater.

A number of additives were used to catalyze the precipitation of wastewater suspended solids. Of these, iron chloride was used to produce a quantity of starchy material that could be used in additional briquetting tests.

3.1.4 Briquette Production

Samples of the recovered solids have been tested to determine their potential for briquetting. In the preliminary tests, pellets were made using a laboratory press (about 1 gram of material) and were tested using simple drop, water immersion, and drying tests. The recovered coal was air-dried prior to pelletizing, at ambient conditions. Two size fractions have been tested, -200 x 0 (Size 1) and -1/4 x 0 (Size 2). Pellets made from the Size 1 material (at 15,000 psi) withstand dropping on a tile floor from 6 feet and maintain integrity when immersed in water for 10 days. They form fissures when heated at 110°C for 1 hour and will break along the fissures, but the broken pieces retain their integrity. Pellets made from the Size 2 material (at 10,000 psi) break more readily and do not maintain integrity in water. When made at 15,000 psi, the pellets have a greater resistance to breaking but still do not have the integrity exhibited by the Size 1 material. It appears that in the small pellets, the presence of large coal particles relative to the size of the pellets causes fracture lines that reduce particle strength.

Additional testing indicated that enough starchy material for optimum breakage resistance was not recovered by simply mixing coal and wastewater without excessive centrifuging or filtration. To improve briquette quality, shredded newspaper and/or additional starchy material (precipitated with iron) was added. The addition of more starchy material resulted in stronger briquettes.

4.0 MULTIPLE-USE MARKETING

4.1 Potential Markets

At least four markets for compliance coal exist within a one-hour delivery time from the production site:

1. American Crystal Sugar Company	170,000 t/yr	\$1.86/MM Btu
2. University of North Dakota	70,000 t/yr	\$1.46/MM Btu
3. J.R. Simplot Company (new)	70,000? t/yr	\$1.51/MM Btu
4. Small Users	1,000? t/yr	\$43/t picked up

Market 1 is presently paying the most and, therefore, sets the upper limit for the value of a quality coal product. To switch from their present supplier at the same cost, it

would probably be necessary to have a higher-quality product (such as less dust, subsidized storage-compaction costs, and/or an ash-removal service). The other possibility is a lower-cost product.

To penetrate Market 2, the product must be delivered at a price below \$25.90/t at 8784 Btu/lb, and/or bid specification changes must include quality parameters that would improve the competitiveness of a local supplier, such as ash removal along with coal delivery (presently ash disposal costs UND \$0.26/t for each ton of coal purchased). Ash disposal would be more important for higher-ash briquette users.

Market 3 would be able to obtain the processed coal at the lowest cost. The coal used in potato-processing wastewater treatment could be transferred to an on-site cogeneration unit without prior briquetting. In this case, the type of combustion unit could be designed to take advantage of the qualities of the feedstock.

Market 4 represents low-coal use by local users. A small market must exist since one supplier of stoker and lump coal is listed in the phone directory. The lignite lump or stoker coal is sold for \$43/t but must be picked up in Lakota, North Dakota. Another, unlisted, supplier in East Grand Forks obtains about a railcar load per year of oil-treated, stoker ($\frac{1}{4} \times 1\frac{1}{4}$ inch) coal (9400 to 9600 Btu/lb) from the Big Horn mine, Wyoming. This coal can be purchased delivered for \$95/t (minimum half-ton lots). It works best in forced-draft systems. Lignites are not used due to dusting, high volume, and high-ash content and since the coal is held over the summer. It is likely that if a local, economical supplier were available, a market would develop for home use. Although small, it could command at least \$43-\$95/t.

4.2 Product Quality

The required quality of the product varies primarily with:

1. convenience of delivery.
2. ease of storage (spontaneous combustion).
3. ease of handling (dusting).
4. performance in the combustion unit (maintenance, efficiency).
5. degree of emissions compliance.
6. ease of combustion-product disposal (ash).

4.3 Processing Economics

4.3.1 Raw Materials

Two primary raw materials are associated with this process: coal and the calcium additive. The delivered cost of coal will be determined by the mining costs, transport costs, and the tons of raw coal required to produce the product. The lowest cost is \$25.90 to deliver 1 t of 8784-Btu/lb coal by rail to Grand Forks from Montana. The shipping costs for lignite is about \$10.50 to Fargo, North Dakota, and \$11.50 to Grand Forks. This shipping cost is higher than an estimated cost of \$10.50 to ship lignite 500 miles (2), but lower than the range of \$13 to \$16/t (4). A nominal, delivered cost for lignite delivered to the city of Grand Forks is \$23.75/t.

The other raw material required is calcium, and the city and American Crystal Sugar are two sources. The sugar beet plant material would probably require, at a minimum, loading and transporting the material to Simplot, which would add production costs. The most economical source at present is the landfill sludge from the city-water treatment plant. This material is presently being trucked to the landfill. Shorter transport from the landfill would represent a cost savings to the city due to less mileage and maintenance savings. The profit from the calcium is estimated to be up to \$1.00/t (indicating a small waste disposal fee charged to the city). In the future as disposal rules tighten, a higher disposal fee of up to \$10.00/t may be feasible.

4.3.2 Wastewater Treatment

Present wastewater disposal costs of wastewater containing 2000 ppm of suspended solids and 575 ppm of chemical oxygen demand (COD) are \$1.06/1000 gal. Of this, \$0.29 is due to the suspended solids and COD content of the water. In this study, we hoped to show that coal could be used to significantly reduce contaminant levels. However, no reduction was evident. Two alternative methods of reducing suspended solids content are the addition of either lime or iron. Lime addition at a rate of 0.1 wt% would cost \$0.25/1000 gal treated, while iron at a treatment rate of 0.02 wt% would cost \$1.90/1000 gal. Compared to the cost of letting the city treat suspended solids, the additional use of a precipitating additive with added equipment would not be cost effective. If the end use of precipitated lime and starchy material was as a binder, the briquette cost would increase since it would have to include the cost of processing the wastewater.

4.3.3 Briquette Production

The cost of producing briquettes at the rate of 20 t/hr (170,000 t/yr) is estimated at \$3.18 per ton (see Appendix C for details), but this does not include the cost of binder. Since needs differ with the client, a product with different heating values would be desirable, such as a 20% moisture product with a heating value in the low 8000s and a 10% to 15% moisture product with a heating value in the low 9000s.

4.3.4 On-Site Cogeneration

One option for the existing J.R. Simplot plant that potentially reduces energy costs, provides excess energy-generating capacity for expansion, and stabilizes future energy costs is to develop an on-site cogeneration capability. Although the lowest-cost fuel is generally coal, the low cost is partially offset by the higher capital and operation costs associated with coal. However, in the present political climate of governmental enhancing of industry growth, it is likely that state, local, and possibly, federal financial assistance would be available if a North Dakota coal were utilized and because local construction work and additional permanent jobs would result from a cogeneration facility.

Present energy usage by J.R. Simplot is 3,207,704 kWh of electricity (4.5 MW) and 100,000 lb/hr of steam (a combined total of about 150,000 lb/hr of steam) with an expansion planned by September of 1994. The expansion could increase demand to 250,000 lb/hr of steam. If water-treatment energy demands increase, additional steam would be required. The installation of two coal-fired boilers, each rated at 170,000 lb/hr of steam, and two turbines (8.25 MW each) would provide 170,000 lb/hr of steam and 16.5

MW of electricity. Excess electricity would be available to market and for future expansion.

Steam production is most sensitive to capital and fuel costs and, in the case of coal as fuel, to a lesser extent to fuel quality (moisture and sulfur content) and boiler efficiency (carbon burnout and NO_x production). Firing with coal is more equipment-intensive but creates more local jobs. The information used is from "Proceedings of the Fluidized-Bed Conference (1988 and 1991)" (1,2) concerning two 170,000-lb/hr boilers recently installed at Iowa State University. The choice of the fuel and firing method were determined primarily by fuel cost and environmental regulations. A bias to use an Iowa coal also appeared to be present.

The coal costs in their economic study ranged from \$1.38/MM Btu to \$1.93/MM Btu (during actual operation they report a coal cost of \$1.28/MM Btu), while the cost of natural gas was reported to be \$3.25/MM Btu. In Grand Forks, North Dakota, 1993 coal costs were in a similar range, but natural gas costs \$5.18/MM Btu or 1.6 times more than natural gas in Iowa cost in 1987. All options economically evaluated showed that coal-fired units (fluidized-bed, spreader-stoker, or pulverized-coal) with pollution control equipment, were 2 to 3 times more expensive than natural gas at five years of operation because of initial capital costs. At 15 years, the economic effect of capital costs for coal-fired units is offset by the higher prices of natural gas, while the coal option Iowa chose shows natural gas would have been 1.3 times more expensive to use as a boiler fuel. Capital costs for a coal-fired boiler would be higher in 1993, but the natural gas cost in Grand Forks is also much higher than the cost quoted in the Iowa study. The following compares the Iowa fuel costs to those determined for Grand Forks:

	Iowa Approximately 1987	Grand Forks 1993
Unwashed Iowa	\$1.38/MM Btu	—
Washed Iowa	1.75	—
Western (low S)	1.93	\$1.68/MM Btu
Lignite		1.66
Natural Gas	3.25	5.18

The actual cost of unwashed Iowa coal was \$1.28/MM Btu (\$25.30/t delivered, 3.5%–5.5% S). In their economic evaluation, the best option was a circulating fluidized-bed (CFB) boiler with a baghouse, which was rated as 7%–10% more economical than a spreader-stoker or pulverized-coal boilers burning washed Iowa coal. The CFB option includes sulfur capture in the boiler. Adding flue-gas desulfurization equipment to the other options made the total cost more expensive by 30%. The CFB option had higher capital costs but lower operating costs. Natural gas was the highest option at a price of \$3.25/MM Btu. It would be expected to be more at the present natural gas cost of \$5.18/MM Btu.

Iowa found that a fluidized-bed boiler with a baghouse was the most economical since it 1) resulted in the lowest NO_x emissions and 2) enabled the use of a less-expensive

(high-sulfur) Iowa coal. The use of a calcium bed decreased sulfur dioxide emissions, while the lower firing-temperature of a fluidized-bed reduced NO_x emissions to within environmental limits. Spreader-stoker or pulverized-coal fired units would require flue gas clean-up at a much higher capital cost.

A growing concern is disposal of ash and spent limestone since landfill regulations are increasingly strict. The limestone costs \$11.33/t delivered (100% minus 4 mesh). The disposal of ash and spent lime at the mine site (\$7.27/t) is being restricted, causing it to be locally landfilled (expected to cost about \$10.27/t). Sulfur entrainment as sulfates makes the ash unusable directly as a concrete substitute.

A number of other considerations are reported. Obtaining U.S. Environmental Protection Agency (EPA) approvals on prevention of significant deterioration took one year at a cost exceeding \$100,000. This time and cost was low, since required meteorological information was available. Fugitive-dust evaluations are adding an additional cost of \$35,000 to \$40,000.

4.3.5 Ash in Concrete

Ash disposal can represent a cost that is subject to stricter, more-expensive environmental rulings. If operating at capacity, UND would currently pay about \$18,000/yr in ash disposal costs (70,000 t/yr, 6.5% ash at \$4/t ash) or \$0.26/t of coal burned. If the contracted disposal company had to pay the industrial tipping fee, the cost of ash disposal would be increased by \$59,150/yr or to \$1.10/t of coal burned. Ash properly prepared to act as a cement replacement has an end-user value of \$33/t. The combustion of 170,000 t/yr of product would produce about 15,000 to 20,000 tons of ash. As a cement replacement, the ash has a potential gross value of \$495,000/yr.

With shipping costs and profits included, the value of directly-marketed specification ash for use as a cement replacement is \$33.00/t in the city of Grand Forks. The ash produced by the local combustion of coal is obtainable free or with a disposal fee (\$4.00/t). Disposal fees (up to \$17.00/t) will only increase with inflation and even more so as stricter environmental laws and landfill space become important. Although full information has not as yet been developed, rough numbers are:

Cost of Raw Material, per ton	-\$4.00
Cost of Processing, per ton	
Pulverizing	\$6.00?
Heat Treatment	6.00?
Bulk Delivery	6.00?
Waste Disposal	1.00?
Personnel	2.00?
Subtotal	\$17.00
Value of Product, per ton	\$33.00

A very rough processing-cost estimate is \$255,000 to produce 15,000 tons of material with a market value of \$495,000. The difference of \$240,000 would have to cover capital, financing costs, profit, etc. If the product were sold to a distributor, this difference would be smaller. The cost of ash disposal will certainly increase, especially if a landfill is

placed under a regional authority. If not marketed with a positive value, ash disposal will create an increasing liability.

The South Dakota facility has found that the ash they produce is too high in sulfate to be used as a cement additive. However, they are burning relatively high-sulfur coal. Further evaluations, possibly including combustion testing, would be required to determine if cement-quality ash could be produced for a lignite with lime additive.

4.3.6 Coal Feed Cost and Product Value

The production and marketing of a compliance coal from lignite requires the product from its use in wastewater treatment to have multiple-use value. Table 4 shows that the cost of the raw coal and delivery cost of a compliance 9300-Btu/lb product provides a tight picture when briquettes are produced and marketed off-site (the cost of processing must be absorbed by other processing steps). However, if Market 1 is penetrated, there is an overall positive result. The most competitive alternative is the on-site use of the product where briquetting and local transport costs are eliminated. In this case, a compliance fuel is obtained at a cost of \$1.51/MM Btu, which is very similar to the \$1.47 MM Btu/lb-price paid by Market 2. Compared to the use of oil or gas to produce steam, this represents a substantial reduction in energy costs. However, as has been discussed no advantage was seen in mixing coal with wastewater. Therefore, the optimum alternative is to burn coal rather than burn natural gas.

TABLE 4

Comparison of Feed Coal Costs to Market Value

Coal Cost/t, Delivered, 7073 Btu/lb	\$23.88
Yield Factor, ton of Coal, ton of Product, 9300 Btu/lb	1.32
Cost/t Product	31.23
Delivery	2.00?
Delivered Price	\$33.23

		\$/t for 170,000 t/yr	
		Value/t	Value/yr
Market Value	Market 1	\$34.80	\$5,892,200
	Market 2	27.42	
	Market 3	40.00	40,000
	On-Site	28.05	
		Total	5,921,200
		Cost of Coal	5,649,100
		Gross	272,100

5.0 CONCLUSION

The potential costs (per value) for processing areas expressed as the change in \$/t of fuel product for this multiple-use process are as follows:

1. Costs of coal, receiving and storage	-0.20
2. Crushing of coal	-1.00
3. Receiving of calcium sludge	0.00
4. Contact of wastewater, coal, and sludge	1.62
5. Recovery of solids and cleaned water	-1.00
6. Partial drying of solids	<u>-2.00</u>

Subtotal	-2.58
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7. Briquetting of solids	-3.18
8. Marketing of compliance fuel	1.60
9. Production and marketing of a cement replacement	<u>0.59</u>

Scenario 1 Total	-3.57
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or

7. Utilization of the fuel in an on-site cogeneration unit	3.01
8. Production and marketing of a cement replacement	<u>0.59</u>

Scenario 2 Total	1.02
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The desired low costs associated with the coal-crushing and coal-drying steps would require the integration of a cogeneration unit to decrease energy costs to these units. All values—except calcium cost, briquetting cost, and maximum value of a compliance fuel—are optimistic figures. With completion of the feasibility tests, where coal was in contact with wastewater, the positive value of Area 4 of \$1.62/t is obviously not reasonable. The final conclusion is that the long-term cost savings of burning stable-priced lignite rather than natural gas is the primary reason to use coal.

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APPENDIX A

**MULTIPLE-USE MARKETING
(MUM) OF LIGNITE—
POTATO WASTEWATER CLEANUP**

MULTIUSE MARKETING (MUM)—POTATO WASTEWATER CLEANUP

HYPOTHESIS

Wastewater from potato processing at the J.R. Simplot plant contains raw and cooked potato waste, oil, and "dirt." Lignite coal has surface active sites which adsorb polar organic and charged moieties. Dissolved and suspended potato waste will be adsorbed to the lignite and, on partial drying and compaction, will bind the coal particles together. The dissolved and suspended solids in the wastewater will be decreased.

PROCEDURE

Potato processing wastewater (WW) was collected in a 5-L brown glass bottle from the primary clarifier at the J.R. Simplot plant. The temperature and pH were measured, and the water was treated the same day as collected, unless used in tests to determine the effect of aging the water. Wastewater was stirred with Knife River coal (KR) and landfill sludge (LS) from the city water processing plant for a specified amount of time; then, water and solids were separated by filtration or centrifugation. The amount of coal, water, and landfill sludge was varied between 200 cm³ of WW : 9.6 g of LS : 20 g of KR and 100 cm³ of WW : 1.6 g of LS : 20 g of KR to try to obtain the cleanest water and the strongest pellets. Flocculation of the starch in wastewater was tested using Fe³⁺ from Fe(NO₃)₃ or Fe₂(SO₄)₃ applied to coal by aqueous impregnation in a weight ratio from 0.02-2 Fe³⁺ : 100 coal.

A typical example of initial test procedure is as follows:

WW was magnetically stirred with LS for 15 to 30 minutes in a ratio of 100 cm³ of WW : 2.4 g of LS. KR was then added in the ratio 100 cm³ of WW : 2.4 g of LS : 20 g of KR and the mixture stirred for 30 to 60 minutes. The water and solids were separated by decantation, filtration, or centrifugation. In selected experiments, the filtrate (centrate) was treated a second time by adding KR in the same ratio to WW as in the first cleaning step.

Later WW treatment tests involved lime for pH adjustment and Fe³⁺ as a flocculating agent. These tests were carried out on water volumes from 200 mL to 5 L. Test parameters for successful smaller scale (<500 cm³ of WW) tests are shown in Table 1.

Approximately 1-g samples of the coal collected following WW treatment were pressed into pellets using laboratory equipment designed for preparing pellets for infrared (IR) analysis. The cylindrical pellets were approximately 1 cm in diameter and 0.5 cm high. Preliminary testing of the integrity of the pellets included dropping from 6 feet and soaking in water. Some pellets were cured in air for several days prior to testing.

Treated WW was allowed to stand at room temperature for several days to observe whether cloudiness would increase with time. Total solids in WW, before and after treatment, were determined for several samples according to a method similar to Standard Methods of Water and Wastewater Analysis 2540 B. The results are shown in Tables 2 through 6.

TABLE 1

Summary of Selected Small-Scale Test Procedures

Treatment	76-1	78-1	82-1	82-2	82-3	82-4
Volume Potato WW	200 cm ³	200 cm ³	500 cm ³	500 cm ³	300 cm ³	300 cm ³
Weight KR	40 g -60 mesh	40 g -60 mesh	None	None	60 g	60 g
Stir Time (KR)	Added 2nd 30 min	Added 1st 30 min	Bubble air for 24 hrs	Anaerobic for 24 hrs	Stir for 24 hrs	Added 2nd, stir for 24 hrs
LS	9.6 g Added 1st	9.6 g Added 2nd	None	None	None	7.2 g Added 1st
Stir Time (LS)	15 min	15 min	None	None	None	1 hour
Centrifuge	None	None	None	None	None	None
Final WW Condition	Clear on Filtering	Clear on Filtering	Cloudy	Cloudy	Cloudy	Clear on Filtering
Initial WW pH	5	5	4	4	4	4
Treated WW pH	8	7	Not Recorded	Not Recorded	Not Recorded	Not Recorded

Treatment	82-5	83-1	84-1	84-2	88-1	88-2
Volume Potato WW	300 cm ³	100 cm ³	300 cm ³	300 cm ³	200 cm ³	500 cm ³
Weight KR	None	20 g	60 g Leonardite	60 g Leonardite	40 g	None
Stir Time (KR)	None	15 min	Added 2nd 1 hour	2 hour	30 min	Anaerobic for 24 hours
LS	7.2 g	2.4 g Added 1st	7.2 g Added 1st	None	None	None
Stir Time (LS)	Stir for 24 hours	15 min	1 hour	None	None	None
Centrifuge	None	1 hour	1 hour	1 hour	1 hour	None
Iron(III) Additive	0 g	0 g	0 g	0 g	2% Fe as sulfate	2% Fe as nitrate
Final WW Condition	Clear	Very clear	Clear, brown tint	Cloudy, brown tint	Clear, brown- orange	Very clear, yellowish
Initial WW pH	4	5	5	5	5	5
Treated WW pH	Not recorded	8	7	5	2	3

TABLE 2

Total Solids in Raw and Treated Potato Processing Wastewater

	76-1 Water Weight Residue, g		78-1 Water Weight Residue, g	
	Raw	Treated	Raw	Treated
	0.2072	0.1598	0.4448	0.1791
Solids Removed, wt%	23		Not available	

TABLE 3

Solids Removed from Wastewater During Various Treatments*

	82-1	82-2	82-3	82-4	82-5	83-1
Before Centrifuging, g	0.1940	0.1916	0.1989	0.2086	0.2137	
After Centrifuging, g	0.1671	0.1175	0.1370	0.1576	0.1610	0.1809
Solids Removed, wt%						
H ₂ O + Coal + Additive	14	39	31	24	25	
H ₂ O Suspended and Dissolved Solids, min	14	39	29	19	17	7

- *82-1 500cm³: Bubble air for 24 hr.
 82-2 500cm³: Anaerobic for 24 hr.
 82-3 300cm³: 60-mesh KR, stir in closed 500-cm³ flask.
 82-4 300cm³: 7.2g LS, stir 1 hr.; 60 g KR, stir in closed 500-cm³ flask.
 82-5 300cm³: 7.2g LS, stir in closed 500-cm³ flask.
 83-1 100cm³: 2.4g LS, stir 15 min.; 20g 60-mesh KR, stir 15 min, then centrifuge for 1 hr. Water appeared very clean, pH = 8.

TABLE 4

Total Solids in Raw WW and WW Treated with Leonardite
Tests 84-1 and 84-2

	84-1 Water Weight Residue, g		84-2 Water Weight Residue, g	
	Raw	Treated	Raw	Treated
	0.1667	0.1630	0.1667	0.1921
Solids Removed, wt%		2		-15

- 84-1 (Repeat 82-3) 300 cm³ of WW, 7.2 g LS, stir 1 hr; 60g of Leon., stir 1 hr.
 84-2 (Repeat 82-4) 300 cm³ of WW, 60 g Leon., stir 1 hr.

TABLE 5

Total Solids in Raw WW and WW Treated with Iron Salts

	88-1 Water Weight Residue, g		88-2 Water Weight Residue, g	
	Raw	Treated	Raw	Treated
Total Solids, g	0.0814	1.1086	0.0814	1.1265
Solids Removed, wt%		-1262		-1284

88-1 Clean WW with KR/2% Fe from iron sulfate.

88-2 Clean WW with KR/2% Fe from iron nitrate.

TABLE 6

Total Solids in Raw WW and Decantate and Filtrate
from WW Treated with Calcium and Iron
Test 98-1

	98-1 Water (Dried 50-mL H ₂ O) Weight Residue, g		
	Raw	Decant	Filter
Total Solids, g	0.1439	0.1788	0.0798

98-1 Clean 4950 mL of WW with 29.7 g of KR, 9.7 g of hydrated lime, and 1.7 g of iron chloride

The numbering system used for reporting the test results is according to the usual convention, i.e., derived from the lab book page number followed by the chronological order of the sample discussed on that page, e.g.; 76-1 is the first sample recorded on page 76.

Odor was not measured quantitatively, but was determined on undiluted samples and reported in very broad subjective terms.

The results of the initial tests were used in designing tests with at least a tenfold increase in scale. Test parameters for larger-scale tests are given in Table 7.

Pellets were prepared in a hydraulic pellet press from 1-1.5 g of damp coal recovered following WW treatment. Pellets were prepared at either 10,000 lb/in² or 15,000 lb/in². The integrity of the pellets was evaluated by their resistance to breakage when dropped from a height of about 6 feet onto a tile floor and their ability to remain intact when soaked in water. Raw pellets, some air-dried, and a few oven-dried pellets were tested.

TABLE 7

Summary of Larger-Scale Bench Testing Parameter

Treatment	92-1	92-3	95-1	95-2	96-3	98-1
Volume Potato WW	About 6 L	About 3.8 L	5.11 L	5.12 L	In this test, a 50/50 mix of coal obtained from Test 95-1 and raw Knife River coal were used to make the pellets, along with about 1 mL of DI H ₂ O to dampen the mixture.	4.95 L
Assumed WW Starch	ca. 12 g	ca. 7.2 g	10.20 g	10.21g		9.90 g
Weight KR	100 g (20 g fine received)	375 g (20 g fine received)	30.6 g	30.6 g		29.65 g
Lime	0 g	0 g	0 g	0 g		0 g
Hydrated Lime	0 g	0 g	0 g	10.00 g		9.67 g
Ferric Nitrate	1.20 g (200 mg/L)	12 g (2000 mg/L)	7.81 g	0 g		0 g
Iron(III) Chloride	0 g	0 g	0 g	1.79 g		1.73 g
Final WW Condition	Clear, orangish brown	Not good	A little cloudy, yellowish	Clear		Very clear
Initial WW pH	Not recorded	Not recorded	5.30	5.43		4.96
Treated WW pH	Not recorded	Not recorded	11.46	10.90		9.99
Pellet Condition in H ₂ O						
Fresh Pellets	Good	Good	Good	Good	Good	Good
Dried Pellets	Good	Not done	Good	Bad	Not done	Bad

GENERAL WATER TREATMENT RESULTS

The pH of the WW ranged between 4 and 5. The temperature was typically 74° to 78°F.

The appearance and smell of the treated wastewater was noted intermittently over a period of up to 10 days. The process generally removed some solids and most of the odor from the water. Ion exchange between WW and KR caused the pH of the treated water to rise to between 7 and 8.

Increased cloudiness of treated water with time was observed, but not to the same extent in all cases. The treated water was separated into vials, and a small amount of

formic acid was added to one vial to preserve its condition. Comparisons of the aging treated water could then be monitored over time. The treated water got somewhat cloudy and acquired a smell over time.

Dense flocculation of the starch in the presence of the Fe^{3+} occurred. The coal fines appeared to agglomerate and settle more rapidly and completely in the presence of Fe^{3+} . Flocculation continued over a period of 2 to 3 days, and the water was clear, although colored due to excess Fe^{3+} . Unpleasant odor due to decomposition of starch was absent and remained absent indefinitely. The water treated with $\text{Fe}(\text{NO}_3)_3$ had a noticeably pleasant, fruity, acid odor, probably due to chemical oxidation of starch fragments.

Water treated with a combination of coal, lime, and iron and recovered with combined decantation and filtration was clear and slightly yellow. Optimization has not been attempted.

Thermogravimetric analysis of residues from total solids showed approximately 50% was not volatile or combustible at temperatures up to 750°C . The treatment reduces the suspended solids to ca. 25% of raw WW, but chemical oxygen demand (COD) remains at ca. 70% that of untreated WW as shown in Table 8. The results shown in Table 8 were obtained when the wastewater treated with lime and iron was analyzed by the Environmental Control Laboratory at the J.R. Simplot plant.

PELLET RESULTS

Solids were air-dried until suitable for making pellets. Pellets were made using 10 and 15 thousand pounds of pressure in an IR press. The integrity of the pellets was then tested by dropping them from a height of about 6 feet and by allowing them to soak in water. Some were also air- and oven-dried at 80°C to test the effect of curing them. When the pellets were heated, they became weaker, and for the most part, air-drying also seemed to weaken the pellets. In cases in which the pellets were not apparently weakened by drying, they were not stronger than the undried pellets. The tests that produced the best pellets were some of the earliest tests, 69-3 (using 200 cm^3 of WW, 9.6 g of LS, and 40 g of KR, with the latter material added in the order given and stirred for 15

TABLE 8

Analysis of Raw and Treated Wastewater Collected May 19, 1993

Sample	Suspended Solids, mg/L	COD, mg/L
Raw WW	636	3677
Treated WW:		
Decantate	162	2564
Filtrate	94	2546

The treated 69-3, 70-1, 72-1, 72-2, 95-2, and 98-1 water was very clean.

and 30 minutes respectively), and 92-1 and 95-1 solids at 10 Klb; the undried and air-dried pellets held together in water for at least one day. Test 70-1 was a repeat of 69-3 with H_2SO_4 added. This test produced pellets that flaked in water, but still had a great deal of integrity after a few days. When the pellets were air- or oven-dried, however, they fell apart. Tests 72-1 and -2 were repeats of 69-3 and 70-1 respectively, and replicated the previous results, although no 72-1 and -2 pellets were air-dried. In general, 15 Klb pellets had less stability in water than 10 Klb pellets. Pellet test results were reported using a binary system, i.e., good or bad.

Pellets made at a pressure of 10 Klb/in² from the coal, lime, and iron recovered from WW treatment and containing up to 10%-15% starch had good resistance to dropping and good water resistance. On standing in water for a time (a day or longer), starch appeared to be leaching from the pellet, although the pellet maintained its integrity.

SUMMARY

- Lignite coal neutralizes the acidic potato processing wastewater.
- Lignite adsorbs 5 to 50 wt% of potato solids from wastewater.
- Centrifuging wastewater after treatment with limestone and coal results in a very clear supernatant.
- Addition of Fe^{3+} causes copious flocculation of starch and clarification of supernatant without centrifugation.
- Treatment of wastewater with Fe^{3+} or Ca^{2+} reduces the odor of wastewater.
- Addition of flocculent to coal results in pellets with improved integrity.
- Pellets prepared from coal used to treat wastewater at 80°C had excellent resistance to moisture.
- Coal of -60 mesh produced the best pellets.
- Pellets prepared from coal used with iron to treat wastewater had good resistance to water and were able to withstand impact.

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APPENDIX B

**MULTIPLE-USE
MARKETING (MUM)
OF LIGNITE**

REPORT 1

POTATO WASTEWATER ADSORPTION TESTING AND COAL BRIQUETTING

1.0 OBJECTIVES

The purpose of the testing program was twofold: 1) to investigate the removal of dissolved and suspended starch solids from Simplot potato processing wastewater by a coal adsorption method, and 2) to aggregate the adsorbent coal, without additional binder, for use as a value-added stoker fuel. The coal, in this case a Beulah lignite supplied by the Knife River Coal Company, was presumed to be a potential starch getter by virtue of its characteristically high surface oxygen content. It was envisioned that the starch species, compatible with the coal surface oxygen functionalities, would preferentially adhere to the coal. The starch, due to its excellent adhesive and cohesive properties, would function as a binder to allow subsequent tableting and/or briquetting of the coal.

A calcium carbonate-based by-product from potable water clarification, presently landfilled as a wet sludge, was used as a potato wastewater clarification aid. The landfill sludge would ideally become associated with the starch/coal solid and, presuming successful briquetting, the calcium-based material would be beneficial for in situ sulfur capture during briquette combustion.

2.0 EXPERIMENTAL

2.1 Adsorption Testing

The Beulah lignite was crushed to a nominal top size of $\frac{1}{4}$ " using a hammer mill crusher. The crushed coal was largely (>96 wt%) under 16 mesh (1.2 mm) in size, and the moisture content was 35.8 wt%.

Adsorption tests with the potato wastewater were performed on a technical-scale level using the processing methodology presented in Figure 1. Fresh potato wastewater was pumped into a mixing vessel, and during continuous agitation, the Beulah lignite was incrementally added to the wastewater. The calcium carbonate-based landfill sludge was then added to the wastewater/coal mixture, after which the mixing vessel contents were blended for a specified period. After the blending period, the contents were allowed to stand unagitated to facilitate gravity settling of the coal. The liquid phase was decanted, via a diaphragm pump, to the centrifuge feed storage vessel and then centrifuged to recover the unsettled solids. The coarse settled solids and the centrifuge cake were stored separately prior to briquetting testing. The moisture contents of the settled coal and centrifuge cake fractions and the solids contents of the raw wastewater and centrate were determined by a thermogravimetric method.

2.2 Briquetting Testing

Briquetting of the adsorbent coal/landfill sludge mixtures was performed with a Komarek-Greaves roll-press briquetter rated for 1- to 5-ton/hr throughput. The rolls were configured to produce pillow-shaped briquettes with dimensions of $1\frac{1}{4}$ " x $1\frac{1}{4}$ " x $\frac{7}{8}$ ". The

Figure 1. Adsorption testing processing schematic.

separation force on the rolls was maintained at approximately 15 tons. The briquettes were air-dried for 7 days at prevailing ambient conditions and were then evaluated for mechanical strength. The mechanical strength tests performed included drop (shatter) resistance, tumble (abrasion) resistance, and compressive load strength.

3.0 RESULTS

3.1 Adsorption Testing

Three adsorption tests were performed with the potato wastewater and Beulah lignite, and the conditions of the tests are summarized in Table 1. Tests 1 and 3 were performed at a wastewater/coal ratio of 5/1, and Test 2 was performed at a wastewater/

TABLE 1**Adsorption Testing Condition Summary**

	Test 1	Test 2	Test 3
Wastewater, lb	251	251	250
Coal, lb	50.0	25.0	50.0
Landfill Sludge, lb	5.52	2.76	5.60
Wastewater Solids Content, wt%	0.2	0.2	0.2
Coal Solids Content, wt%	64.2	64.2	64.2
Landfill Sludge Solids Content, wt%	27.7	27.7	27.7

coal ratio of 10/1. The solids content of the wastewater was approximately 0.2 wt%, and the landfill sludge was added to the coal/wastewater mixture at a concentration of approximately 3.5 wt% (moisture-free). The mixing time in each test was 30 minutes, and the specified settling time of Tests 1 and 2 was 60 minutes, but for Test 3 no settling time was allowed initially.

The masses of settled solids, centrifuge cake, and centrate recovered in each test are presented in Table 2. The decanting diaphragm pump became plugged in Tests 2 and 3, resulting in extension of the coal settling periods by 28 and 23 minutes, respectively.

The majority (83 to 94 wt%) of the feed coal/landfill sludge/wastewater solids was recovered as settled coal, and less than 2 wt% of these solids remained in the centrifuge centrate.

TABLE 2**Adsorption Testing Material Recovery Results**

	Test 1	Test 2	Test 3
Settling Time, min	60	88	23
Settled Coal, lb	59.5	31.0	53.5
Centrifuge Cake, lb	8.0	2.5	10.5
Centrate, lb	226	237	230
Settled Coal Solids Content, wt%	50.4	53.0	53.2
Centrifuge Cake Solids Content, wt%	45.5	47.3	48.2
Centrate Solids Content, wt%	ND*	ND	ND

* Not determined.

The significant results obtained from the adsorption tests were that 1) the wastewater odor was appreciably reduced after adding only the Beulah lignite, 2) the foul water odor was essentially eliminated after addition of the landfill sludge, and 3) the clarity of the water was not improved during the adsorption tests. The color of the water, a cloudy yellowish white before treatment, changed to a grayish white as a result of contact with the coal and landfill sludge. The color change was presumed to have been caused by suspended micron-sized coal particles that were stabilized by the wastewater starch solids and, consequently, were not settled by the tremendous force of centrifugation. Also, it was presumed that, prior to the addition of the neutralizing landfill sludge, the acidic potato wastewater may have leached humic acids from the coal, and these coal constituents may have contributed to the water discoloration.

3.2 Briquetting Testing

It was presumed that, for the application of briquetting, most of the potato wastewater starch solids that had been removed by adsorption adhered to the fine unsettled coal particles that were recovered during centrifugation. Consequently, the centrifuge cake (fine coal) was considered the binder, and the settled coal was considered the material to be aggregated. Mixtures of centrifuge cake (binder) and settled coal were prepared from products of each of the three adsorption tests, and the test condition summaries are presented in Table 3.

All three mixtures were air-dried prior to briquetting to reduce the surface moisture content to minimize roll pocket plugging and ensure formation of dense briquettes. The moisture contents of the mixtures before and after air drying are presented in Table 4.

Briquetting was only attempted with Mixtures 1 and 3. Mixture 1, which was tested first for briquetting, produced excessive roll pocket plugging as a consequence of an inappropriate surface moisture content. The few briquettes that were produced were poorly formed and soft, indicating insufficient compaction, i.e., densification. Similarly, briquetting testing with Mixture 3 was difficult as the roll pockets plugged, causing the rolls to stall (stop turning). Corrective measures were investigated, including a modified material feeding procedure that allowed the briquettes to be released from the pockets, eliminating roll plugging and stalling. The modified feeding procedure resulted in a significant number of well-formed, dense briquettes from Mixture 3. However, the modified procedure, when used with the previously unsuccessful Mixture 1, produced

TABLE 3

Briquetting Testing Condition Summary

	Test 1	Test 2	Test 3
Centrifuge Cake Concentration, wt%	11	5	19
Settled Coal Concentration, wt%	89	95	81
Centrifuge Cake, lb	5.0	1.7	9.0
Settled Coal, lb	37	27	35

TABLE 4

Briquetting Testing Feedstock and Briquette Moisture Contents

	Test 1	Test 2	Test 3
Pre-Floor Drying Moisture Content, wt%	51.9	52.2	50.4
Post-Floor Drying Moisture Content, wt%	39.9	48.1	42.8
Briquette Moisture Content, wt%	38.6	---	41.1

relatively few well-formed briquettes. The majority of the briquettes were soft or severely clam-shelled (cracked on the briquette seam).

The briquettabilty of Mixtures 1 and 3 was presumed to be related to their moisture contents. The post-floor-dried moisture content of Mixture 3, at approximately 43 wt%, was sufficient for producing well-formed briquettes, whereas the moisture content of the unsuccessfully briquetted Mixture 1 was 40 wt%, this presumably being too low. The moisture contents of briquettes produced from Mixtures 1 and 3 are also presented in Table 4. The moisture contents of the briquettes are slightly lower than the feedstock moisture contents, primarily because of mechanical dewatering and drying due to heating during compaction. Compared to the raw coal moisture content of approximately 36 wt%, it is estimated that a suitable surface moisture content for briquette formation is in the range of 7 to 8 wt% when using the Knife River Beulah lignite.

Mechanical testing of briquettes from Test 3 that had been air-dried for 7 days indicated poor strength characteristics, probably because of insufficient starch (binder) adsorption or because the adsorbed starch did not have adequate binding properties. The abrasability (material loss) was severe after 25 minutes of tumbling, as only 13 wt% of the briquettes tested remained larger than 4.76 mm. This compares with one variety of commercial barbecue briquettes, of only slightly larger size, that retained almost 90 wt% above 4.76 mm at identical tumble test conditions. Similarly, the drop (shatter) test indicated that only about a quarter of the Test 3 briquettes could be expected to remain larger than 4.76 mm after repeated dropping, while the commercial barbecue briquettes were much sturdier with 92 wt% remaining above 4.76 mm. The third mechanical test, compressive loading, indicated that the average Test 3 briquette strength, 20 lb/in², was inferior to the commercial barbecue briquette strength of 89 lb/in². These mechanical strength values indicate that the briquettes would not endure the stresses associated with handling and transportation without significant product degradation. Combustion testing would have to be performed to determine whether the briquettes produce a stable ash skeleton, which is necessary for proper utilization in a stoker application.

4.0 CONCLUSIONS

- The landfill sludge, at a 45/1 potato wastewater to sludge ratio, can eliminate the foul odor associated with the potato wastewater.

- The potato wastewater clarity was not improved, nor was the starch concentration reduced, by mixing with the Beulah lignite at either a 5/1 or 10/1 potato wastewater to coal ratio.
- Briquettes produced from Beulah lignite that had been used to adsorb starch from the potato wastewater were deficient in strength development compared to a commercial barbecue briquette.

REPORT 2

COAL BRIQUETTING WITH NEWSPAPER SUPPLEMENTAL BINDER

1.0 OBJECTIVES

The purpose of testing was to determine whether reclaimed newspaper could be used as the primary binder for briquetting a Knife River Beulah lignite or as a binding supplement when briquetting starch-adsorbed coal.

2.0 EXPERIMENTAL

The reclaimed newspaper was shredded prior to addition to the coal as a binder. Shredding was performed using both a commercial office-type paper shredder and a laboratory-scale mulching machine for plastic and wood. The first method produced $\frac{1}{4}$ " wide strips of variable length, depending on the dimensions of the paper feedstock. The mulching machine produced paper chips approximately $\frac{1}{8}$ " on the longest side. The coal was wetted as necessary, and the shredded paper was blended with the coal using a batch planetary-type mixer of approximately 30-gal capacity.

Briquetting was performed using a Komarek-Greaves roll-press briquetter rated for 1- to 5-ton/hr throughput. The rolls were configured to produce pillow-shaped briquettes with dimensions of $1\frac{1}{4}$ " x $1\frac{1}{4}$ " x $\frac{7}{8}$ ". The separation force on the rolls was maintained at approximately 15 tons. The briquettes were air-dried for 7 days at prevailing ambient conditions and were then evaluated for mechanical strength. The mechanical strength tests performed included drop (shatter) resistance, tumble (abrasion) resistance, and compressive load strength.

Tableting was performed using a manually operated press configured with a $1\frac{1}{4}$ " ID by 2" long mold. Approximately 15 grams of coal/binder was used to produce an individual tablet. Tablets were prepared using a compaction force of approximately 7300 psig, which was applied for 3 seconds for each tablet produced. The tablets were allowed to air-dry, but mechanical evaluation was not performed due to an insufficient number of tablets.

3.0 RESULTS

Briquetting testing using shredded newspaper as a binder was performed with two coal feedstocks: the nominal $-\frac{1}{4}$ " settled Beulah lignite produced in coal adsorption Tests 1 and 3 and a -60 -mesh Beulah lignite. The smaller coal size was tested for assessing briquette strength enhancement.

The initial briquetting tests using the coal/newspaper mixtures were unsuccessful when the newspaper was added to the $-\frac{1}{4}$ " and -60 -mesh coal fractions in concentrations of 12 and 17 wt% (as-received coal basis), respectively. The relatively few briquettes produced were excessively cracked and insufficiently compacted. The inability to produce well-formed briquettes was attributed to the spring-like action of the newspaper which

tended to resist compaction at the briquetting pressure investigated. This phenomenon, clam shelling, also caused continued expansion of the briquettes after release from the roll pockets. The roll pockets were relatively easily plugged by the coal/newspaper mixture, although the feedstock was not excessively damp. Furthermore, air drying to reduce surface moisture did not aid briquette compaction or formation nor did air drying aid release of the briquettes from the roll pockets.

The coal/newspaper mixtures were successfully briquetted only after dilution of the newspaper concentration with additional coal. The -60-mesh coal and newspaper mixture was first diluted from 17 to 8 wt% newspaper; however, this binder concentration was still excessive for proper briquette formation and release from the roll pockets. Reducing the newspaper concentration to 6 wt% allowed successful briquette production with a tolerable level of roll pocket plugging. The -1/4" coal and newspaper fraction was also reduced from 12 wt% directly to 6 wt% by adding non-potato-wastewater-treated coal; this material was also successfully briquetted. The green briquettes produced from both coal sizes, although not exceedingly smooth, were generally well-formed with a minor amount of clam shelling. Approximately one dozen tablets were also produced using each of the coal/newspaper mixtures that had been successfully briquetted. Green tablets produced with both the coarse and fine coal were very firm under slight finger pressure.

The briquettes, after being air-dried for 7 days, were evaluated for strength development and were then compared to the briquette type previously produced using starch-adsorbed centrifuge cake (binder) and settled coal. The moisture contents of the -1/4" and the -60 mesh coal/newspaper briquettes were both approximately 17 wt%. The briquette strength testing results are summarized in Table 1.

Newspaper, when used at low concentrations, can function as a coal binder. The briquettes produced with the newspaper as a binder were considerably stronger and more durable than briquettes produced only with potato wastewater-adsorbed starch material. Also, the coal/newspaper briquettes made with -1/4" settled coal were consistently

TABLE 1
Coal/Newspaper Briquette Strength Testing Summary

Briquette Type	Drop Recovery, wt%	Tumble Recovery, wt%	Compressive Strength, lb/in ²
-1/4" Settled Coal/ Centrifuge Cake (binder)	26	13	20
-1/4" Settled Coal/ Newspaper	71	49	57
-60-Mesh Coal/Newspaper	66	43	35
Barbecue Briquettes	92	89	89

stronger during the three strength evaluation tests, than briquettes made with the -60-mesh coal. A significant difference was observed in the compressive strength data as the -1/4" coal/newspaper briquettes had a value 70% higher than the -60-mesh coal/newspaper briquettes. The strength differences are probably due to the larger surface area (more coal particles) of the -60-mesh coal which would necessitate more binder (newspaper) to effect similar strength characteristics. None of the manufactured briquette types were near comparable in strength and durability to the strengths of commercial barbecue briquettes, a cooking fuel typically produced with corn or potato starch in concentrations below 10 wt%.

4.0 CONCLUSIONS

- Newspaper concentrations much above 6 wt%, on an as-received coal basis, were unsuitable for coal briquetting at the conditions investigated because of the spring-like resilience of the newspaper.
- Briquettes made with newspaper at a concentration of 6 wt% were superior in strength to briquettes made only with potato wastewater starch-adsorbed coal.
- Briquettes made with the -1/4" coal and newspaper were consistently more durable than briquettes with the -60-mesh coal. The compressive strength of the former was considerably higher than that of the -60-mesh coal/newspaper briquettes.

REPORT 3

COAL CLASSIFICATION WITH POTATO WASTEWATER

1.0 OBJECTIVES

The purpose of the testing was twofold: 1) to classify the Knife River Beulah lignite using potato wastewater in order to produce a fines fraction suitable for briquetting/pelleting, and 2) to produce a coarse coal fraction suitable for fluid-bed combustion application. Briquetting/pelleting of the classified coal fines would presumably be possible due to the adhesion of the wastewater starch material to this coal fraction. Ideally, the coarse coal fraction would be more resistant to dust generation, relative to the raw coal, due to adherence of potato wastewater starch. The adhesive properties of the starch would cause coal fines generated during handling to adhere to larger coal particles or cause the coal fines to aggregate into larger particles.

2.0 EXPERIMENTAL

The coal and potato wastewater classifying circuit, shown in Figure 1, consisted of a wastewater feed vessel (800 mL), a positive-displacement pump, a coal-classifying vessel (1000 mL), and a clarifier (5500 mL). The clarifier functioned as a disengaging vessel for

Figure 1. Fine coal hydroclassifying system.

settling the coal fines from the circulating potato wastewater. Approximately 50 to 75 grams of $-1/4$ " coal was charged to the classifying vessel prior to each test, and then the wastewater feed vessel, clarifier, and coal-classifying vessel were filled to capacity with wastewater. The positive-displacement pump circulated the potato wastewater to the coal-classifying vessel where the water was injected through a dip tube. The coal charge was agitated via the magnetic stirrer in order to suspend the coal and facilitate elutriation of coal from the classifying vessel. The size of coal particles elutriated was roughly controlled by increasing or decreasing the stirring rate. Imparting sufficient force through stirring caused the smaller coal particles to be carried upwards through the narrow discharge area of the tapered classifying vessel. Large particles that did not have sufficient force to reach the tapered neck of the vessel remained.

The wastewater circulation rate in each test was approximately 250 grams/minute, and each coal charge to the classifying vessel was treated for 60 minutes. At the end of each classifying test, the fines in the clarifier were separated from the wastewater via vacuum filtration. The fine coal was either air-dried or tableted while still wet. The coarse coal fraction remaining in the classifying vessel was separated from the wastewater by decanting the liquid. The coarse coal was allowed to air-dry for specified periods prior to tumble (abrasion) testing.

Abrasion testing was performed using a $77/8$ " steel vessel which was rotated at 80 rpm for 30 minutes. The tumbling vessel was outfitted with a three-vane lifting shelf that lifted and dropped the coal as the vessel turned. The tumbled-coal particle-size distribution, determined by Ro-Tap screening, was then compared to the coarse coal particle-size distribution.

3.0 RESULTS

Three coal classifying experiments were performed using Knife River lignite and Simplot potato wastewater. The first experiment was performed with the $-1/4$ " coal and a classifying solution composed of 54 wt% potato wastewater and 46 wt% deionized water. Approximately 380 grams of coal was processed, and 189 grams of coarse, air-dried coal and 93 grams of fine, air-dried coal were recovered. The moisture contents of the coarse and fine coal fractions, each air-dried for 24 hours, were 11.2 and 18.9 wt%, which compare to a raw coal moisture content of 35.5 wt%.

The coarse coal fraction, which had been air-dried for 24 hours, was riffled into three nearly equal mass fractions for subsequent abrasion testing. The first fraction was screened to determine the particle-size distribution of the material prior to tumble testing. The second fraction was tumbled, and the particle-size distribution was then determined. The third fraction was air-dried for an additional 4 days and then subjected to tumbling and screening. The results are presented in Table 1 and Figure 2.

The results of flushing indicated that largely all coal particles smaller than 60 mesh were classified from the raw coal, which had an original particle-size distribution with 26.5 wt% smaller than 60 mesh. Tumbling the 24-hour air-dried coal fraction essentially resulted in no additional nuisance dust (<100 mesh), although there was a reduction in $+10$ -mesh coal and an increase in $+35$ -mesh coal. The prolonged air drying of 5 days

TABLE 1

Particle-Size Distributions of Water-Classified and
Tumbled-Coal Fractions for Raw Knife River Lignite

Screen Mesh Size	1-Day Air-Dried Untumbled	1-Day Air-Dried Tumbled	5-Day Air-Dried Tumbled
10	19.2	14.7	11.2
16	35.5	36.1	30.8
35	39.8	44.4	48.3
60	4.2	3.5	6.7
100	0.5	0.3	1.6
140	0.3	0.3	0.5
Pan	0.6	0.6	0.8

Figure 2. Coarse- and tumbled-coal particle-size distribution.

produced an even greater shift from +10-mesh down to +35-mesh coal, although the nuisance dust production was minimal.

Significantly, no improvement in clarity of the potato wastewater occurred; in fact, the water turbidity increased due to suspended fine coal particles. The resistance to settling of the suspended coal was assumed to be caused by the potato wastewater starch material, which acted as a stabilizer. For this reason, subsequent tests were performed with a fine coal flocculating agent.

The first experiment using a flocculating agent included the Knife River lignite, which had previously been soaked in a 2000 mg/L ferric nitrate solution. Approximately 133 grams of ferric nitrate-treated coal was classified with approximately 7200 grams of fresh potato water. Approximately 60 grams of coarse, air-dried coal was recovered with a moisture content of 9.2 wt%. The coal fines recovered from the clarifier by vacuum filtration were not air-dried, but were submitted for bench-scale tableting.

The coarse ferric nitrate-treated coal recovered after classifying was air-dried for 24 hours and then riffled into two nearly equal masses. Screening and tumbling were performed on the two fractions, and the results are presented in Table 2 and Figure 3. As previously found, potato wastewater classifying largely removed all coal smaller than 60 mesh, and tumbling of air-dried coal did not result in significant production of nuisance dust. Again, as with the previous classifying and tumbling experiments, there was a shift from the +10-mesh down to the +35-mesh coal size.

Although the ferric nitrate-treated coal had similar abrasion resistance relative to the untreated raw coal, the ferric nitrate did not perform as hypothesized. The wastewater clarity was not improved, as neither the starch in the wastewater nor the suspended coal fines were induced to flocculate or precipitate.

An additional classifying and flocculating experiment was performed in which the ferric nitrate was added directly to potato wastewater. Approximately 130 grams of coal was treated by wastewater classifying, and prior to recovering the coarse and fine coal, ferric nitrate was dissolved in the wastewater feed vessel. The ferric nitrate concentration was 1100 mg/L. The modified procedure for ferric nitrate addition was

TABLE 2
Particle-Size Distributions of Water-Classified and Tumbled-Coal
Fractions for Ferric Nitrate-Treated Knife River Lignite

Screen Mesh Size	1-Day Air-Dried Untumbled	1-Day Air-Dried Tumbled
10	14.1	10.7
16	32.1	30.3
35	50.3	54.8
60	2.5	2.8
100	0.3	0.6
140	0.5	0.4
Pan	0.3	0.5

Figure 3. Coarse- and tumbled-coal particle-size distribution, ferric nitrate-treated coal.

extremely effective in flocculating and precipitating all visible fine coal and starch particles within the clarifier. The potato wastewater, however, retained a strong orangish yellow coloring due to the ferric nitrate. The precipitated coal fines and starch were recovered and submitted for bench-scale tableting testing. The coarse coal fraction, recovered from the classifying vessel, was air-dried for 24 hours to a moisture content of 10.4 wt% and then riffled into two nearly equal masses for subsequent screening and tumbling. The results are presented in Table 3 and Figure 4.

TABLE 3

Particle-Size Distributions of Water-Classified and Tumbled-Coal Fractions for Ferric Nitrate-Treated Potato Wastewater

Screen Mesh Size	1-Day Air-Dried Untumbled	1-Day Air-Dried Tumbled
10	17.0	16.6
16	31.9	33.8
35	44.9	42.9
60	4.8	4.5
100	0.8	1.2
140	0.3	0.4
Pan	0.3	0.6

Figure 4. Coarse- and tumbled-coal particle-size distribution, ferric nitrate-treated wastewater.

As with the previous classifying experiments, the -60-mesh coal was largely removed and the particle-size distribution was virtually unchanged after tumbling.

The abrasion resistance of the coarse coal fractions recovered from the classifying experiments was compared against an unclassified Knife River lignite sample of approximately the same initial particle-size distribution. This sample was prepared by air-drying approximately 125 grams of the -1/4" coal for 24 hours to a moisture content of 12.4 wt%. The sample was screened to determine the air-dried particle-size distribution. Coal smaller than 60 mesh was discarded, and the +60-mesh coal fractions were recombined for subsequent tumbling under the previously described conditions. The results of the screening and tumbling tests are presented in Table 4 and Figure 5.

The results indicate that air-dried Knife River lignite, untreated by contact with the potato wastewater, was equally resistant to size degradation via abrasive tumbling testing. As with the previously wastewater-treated coal samples, the air-dried coal showed a slight shift from the +10-mesh down to +35-mesh coal size.

Although the particle-size analysis of the wastewater classified and untreated Beulah lignite samples both showed minor degradation due to tumbling, the latter coal type did produce dust, which remained suspended in the air for a brief period after completion of the tumbling. The wastewater-treated coal did not produce dust that lingered in the air of the tumbling vessel. Also, the dust of the untreated coal tended to adhere to the walls and end caps of the tumbling vessel, whereas dust generated from the wastewater-treated coals did not.

TABLE 4

Particle-Size Distributions of Air-Dried and Tumbled-Coal
Fractions for Raw Knife River Lignite

Screen Mesh Size	1-Day Air-Dried Untumbled	1-Day Air-Dried Bottom-Sized	1-Day Air-Dried Tumbled
10	12.7	16.1	14.6
16	23.3	29.4	29.9
35	34.3	43.3	46.1
60	8.9	11.1	8.0
100	5.8		0.4
140	3.7		0.2
Pan	11.2		0.8

Figure 5. Coarse- and tumbled-coal particle-size distribution, raw coal.

4.0 CONCLUSIONS

- Neither raw nor ferric nitrate-treated coal is suitable for removing starch material from the potato wastewater.
- The starch material in the potato wastewater acts as a stabilizer for the fine coal to prevent gravity-induced settling.
- Ferric nitrate is effective for flocculating the potato wastewater starch solids and for precipitating the starch and suspended coal fines.
- Raw air-dried lignite, when compared to lignite flushed with potato wastewater, is equally resistant to size degradation during tumbling.
- Dust generated during handling of the wastewater-treated coal has reduced adhesive properties relative to dust generated during handling of untreated coal.

REPORT 4

EVALUATION OF POTATO WASTEWATER CLARIFICATION AIDS

1.0 OBJECTIVES

The purpose of testing was to determine the potential for various inorganic substances to flocculate and precipitate the potato wastewater starch solids to produce a visibly clear water.

2.0 EXPERIMENTAL

The procedure consisted of charging between 135 to 150 grams of the potato wastewater to a mixing vessel followed by incremental addition of the potential flocculating agents to the wastewater. After mixing, the wastewater and flocculating agent were allowed to set undisturbed for several minutes to allow the flocs to settle via gravity. The flocculating agents were added until no visible solids were suspended in the water or until no additional change, improvement, or degradation occurred in the water turbidity. The treated water was then decanted from the precipitated flocs.

3.0 RESULTS

The potential flocculating agents tested included pressure-hydrated lime, a fly ash-derived cement replacer, a calcium carbonate-based landfill sludge, calcium acetate, 10 wt% sodium hydroxide solution, ferric nitrate, and iron(II) chloride. The results of testing with the flocculating agents and the concentrations investigated are presented in Table 1.

The hydrated lime and the ferric nitrate were determined to be the only agents tested which were suitable for reducing the turbidity of the potato wastewater which had been caused by the suspended starch. The hydrated lime and ferric nitrate resulted in production of low density flocs which settled well under the influence of gravity. An appropriate settling time to achieve maximum clarity when using the hydrated lime was between 20 and 30 minutes. The production of suspended solids-free water was faster with the ferric nitrate compared to the hydrated lime. The only potential drawback to ferric nitrate as a flocculating agent was the production of a deeply orange water. Apparently, the water discoloration was due to very fine, suspended iron particles, as these orange particles eventually settled from the decantate over a period of several days. The final water was then very clear.

The combination of hydrated lime and ferric nitrate also worked extremely well at producing a clear water with no visible suspended solids. This combination was preferred to either hydrated lime or ferric nitrate alone in that the settling time was more rapid and the resulting water was clear without any orange discoloration.

TABLE 1
Potato Wastewater Clarification Experiments

Test	Flocculating Agent	Concentration mg/L	Water Condition
1	Hydrated Lime	16,000	Clear, suspended solid-free water
2	Hydrated Lime	7,580	Clear, suspended solid-free water
3	Fly Ash Cement Replacer	7,800	Degradation in clarity, brownish tint
4	Landfill Sludge	66,500	No improvement in clarity, color change to brownish yellow
5	Calcium Acetate	12,520	No change in clarity
6	10 wt% Sodium Hydroxide Solution	400,000	Slight flocculation, no change in clarity
7	Ferric Nitrate	3,690	Suspended solid-free water, orange water
8	Iron(II) Chloride	10,940	No change in clarity
9	Hydrated Lime	5,490	Clear, suspended solid-free water
10	Hydrated Lime/ Ferric Nitrate	3,330 2,170	Clear, suspended solid-free water
11	Fly Ash Cement Replacer/ Ferric Nitrate	83,000 2,500	Clear, suspended solid-free water

4.0 CONCLUSIONS

- Hydrated lime and ferric nitrate work well at producing a suspended solid-free water.
- The combination of hydrated lime and ferric nitrate worked better than either hydrated lime or ferric nitrate alone at clearing up the potato wastewater.

REPORT 5

OPTIMIZATION OF POTATO WASTEWATER CLARIFICATION

1.0 OBJECTIVES

The purpose of testing was to determine if a clear, suspended solids-free water could be produced by first basifying the potato wastewater and then adding a minimum amount of a flocculating agent. It was presumed that by adding the minimum quantity of hydrated lime or landfill sludge to achieve a pH above 7 and then incrementally adding a secondary flocculating agent such as iron(II) chloride or ferric nitrate, a clear, suspended solid-free water could be produced.

2.0 EXPERIMENTAL

For each test, approximately 150 grams of potato wastewater was charged to a mixing flask and the pH determined by a selective ion probe. Hydrated lime or landfill sludge was mixed with the wastewater, after which the resulting pH was determined. The condition of the wastewater was also noted. Then the ferric nitrate or iron(II) chloride was incrementally added and the condition of the water noted.

3.0 RESULTS

A total of four experiments were performed: the first using hydrated lime/iron(II) chloride, the second using hydrated lime/ferric nitrate, the third using air-dried landfill sludge/iron(II) chloride, and the fourth using only hydrated lime. The results of the tests are presented in Table 1.

The experiments appeared to indicate that increasing the pH from approximately 5 to 7 (Test 3) and even as high as 9 (Tests 1 and 2) was insufficient to result in a clear, suspended solids-free water even after adding significant quantities of the flocculating agents. A base case test using only hydrated lime indicated that a suspended solids-free water could be produced; however, in contrast to past experiments with hydrated lime, the resulting water had a slight yellowish tint. After approximately 24 hours of undisturbed settling, however, the water cleared, and no yellow tint was visible. After the same length of settling, the waters from the first three experiments did not improve in color, nor were the suspended particles induced to settle.

Based on these experiments, it was hypothesized that the pH of the wastewater must be increased to a higher value, perhaps as high as 10 or 11, to achieve significant flocculation and production of a clear, suspended solids-free water.

TABLE 1
Potato Wastewater Clarification Experiments

Reagents	Concentration, mg/L	pH ¹	Water Condition
Hydrated Lime/ Iron(II) Chloride	1,840 1,090	5.26/9.02	Considerable flocculation Greenish blue coloration Visible suspended solids
Hydrated Lime/ Ferric Nitrate	1,780 1,920	5.25/9.00	Considerable flocculation Yellowish coloration Visible suspended solids
Landfill Sludge/ Iron(II) Chloride	10,900 4,080	5.26/7.10	Minor flocculation Grayish blue coloration Visible suspended solids
Hydrated Lime	6,820	5.25/11.06	Considerable flocculation Clear, suspended solid-free

¹ First value is the raw wastewater pH; second value is the pH after adding hydrated lime or landfill sludge.

4.0 CONCLUSIONS

- The pH of the potato wastewater must be increased above 9 with hydrated lime or landfill sludge before the flocculating agent will produce a clear, suspended solids-free water.

REPORT 6

POTATO WASTEWATER CLARIFICATION AND PRODUCTION OF HYDRATED LIME/STARCH BINDER FOR COAL TABLETING

1.0 OBJECTIVES

The purpose of testing was twofold: 1) to produce a clear, suspended solids-free wastewater, and 2) to use the precipitated solids as the binder for subsequent bench-scale tableting tests.

2.0 EXPERIMENTAL

Approximately 2.5 liters of the potato wastewater was charged to a 5.5-liter clarifying vessel; after which the initial water pH was determined. Hydrated lime was then added to the wastewater, followed by a 10-minute mixing period. Iron(III) chloride was then added to effect the final improvement in water clarity. After mixing for an additional period of 10 minutes, the contents of the clarifier were allowed to stand undisturbed for 60 minutes to allow gravity-induced settling of the flocculated solids. The liquid phase was then carefully decanted using a peristaltic pump, and the settled solids were dewatered via vacuum filtration. The filter cake material was then analyzed for moisture content and tested as a binder for tableting of -60-mesh coal. Tableting was performed using a manually operated lab press capable of pressures up to 50,000 psi. Tablets, weighing between 1.5 to 2.0 grams, were produced at pressures between 10,000 and 15,000 psi. Tablets were either air-dried or placed directly in water to assess their durability with regard to moisture absorption.

3.0 RESULTS

Three water clarification and binder preparation experiments were performed and the conditions and results are presented in Table 1. Testing indicated that relatively small concentrations of hydrated lime and iron(III) chloride function extremely well at producing a visibly clear decantate. The settling time of 60 minutes was sufficient to allow all flocculated solids to precipitate under the influence of gravity. The slight discoloration in Test 1 may have been due to a slight oversaturation with hydrated lime. The precipitated solids were also very easy to filter using only vacuum filtration; this is in sharp contrast to the extreme difficulty filtering the raw potato water. The filter cakes also easily flaked off the filter paper, indicating that the material will present little difficulty for handling. The filtrate in Test 1 was clearer than the decantate, although in Tests 2 and 3 no color difference was visible between the decantate and filtrate. In each of these experiments, approximately $\frac{2}{3}$ of the initial wastewater was recovered as decantate, and $\frac{1}{3}$ was recovered as filtrate.

The decantate and filtrate from Test 3 were analyzed for chemical oxygen demand (COD) and suspended solids to determine if the starch content of the potato wastewater was reduced. The results are presented in Table 2. The results indicated that the

TABLE 1

Potato Wastewater Clarification and Binder Production

Test	Hydrated Lime Concentration, mg/L	Iron(III) Chloride Concentration, mg/L	Water Condition
1	5500	650	Minor visible suspended solids Yellowish coloration
2	3340	340	Clear, suspended solids-free
3	3450	690	Clear, suspended solids-free

TABLE 2

COD and Suspended Solids for Wastewater Clarification
Test 3, mg/L

	Raw Wastewater	Decantate	Filtrate
COD	3680	2560	2550
Suspended Solids	636	162	94

suspended solids were significantly reduced during the clarification test. In contrast, the COD was reduced by only about 30%, which was hypothesized to be caused by one or more factors:

- The starch in the wastewater exhibits characteristics of a true solution.
- Some of the oxygen utilization may have resulted from chemical reaction with the soluble iron of the iron(III) chloride.

If the starch exists as a true solution, it may not be possible to flocculate for removal, but will have to be precipitated by another mechanism.

The filter cake from Test 3 was used as binder for tableting -60-mesh Knife River lignite. The filter cake, however, was difficult to blend with the coal, and tablets produced with the mixture failed immediately after being placed in water.

4.0 CONCLUSIONS

- Treatment of the potato wastewater with a combination of hydrated lime and iron(III) chloride can produce a clear, suspended solids-free water.
- The hydrated lime/starch settled solids are easily dewatered using vacuum filtration.
- The hydrated lime/starch filter cake is difficult to blend with coal, and the raw tablets have no resistance to water immersion.

REPORT 7

POTATO WASTEWATER CLARIFICATION AND PRODUCTION OF HYDRATED LIME/STARCH/COAL FILTER CAKE FOR TABLETING

1.0 OBJECTIVES

The purpose of testing was twofold: 1) to produce a clear, suspended solids-free potato wastewater, and, simultaneously, 2) to produce a filter cake containing hydrated lime, coal and precipitated starch as a binder.

2.0 EXPERIMENTAL

Approximately 5 liters of the potato wastewater was charged to a 5.5-liter clarifying vessel; after which the initial water pH was determined. A sufficient quantity of -35-mesh Knife River lignite was added to the potato wastewater to achieve a 3/1 coal/starch ratio, presuming that the starch concentration of the wastewater was 2000 mg/L. The coal/wastewater mixture was blended for 10 minutes; after which either ferric nitrate or hydrated lime/iron(III) chloride was added to cause flocculation of the coal and starch and effect an improvement in water clarity. After mixing for an additional period of 10 minutes, the contents of the clarifier were allowed to stand undisturbed for 60 minutes to allow gravity-induced settling of the flocculated solids. The liquid phase was then carefully decanted using a peristaltic pump, and the settled solids were dewatered via vacuum filtration. Tableting was performed on the filter cake using a manually operated lab press capable of pressures up to 50,000 psi. Tablets, weighing between 1.5 to 2.0 grams, were produced at pressures between 10,000 and 15,000 psi. Tablets were either air-dried or placed directly in water to assess their durability with regard to moisture absorption.

3.0 RESULTS

Three water clarification and starch/coal preparation experiments were performed and the conditions and results are presented in Table 1. The concentration of coal used in each experiment was approximately 6000 mg/L. The results indicated that the combination of hydrated lime and iron(III) chloride was preferred to ferric nitrate for producing a relatively clear, suspended solids-free water. The slight yellow tint remaining after using the hydrated lime/iron(III) chloride was presumed to have been produced from humic acids which were leached from the coal by the acidic potato wastewater. The yellowish green coloration of the water resulting from treatment with only ferric nitrate was presumed to be an artifact of a water pH below 7.

The flocculated solids from each of the three tests were extremely difficult to dewater via vacuum filtration, and this was presumed to have resulted from the presence of the fine coal. The filter cake from Test 1 using only ferric nitrate produced firm, well-formed tablets which retained their shape even after being immersed immediately in water. The filter cake produced in Tests 2 and 3 using hydrated lime, although relatively

TABLE 1**Potato Wastewater Clarification and Binder Production**

Test	Flocculating Agent(s)	Concentration mg/L	Water Condition/Tablet Integrity
1	Ferric Nitrate	1530	Suspended solids-free water Yellowish-green coloration Water-resistant tablets
2	Hydrated Lime Iron(III) Chloride	1950 350	Suspended solids-free water Minor yellow tint Water-resistant tablets
3	Hydrated Lime Iron(III) Chloride	1950 350	Suspended solids-free water Minor yellow tint Water-resistant tablets

dry in appearance, had sufficiently high moisture content to produce difficulties during tableting. The hydrated lime may have caused some additional retention of moisture. The filter cake had to be partially air-dried to allow preparation of firm, well-formed tablets. The raw tablets produced from Tests 2 and 3 filter cake also maintained their integrity after immediate water immersion.

The clarification experiments, although successful in reducing the turbidity of the wastewater, had essentially no effect on the total solids content of the water. The total solids content of the raw wastewater and the decantate and filtrate from each test are presented in Table 2.

Although the clarity of the wastewater was significantly improved in each test, suggesting that suspended solids including starch were removed from the water, the increase in solids contents of decantates from Tests 2 and 3 was presumed to be caused by soluble ions of the hydrated lime and iron(III) chloride.

TABLE 2**Solids Contents of Clarified Wastewater,
mg/L**

Test	Raw Wastewater	Decantate	Filtrate
1	2880	2700	2500
2	2880	3180	1230
3	2880	3580	1600

4.0 CONCLUSIONS

- Hydrated lime/iron(III) chloride is preferred to only ferric nitrate for producing a clear, suspended solids-free water.
- The presence of coal and hydrated lime diminishes the ability of the precipitated solids to be dewatered via vacuum filtration.
- Tablets produced with precipitated solids using both ferric nitrate and hydrated lime/iron(III) chloride flocculating agents were well formed and exhibited resistance to moisture reabsorption during water immersion.

COAL BRIQUETTING: PRINCIPLES, PRACTICES, AND POTENTIAL

Brian C. Young

INTRODUCTION

Briquetting involves the compaction of fine material into a larger form with or without a binder, typically at moderate pressure (5,000 to 13,000 psi) and at ambient or elevated temperatures (200° to 500°C). Many different types of materials have been briquetted, including coal (anthracite, bituminous, subbituminous, lignite, and brown), coal char, coke breeze, sawdust, and other biomass waste from agricultural sources. The briquetting process relies on the cohesive forces between solids, the adhesion of binders, and the rheology of particles and lump materials.

The development of strong and cohesive briquettes is a function of the properties of the coal (including size, ash level, hardness, and surface and chemical characteristics), the nature of the binder, the mixing technique, and briquette processing conditions. The selection of the coal, binder, and processing conditions will largely depend on the ultimate utilization and potential value of the briquetted product.

The particle size of coal for briquetting is generally less than 6 mm (0.25 inches), but larger size coal (e.g., 10 to 15 mm (0.4 to 0.6 inches) can be briquetted. However, stable and effective briquettes also require an appropriate size distribution of particles. Briquetting fine coal of -4 mm would typically contain 30%-60% fines less than 1 mm (0.04 inches).

Tableting and stamping machines, as well as extruding and double-roll press machines, have been used for making briquettes. In recent years, the double-roll press has often been preferred as it offers significant advantages, including high throughput, relatively low energy usage and maintenance, insensitivity to material variability, and a variety of compact shapes and sizes.

The working principle of a double-roll press is shown in Figure 1. The rolls contain accurately machined pockets. The briquetting mixture is typically injected onto the spinning rolls using a screwfeeder which assists in removing air between the particles and ensuring more stable briquettes. The briquettes are released from the pockets, sometimes with the help of a chemical lubricant contained in the mixture, onto a conveyor belt or into a chute for curing or other posttreatment, if necessary, before packaging and storage.

The size and shape of the briquettes depend on the size of the roll and the machine, as well as the desired use of the briquettes. Typically, briquettes from double-roll presses cover a size range from approximately 20 x 13 x 10 mm (0.8 x 0.5 x 0.4 inches) to 70 x 50 x 40 mm (2.8 x 2.0 x 1.6 inches). Commonly available briquette shapes include almond, ovoid, pillow or cushion, capsule, and egg, as shown in Figure 2.

Binder selection is a key issue in determining the quality, durability, and acceptability of briquettes and their cost. Important factors influencing the choice of binder are the imparted strength, water resistance, benign nature of the binder (in preparation and use of the briquettes), availability, and cost. Although the list of binders currently used or potentially useful is extensive, the following are some common examples: starch (corn,

Figure 1. Schematic diagram showing the operational principle of a double-roll briquetting press.

Figure 2. Some common shapes of briquettes.

potato, tapioca), molasses/lime, polyvinyl alcohol, lignosulfonates, clays, bitumens and asphalts, coal tars, and metal stearates.

Agglomeration of fine coal into a lump form through briquetting allows the product to be sold into traditional markets, for example, the power sector and industrial markets. Briquettes for heating and cooking have also been developed for the commercial (e.g., South Korea) and domestic (e.g., United Kingdom, Europe, China, and South Korea) markets. In the last three decades, briquette development for domestic applications has been directed towards "smokeless" fuels, i.e., those which produce little smoke on burning. The requirements for an industrial stoker fuel have been less demanding, although recent increasingly stringent environmental emission standards require low release levels of sulfur oxides (SO_x) and nitrogen oxides (NO_x), as well as particulates.

Briquettes derived from coal have other potential applications as a metallurgical reductant (e.g., as a substitute coke for the steel industry), as an activated carbon, and, in some circumstances, as a fertilizer. The use of coal briquettes can be expanded by including other waste residues with coal. Hence briquetting offers the further advantages of reducing disposal costs and limiting the environmental impact of coal fines and other residues.

Evaluation of Briquette Performance

Whatever the briquette application, it will be necessary for the coal briquettes to meet specific mechanical strength and moisture durability criteria. The required minimum strength and moisture resistance will depend on the desired use, as well as on the type of binder and the extent of the processing conditions.

The mechanical strength of briquettes is usually determined in three ways: a drop or impact resistance test, a tumble (or abrasion resistance) test, and a compressive strength (applied load) test. The first two tests are expressed as the percentage of material remaining intact, whereas the compressive strength is related to the cross-sectional area in the plane of breakage and is expressed as a stress value.

Water resistance is measured by immersion in water (immersion test) for a set time or by applying a water spray (shower test) for a period of time. The qualitative appearance of the briquettes is monitored periodically, and, at the end of the test period, the compressive strength of the briquettes can be measured.

Combustion reactivity and emission tests are performed when the briquettes are to be used as a fuel. These tests involve determining the ease of ignition, carbon burnout, gaseous (SO_x , NO_x) and smoke emissions, and ash residue composition.

Briquetting Machinery

Substantial changes in the design, size, and operation of briquetting machines have occurred over the last four decades, particularly in the case of double-roll presses. The changes in double-roll presses have entailed improved, higher-pressure, and higher-throughput machines containing variable speed motors and automatic sensor controls. Of course, these developments have also translated into higher prices charged for these machines. Nonetheless, the low operating costs and the longevity of a double-roll press

can partially compensate for the increased cost. Additional savings are derived from the high production volume.

Double-roll presses typically range from 0.1 to 100 tons per hour (depending on size of machine and feedstock material) having a roll separating force from 20 to 600 tons. The roll diameter and width normally can range from 130 x 25 mm (5.1 x 1 inches) to 1110 x 760 mm (44 x 30 inches). The larger-diameter rolls can also be purchased in narrower widths. Roll geometry, which includes diameter, width, size, shape, and arrangement of briquette pockets, is a fundamental parameter which influences all other properties of the briquetting machine.

The cost of a new double-roll briquetting machine ranges from \$50,000 to over \$600,000. To optimize production costs, it is advisable to design a briquetting plant in modular form such that there is more than one machine of sufficient capacity to meet the required total output and to allow for maintenance shutdowns. Hence several smaller machines would be more appropriate than one big machine to deliver, for example, 1000 tons of briquettes per day.

There is a sizable market in secondhand briquetting machines. If these machines are sold as refurbished units by the manufacturers, they will typically cost about two-thirds of the new price, but still come with a warranty.

Briquetting Costs

The approximate costs for briquetting coal without a binder are given in Table 1. The highest individual cost will be that associated with the binder, unless this is obtained as a waste product for a nominal price. The given costs are estimated only, and some costs will be site-specific. The data in the table are based on a secondhand 20-ton/h, 710-mm- (28 inches) diameter double-roll press.

Briquetting Operations Space

Briquetting machines, together with ancillary equipment, require sufficient dedicated space (including overhead) to allow good access, freedom of movement of feedstock and product materials, mixing operations, mechanical performance testing, and storage. For example, for a briquetting machine having a capacity of 20 ton/h, the typical space required would be approximately 20 ft (width) x 35 ft (length) x 14 ft (height). However, the space requirement and the arrangement of machinery will depend not only on the size, but also on the style of the specific machine.

TABLE 1

**Approximate Costs for Coal Briquetting without a Binder
(Using a Secondhand 20-Ton/H, 710-mm- (28 inches) Diameter Roll Press)**

Item	Assumptions for Estimate	Cost per Ton of Briquettes
Rollwear	\$36,000 per set of rolls ÷ 6000 hours at 20 tons/h	\$ 0.30
Other Briquette Machine Maintenance	Equals roll wear	0.30
Other System Maintenance (mixer, conveyors)	Equals roll wear	0.30
Power for Briquette Machine	7 kWh/ton at \$0.05/kWh	0.35
Power for the Rest of System	Same as briquette machine	0.35
Labor	One man at \$16/h ÷ 20 tons/kWh	0.80
Amortization of Briquette Machine	\$220,000 at 9% on reducible balance over 5 years with monthly payments; cost per year = \$54,802; 7000 hours per year at 20 tons/h \$54,802 ÷ 7000 h x 20 tons/h	0.39
Amortization for Rest of System	Same as briquette machine	0.39
Total		3.18

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APPENDIX C

**LIBRARY SEARCH
INFORMATION**

LIBRARY SEARCH INFORMATION

Copies of the following articles (arranged in reverse chronological order) are on file at the Energy and Environmental Research Center.

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