June 15, 2006

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Dear Mr. Evans:

Subject: Final Report Entitled "Regional Assessment of the Beneficial Use of Coal By-Products"

Please find enclosed one copy of the final report for the subject project. If you have any questions regarding this report, I can be reached at (701) 777-5261 or e-mail at dphassett@undeerc.org.

Sincerely,

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DFPH/kal

Enclosure

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REGIONAL ASSESSMENT OF THE BENEFICIAL USE OF COAL BY-PRODUCTS

Final Report

Prepared for:

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NOTE: This report is an updated version of one originally prepared for Excelsior on June 13, 2005, and uses the assumptions stated in the report introduction. Since the original report was published, Excelsior has indicated that a 606-MW integrated gasification combined-cycle (IGCC) plant is of greatest interest to the company. In this updated report, the Energy & Environmental Research Center (EERC) focused on descriptions of and market entry strategies for beneficial use applications for by-products from supercritical pulverized coal-fired and IGCC power plants. The EERC did not update the estimates of by-product quantities for the larger facility which were calculated based on a 500-MW facility utilizing the fuel options noted. Increased quantities of by-products are expected to be generated from the larger 606-MW facility; however, these increased quantities are not expected to change the by-product use applications or market entry strategies.

2006-EERC-06-02 June 2006

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REGIONAL ASSESSMENT OF THE BENEFICIAL USE OF COAL BY-PRODUCTS

1.0 INTRODUCTION

The University of North Dakota Energy & Environmental Research Center (EERC) was contracted by Excelsior Energy (Excelsior), Inc., to assess postproduction by-product management issues from a new power generation facility in Minnesota. Excelsior made the following assumptions regarding the proposed new facility:

1. A supercritical pulverized coal (pc)-fired power plant burning Powder River Basin (PRB) subbituminous coal could be located in the vicinity of Becker or Virginia, Minnesota. The plant would use either wet limestone flue gas desulfurization (FGD) or Powerspan Corporation's (Powerspan's) control technology (Powerspan, 2005). The supercritical plant's by-products were limited to fly ash, bottom ash, wallboard-quality gypsum, and ammonium sulfate–ammonium nitrate mixtures.

2. An integrated gasification combined-cycle (IGCC) plant burning 80% PRB subbituminous coal and 20% petroleum coke would be located in the Iron Range in northern Minnesota (Virginia, Minnesota, was used as the potential location; however, Grand Rapids, Minnesota, and Hoyt Lakes, Minnesota, are also being considered). The IGCC by-products were limited to pure elemental sulfur and IGCC slag.

3. Both proposed plants would produce 500 MW of electricity (500 MW_e).

2.0 BY-PRODUCT PRODUCTION AND CHARACTERISTICS

Development of a realistic by-product management plan requires an estimate of the types, quantity, and quality of the by-products to be produced. The two types of conversion systems under consideration by Excelsior will result in very different by-products. The supercritical pc-fired unit will produce fly ash and bottom ash typical of those produced broadly across the United States. In addition, two different FGD processes, wet limestone scrubbing with forced oxidation and the Powerspan process, are under consideration for use in conjunction with the supercritical pc-fired plant. Wet limestone scrubbing with forced oxidation will produce FGD gypsum while the Powerspan technology will produce an ammonium sulfate–ammonium nitrate mixture. Based on the fuel data provided by Excelsior, the predicted size of the power plant, and input from Fluor Corporation, the estimates of by-product production rates were made and are included in Tables 1 and 2.

As indicated in Tables 1 and 2, there are minor discrepancies between the EERC's and Fluor's estimates of fly ash and bottom ash. These discrepancies are not expected to impact any market potential for these materials. Another discrepancy is noted between the Fluor estimate of ammonium sulfate production and that estimated by a Powerspan representative who spoke with the EERC about Powerspan's by-product marketing strategies. Again, the discrepancy did not impact the marketing options for that by-product.

Table 1. EERC Annual By-Product Production Estimates – 500-MW Supercritical pc Unit

	Avg. Wyoming Subbituminous	Avg. Montana Subbituminous
Ash Content, %	5.2	9.0
Sulfur Content, %	0.37	1.04
Calculated Fuel Use (M metric tons/M short tons)	2.3/2.53	2.3/2.53
Calculated Ash Production, total, short tons	130,000	230,000
Estimated Fly Ash Production, short tons	104,000	184,000
Estimated Bottom Ash Production, short tons	26,000	46,000

Table 2. Fluor Annual By-Product Production Estimates – 500-MW Supercritical pc Unit

	Subbituminous Coal
Estimated Fly Ash Production, short tons	118,800
Estimated Bottom Ash Production, short tons	25,142
Calculated Gypsum Production, short tons	198,000
Calculated Ammonium Sulfate, short tons	41,025*

* Powerspan representatives estimated 80,000 to 100,000 short ton/year of ammonium sulfate production based on a 500-MW plant burning 0.4% sulfur content subbituminous coal (Wolfe, 2005).

2.1 Supercritical PC By-Products

Supercritical coal-fired power plants use higher steam temperatures and pressures than subcritical pc generation and are, therefore, more fuel-efficient and produce lower levels of emissions. To control emissions, the proposed plant would use either wet limestone FGD or Powerspan's control technology (Powerspan, 2005). Although supercritical power generation requires more sophisticated technology in equipment design to withstand the high temperature and pressure levels, the by-products produced from supercritical and subcritical pc power plants are similar in chemical and mineralogical characteristics. A forced oxidation wet limestone FGD system and Powerspan technology were considered over other SO_2 removal systems because sodium-based scrubber by-products and high-sulfite-containing scrubber by-products have a very low rate of utilization. The American Coal Ash Association (ACAA) reported that nonoxidized wet FGD material was utilized at ~7%, dry FGD material for spray dryer atomization at ~10%, and other dry FGD material (sodium-based) at ~3%, while FGD gypsum from forced oxidized wet FGD systems were utilized at ~76% (ACAA, 2004).

2.1.1 Fly Ash

Fly ash is the inorganic portion of finely pulverized coal that is carried out of the boiler with the flue gases and collected by an electrostatic precipitator (ESP) or a fabric filter (baghouse). Depending on the efficiency of the particulate control device, a small portion of the smallest size fraction of the fly ash may exit the stack.

The characteristics of the fly ash that are most commonly used to categorize or assess its utilization potential are bulk major chemical composition, fineness, and pozzolanic activity.

Additionally, for nonconcrete applications, fly ash is usually tested by the use of a designated leaching procedure. The mineral analysis of the ash from the coals under consideration, as noted in Table 3, provides a preliminary estimate of the chemical composition of the fly ash expected to be generated at the potential supercritical pc-fired unit. The bulk chemical composition, reported as oxides, is typical of the composition of subbituminous fly ash appropriate for use as a mineral admixture in concrete, with the exception of the sulfur trioxide, which is higher than the limit noted for ASTM International (ASTM) C618 –Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete. The sulfur trioxide value represents all sulfur in the coal that becomes part of the ash. Since a portion of the sulfur will also leave the boiler with the flue gas, this value is higher than would be anticipated in the actual fly ash. The EERC expects that the fly ash produced will meet the chemical composition and Class C specifications under ASTM C618. Pilot-scale testing of the actual fuel, once selected, will provide adequate samples to perform laboratory tests, including environmental performance tests, which more accurately predict the appropriateness of the fly ash for various uses. Should the fly ash be found inappropriate for use as a mineral admixture in concrete, it would be available in quantities appropriate for use in markets such as structural fill, soil stabilization for construction, and other high-volume applications. Based on past experience with PRB subbituminous coal fly ash, the EERC does not anticipate that environmental performance testing will limit the use of the fly ash; however, permits would have to be obtained from the Minnesota Pollution Control Agency (MPCA) for nonconcrete uses in Minnesota. For concrete uses in state or federally funded highway projects, the fly ash would need to be certified by the Minnesota Department of Transportation (MNDOT).

Table 3. Calculated Mineral Composition of Fly Ash

	Wyoming Subbituminous Avg %	Montana Subbituminous Avg %	ASTM C618 Standard Specifications Class C Fly Ash
Mineral Analysis of Ash, ignited basis			
Silica (SiO_2)	29.8	38.9	
Alumina (Al_2O_3)	16.4	16.6	
Ferric Oxide (Fe_2O_3)	5.8	10.7	
$SiO_2 + Al_2O_3 + Fe_2O_3$	52	66.2	Min. 50%
Lime (CaO)	24.6	11.6	
Magnesia (MgO)	5.9	3.8	
Potassium Oxide (K_2O)	0.3	0.7	
Sodium Oxide (Na_2O)	1.8	2.1	
Sulfur Trioxide (SO_3)	11.9	13.8	Max. 5.0%
Phosphorus Pentoxide (P_2O_5)	0.7	0.3	
Strontium Oxide (SrO)	0.44	0.3	
Barium Oxide (BaO)	0.62	0.6	
Manganese Dioxide (MnO_2)	0.03	0.1	

2.1.2 Bottom Ash

Bottom ash falls to the bottom of the furnace and is removed as nonmolten particles (clinkers). It is composed of a range of fine to coarse angular particles, which are generally gray to black in color, with the bulk of the material resembling sand. Some may appear glassy, but, more commonly, the particles are porous. The bulk chemical composition of bottom ash is usually similar to the fly ash produced, and the mineral analysis of fly ash shown in Table 3 is a reasonable prediction of the bulk chemical composition of bottom ash to be produced with the exception of the sulfur trioxide. Bottom ash generally does not contain significant percentages of sulfur. While not shown in the mineral analysis, the trace element composition of bottom ash and fly ash produced from the same coal can be very different, with more trace elements being associated with the fly ash, especially those with higher volatility such as bromine, fluorine, arsenic, and selenium. Bottom ash is most appropriately used as replacement for aggregates, engineered fill applications, and some soil stabilization applications. These uses will generally require the material be evaluated for environmental performance via a leaching test. Some bottom ashes have been found to leach extremely low amounts of constituents, allowing their classification as inert waste, which permits broad uses of the material.

2.1.3 FGD Gypsum

The proposed wet limestone system includes a forced-oxidation system to produce FGD gypsum (calcium sulfate dihydrate [$CaSO_4 \cdot 2H_2O$]). FGD gypsum formed with the use of in situ forced oxidation is generally >95% pure. FGD gypsum leaves the oxidation system with relatively high percentages of free water (free water does not include the waters of hydration). Dewatering is required prior to marketing FGD gypsum so that the free-water requirements of various applications are met and so transport of the FGD gypsum does not include transport of free water. Dewatering to ~10% can be easily achieved with standard dewatering equipment. FGD gypsum is a fine white to off-white powder, so if the material is not to be used on-site, pelletizing it offers advantages for transport and for potential users. Typical markets for FGD gypsum are wallboard, cement manufacture, and agricultural soil amendments.

2.1.4 Ammonium Sulfate–Ammonium Nitrate

The Powerspan integrated air pollution control technology is predicted to substantially reduce emissions of the four primary air pollutants of concern from coal-fired power plants, specifically 98% reduction of sulfur dioxide (SO_2), 90% of nitrogen oxide (NO_x), 80%–90% of mercury (Hg), and 95% of fine particulate matter ($PM_{2.5}$). This system, using Powerspan's electrocatalytic oxidation technology (ECO®), also produces a commercially salable ammonium sulfate–nitrate coproduct. Powerspan indicates that the ammonium sulfate and ammonium nitrate created in the ECO® process can be treated and used as a commercial fertilizer (Wolfe, 2005). The drying and granulating system for this fertilizer coproduct incorporates the same equipment and process used in commercial fertilizer processing plants.

2.2 IGCC By-Products

In coal gasification systems, the coal is converted to a combustible gas, volatiles, char, and ash/slag. Commercial gasifiers differ widely in the way in which they produce ash, and either dry ash, agglomerated ash, or slag may result (Pflughoeft-Hassett, 1997).

The IGCC system under consideration by Excelsior is the ConocoPhillips E-Gas technology and will produce elemental sulfur and a slag by-product stream. This technology is also in place at the SG Solutions, LLC, Wabash River IGCC plant in West Terre Haute, Indiana, which has been in operation since the mid-1990s. The EERC estimates of the slag and sulfur production rates from the IGCC plant are shown in Table 4; Fluor estimates are shown in Table 5.

2.2.1 Elemental Sulfur

Elemental sulfur is a by-product of the E-Gas system. The Electric Power Research Institute (EPRI) (Dalton, 2004) indicates that the sulfur removed from the syngas at IGCC plants will range in purity from 98.5% to 99.99%. The sulfur being produced at the Wabash River IGCC plant is 99.99% pure (Lynch, 2005). A Wabash River representative (Lynch, 2005) indicated that the high-purity elemental sulfur from its plant is being successfully marketed in the agricultural chemicals market. With the quantities expected from the potential IGCC plant, the EERC assumes that the quality and market for that material should be similar to that from the Wabash River plant.

Table 4. EERC Annual By-Product Production Estimates – 500-MWe IGCC pc Unit

	80% Avg. Wyoming Subbituminous + 20% Petroleum Coke	80% Avg. Montana Subbituminous + 20% Petroleum Coke
Ash Content, %	4.29	7.33
Sulfur Content, %	1.43	1.96
Estimated Fuel Use, M short tons	2.28	2.28
Slag Production, short tons	97,000	167,000
Sulfur Production, short tons	33,000	45,000

Table 5. Fluor Annual By-Product Production Estimates – 500-MWe IGCC pc Unit

	79% Subbituminous + 21% Petroleum Coke
Slag Production, short tons	87,120
Sulfur Production, short tons	23,892

2.2.2 IGCC Slag

IGCC slag is generally a black, angular, vitreous material having the appearance of coarse black sand. Char that is formed in the IGCC system is associated with the slag as it exits the gasifier system, but in the E-Gas system, the char is separated from the slag, so the slag stream is relatively free of char. The chemical composition and hardness are key properties of the slag that will dictate its potential applications. Quantitative technical data on hardness were unavailable, but a qualitative estimate from representatives of the Tampa Electric Company (TECO) IGCC Polk Power Station in Polk County, Florida, indicated that the slag produced is "very hard" (Berry, 2005). Wabash River representatives did not provide an indication of the hardness of the slag produced. The mineral analyses of ash from the fuels under consideration were used to assemble the calculated mineral composition of the coal–petroleum coke blends expected to be used in the IGCC. Because petroleum coke has very low ash content, the calculated mineral analyses are very similar to those reported for coal only in Table 3. Browning et al. (1999) indicate that the IGCC process is expected to result in an enrichment of silicon in the slag as compared to the mineral analysis of the ash. Based on this statement, the potential IGCC slag would be expected to have a greater percentage of silica in the chemical composition than is presented in Table 6. Successful applications for IGCC slag reported by representatives at the TECO and Wabash River IGCC plants are concrete cement feedstock, road construction applications such as filler for asphalt, blasting grit, roofing material, structural fill, and

Table 6. Calculated Mineral Composition of Coal–Petroleum Coke Ash

	80% Avg. Wyoming Subbituminous + 20% Petroleum Coke Avg. %	80% Avg. Montana Subbituminous + 20% Petroleum Coke Avg. %
Mineral Analysis of Ash, ignited basis		
Silica (SiO_2)	29.5	38.6
Alumina (Al_2O_3)	16.2	16.5
Ferric Oxide (Fe_2O_3)	5.8	10.6
$SiO_2 + Al_2O_3 + Fe_2O_3$	51.5	65.7
Lime (CaO)	24.2	11.6
Magnesia (MgO)	5.8	3.8
Potassium Oxide (K_2O)	0.3	0.7
Sodium Oxide (Na_2O)	1.8	2.1
Sulfur Trioxide (SO_3)	12.2	13.9
Phosphorus Pentoxide (P_2O_5)	0.7	0.3
Strontium Oxide (SrO)	0.44	0.3
Barium Oxide (BaO)	0.60	0.6
Manganese Dioxide (MnO_2)	0.03	0.1
Nickel Oxide (NiO)	0.14*	0.08*
Vanadium Pentoxide (V_2O_5)	0.47*	0.28*

* Based on petcoke contribution only. No data were provided for nickel or vanadium in the coal.

alternative landfill cover. In the EERC report "IGCC and PFBC By-products: Generation, Characteristics, and Management Practices" (Pflughoeft-Hassett et al., 1997), the trace element leachate concentrations of a limited number of IGCC slags were reported. These data indicated extremely low mobility of trace elements from the IGCC slag samples both from pilot-scale and full-scale systems. For several of the potential applications, permits will likely be required for slag from a potential IGCC facility, but the leaching data presented in the EERC report imply that the environmental performance will not prohibit the slag from being incorporated into a variety of applications. The material should be evaluated to assess its potential for meeting inert waste criteria.

3.0 BY-PRODUCT MARKET ASSESSMENT

3.1 Minnesota CCB Use Regulations

Under Minnesota regulations, fly ash, bottom ash, slag, and FGD material generated from the combustion of fuel which is at least 51% coal or other fossil fuels, with the balance not containing hazardous waste, is exempt from regulation as hazardous waste. Reuse of coal combustion by-products (CCBs) is not specifically authorized under Minnesota law or regulations. Serveral CCB utilization options have standing BUDs (beneficial use determinations) in Minnesota. These include the use of fly ash and FGD material in manufactured aggregate. Other use applications require submission of information to obtain a BUD, and these applications are approved on a case-by-case basis. Permits and BUDS authorizing the use of CCBs from specific facilities have been issued for soil stabilization and agriculture amendments.

3.2 Supercritical PC By-Products – Fly Ash

3.2.1 Market Supply and Demand

The American Coal Ash Association (ACAA, 2004) reported that more than 70 million tons of fly ash was produced in 2004, with 39.65% used in beneficial applications. Figure 1 illustrates leading fly ash applications in 2004.

Superior-quality fly ash is in high demand for concrete products, whereas lower-quality fly ashes have limited demand. Low-quality fly ashes are typically used in large-volume, low-value applications such as structural fill.

It is anticipated that the proposed power plant will produce a fly ash acceptable for use in concrete applications, meeting requirements set by ASTM C618. Because concrete markets are subject to seasonality, short-term storage may be required in order that the maximum quantity of fly ash can be placed in that market during peak construction times.

Based on conversations with industry (Christianson, 2005; Corrigan, 2005), Minnesota's demand for fly ash for concrete is at about 350,000 tons per year based on a 15%–30%

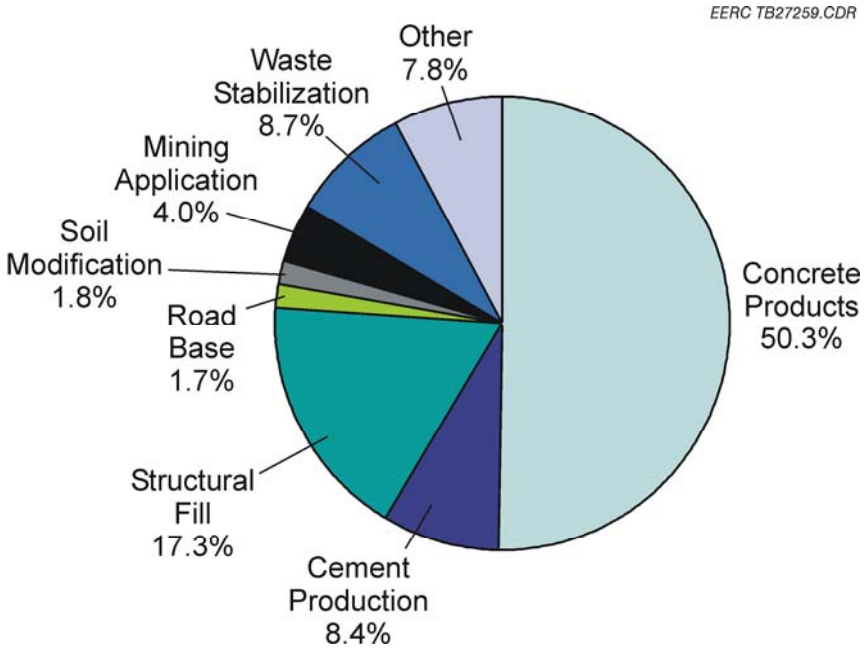

Figure 1. Leading fly ash applications in 2004.

replacement rate of fly ash for portland cement. That demand is expected to rise on parallel with concrete demand. The replacement rates for fly ash are frequently dictated by practices accepted by state Departments of Transportation and typically include a percentage range for replacement; however, there is great interest among industry to move toward performance-based specifications that may increase the amount of fly ash used as a replacement for portland cement depending on the application. If MNDOT were to raise the limit for fly ash in concrete for transportation projects to 40% replacement, the market demand would likely reach 600,000 tons.

3.2.2 Expected Value

The value of fly ash varies significantly among producers (power plants) depending on product quality, the plant's proximity to the market, and product availability. Great River Energy's Coal Creek Station in Washburn, North Dakota, produces a superior-quality fly ash that sells for $4–$14/ton free on board (FOB). In contrast, Otter Tail Power Company's Hoot Lake plant in Fergus Falls, Minnesota, has offered its fly ash at no or minimal cost depending on the beneficial use application. Prices for fly ash being sold into the concrete production market nationwide are extremely variable and range from $3–$40 per ton. Selling the fly ash, or any CCB, is considered by most people in the coal ash industry to be a much-preferred option to giving it away. It has been suggested that the legal liability of the provider may be reduced should the material be misused or mishandled if the material were sold as a product. The EERC is not aware of any legal precedent in this area. Many coal ash producers prefer to subsidize the cost of transportation for ash rather than provide ash at no cost for the reason noted.

3.2.3 Existing Market Potential

3.2.3.1 Concrete

Approximately 5.1 million cubic yards of concrete is used per year in Minnesota. About 25% is used for street, road, and highway construction; 25% for public buildings/projects; 25% for residential markets; and 25% for commercial markets (Aggregate & Ready Mix Association of Minnesota, 2005).

Minnesota, like other states, requires portland-pozzolan cement to conform to American Association of State Highway and Transportation Officials (AASHTO) M240, Type IS or Type IP, except as modified by the following: the fly ash constituent of the interground cement shall not exceed 20%, and the fly ash constituent of blended cement shall not exceed 15%. Fly ash for use in portland cement concrete shall confirm to ASTM C618, Class F or Class C, except as modified by the following:

- Maximum CaO for Class F is 30%; maximum CaO for Class C is 40%.
- Maximum loss on ignition is 3.0%.
- Maximum available alkalies expressed as Na_2O is 3.0%.
- Minimum air permeability is 650 mm^2/kg.
- Maximum retained when wet-sieved on a 45-µm sieve is 30%.
- Minimum strength activity index with portland cement at 7 days is 75%.
- Maximum variation from established specific gravity value is ± 0.12.

According to Minnesota state regulations, fly ash produced at plants where the limestone injection process is used for controlling air pollutants will be considered unacceptable for use in portland cement. Fly ash which meets the requirements of both Class C and Class F shall be considered as being Class C. Fly ash is permitted as a partial cement replacement for up to 15% by weight for Class C and Class F in general concrete applications. Special provisions may allow higher percentages of fly ash substitutions. A fly ash substitution rate of 30% is allowed for concrete pavement and high-performance full-depth bridge decks. It should be noted, however, that 30% replacement of cementitious material in concrete is becoming the standard in Minnesota, and MNDOT will allow 30% replacement in its mix designs with approved sources (Corrigan, 2005).Only ashes from certified sources are allowed. A list of approved fly ash sources meeting MNDOT specifications is in Appendix A. Mixing of fly ash from different sources or of different classes in one storage bin or silo is not acceptable (Dockter, 2005).

3.2.3.2 Road Building Applications

Fly ash use in road base and engineered fills has been successfully demonstrated in large-scale field studies in Minnesota. The MPCA requires special permits for these applications; however, work is under way to develop provisions for certain applications. For example, the Aggregate & Ready Mix Association of Minnesota is working with MPCA on a Case-Specific Beneficial Use Determination for the use of CCBs in controlled low-strength material (CLSM).

It should be noted that this market is highly dependent on MNDOT funding for road construction. In the past, MNDOT has had ample funding for new road construction projects, but because of the state's current budget crisis, MNDOT may experience significant budget cuts in the future (Siekmeier, 2005).

3.2.4 Recommended Approach to Market Entry

Based on the market supply and demand analysis, it is expected that a supercritical PC fly ash producer will be able to sell all of its fly ash into the regional concrete market. Seasonal demands would also need to met by the producer, and short-term storage will likely be required to meet peak demands. Storage will have to meet MPCA requirements. It is recommended that a professional ash marketing company that has an established reputation in the region be used to enter the concrete and road-building markets. It is also important to note that if the fly ash quality is not adequate for use in these markets, then the fly ash may need to be disposed.

3.3 Bottom Ash

3.3.1 Market Supply and Demand

According to the ACAA (2004), 17.2 million tons of bottom ash were produced by North American coal-fired power plants in 2004, and 47.40% was used in beneficial use applications. Listed in order of percentage utilized, these include structural fills/embankments, mining applications, road base/subbase/pavement, snow and ice control, aggregate, cement/raw feed for clinker, and concrete products.

There are no standing BUDs for bottom ash, and MNDOT does not specify bottom ash for any applications; however, counties and cities can use the material at their discretion. Siekmeier (2005) said MNDOT prefers to use CCBs only in applications were the material is bound by pozzolanic reactions, such as concrete, and, therefore, does not allow the use of bottom ash in applications such as snow and ice control. From an engineering perspective, bottom ash could be used in a number of applications, but environmental impacts are a concern (Siekmeier, 2005).

3.3.2 Expected Value

In general, bottom ash is a low-value, high-volume commodity whose delivered price is highly dependent on haul distance. Unless a local market (within 30 miles) has a high demand for bottom ash, it is not anticipated that a profit will be realized from the sale of this material. Disposal may be required for bottom ash if the market is limited and during the off season.

3.3.3 Existing Market Potential

3.3.3.1 Aggregate

The Aggregate & Ready Mix Association of Minnesota (2005) reports that the state uses 51.2 million tons of aggregate per year in public and private construction. Minnesota has 5000 gravel pits and 1500 quarries, with annual sales over $250 million. Transportation costs range

from $0.10 to $0.15/mile/ton by truck. Hauling aggregate 20–30 miles doubles the cost, making a local supply highly desirable. The Association reported that Minnesota has a limited supply of quality aggregate, and this problem is expected to increase as the population grows in Minnesota's metropolitan areas.

Bottom ash aggregate may be graded to meet the requirements of ASTM C331 specification for lightweight aggregate for use in concrete masonry units and can be blended with other lightweight aggregates to achieve greater quantities. Bottom ash may also be used as conventional aggregates are for use in asphalt, concrete, and road construction.

3.3.3.2 Mining Applications

Given the proposed plant's proximity to the Minnesota Iron Range, mining applications are a likely candidate for large-volume applications. Bottom ash is used to improve the economics of mining when used as a nontoxic fill within the spoil area prior to grading and final reclamation. Uses include 1) a seal to contain acid-forming materials and prevent the formation of acid mine drainage, 2) an agricultural supplement to create productive artificial soils on abandoned mine lands where native soils are not available, 3) a flowable fill that seals and stabilizes abandoned underground mines to prevent subsidence and the production of acid mine drainage, 4) a construction material for dams or other earthlike materials where such materials are needed as a compact and durable base, and 5) a nontoxic, earthlike fill material for final pits and within the spoil area (Vories, 2002).

It is important to note that mining uses for CCBs are under national regulatory debate and it is unknown if these applications will be allowed in the future. In 2006, the National Research Council of the National Academies released a prepublication of its report "Managing Coal Combustion Residues in Mines" prepared by the Committee on Mine Placement of Coal Combustion Wastes (2006). The report made some conclusions that will certainly fuel the national regulatory debate including:

- "Of the three methods currently available for disposal of CCRs [coal combustion residue] (surface impoundments, landfilling, and minefilling), comparatively little is known about the potential for minefilling to degrade the quality of groundwater and/or surface waters particularly over longer time periods. Additionally, there are insufficient data on the contamination of water supplies by placement of CCRs in coal mines, making human risk assessments difficult."

- "…the committee concludes that the presence of high contaminant levels in many CCR leachates may create human health and ecological concerns at or near some mine sites over the long term."

- "With regard to CCR placement in minefills, the committee concludes that while potential advantages should not be ignored, the full characterization of possible risks should not be cut short in the name of beneficial use."

3.3.4 Recommended Approach to Market Entry

A local market for bottom ash is key to utilizing the material, and aggregate and mining applications appear to be best local markets. Given the ongoing evaluation of the use of CCBs in mine reclamation applications, a focus on marketing as aggregate is recommended. Given Minnesota's current demand, the state's market will likely be able to absorb an additional 25,000 tons of aggregate.

If in order to pursue applications that would generate a profit, novel approaches to utilization that meet local needs should be considered. For example, Cincinnati Gas & Electric Company, a subsidiary of Cinergy Corporation, uses its bottom ash to backfill joint trench utilities of gas, electric, telephone, and cable television. In the first 3 months of trying this method, the company saved $62,977 by using 8074 tons of bottom ash in place of sand (Beck et al., 2003). Identifying novel applications will require an in-depth analysis of local needs. Bottom ash that does not meet specification for aggregate may require disposal, and off-season disposal may also be necessary.

3.4 FGD Gypsum

3.4.1 Market Supply and Demand

Domestic gypsum consumption (mined and synthetic gypsum used plus imports) was nearly 36.6 million tons in 2003, a 9% increase from 2002. Domestic sources satisfied 77% of the demand and the remainder was supplied by imports (Founie, 2003).

In 2004, 18 domestic coal-fired power plants generated approximately 12 million tons of synthetic gypsum from their FGD systems. About 9 million tons or 75.69% of all FGD gypsum was used in 2004, as the utilization rate for FGD gypsum continues to rise each year. Of all synthetic gypsum produced in 2004, 90% was used for wallboard production, 8% for cement and concrete manufacture, and a nominal amount was used in agriculture applications (ACAA, 2004).

FGD gypsum has experienced a steady increase in demand in recent years; however, over the next 20 years, the North American supply of FGD gypsum is expected to exceed the demand by a wide margin, with a surplus of 11–14 million tons per year by 2015 and 15–18 million tons per year by 2020. This surplus can be directly attributed to the government's initiatives to reduce SO_2 emissions, thereby resulting in an increase in the supply of FGD gypsum. In addition, demand for synthetic gypsum is expected to peak at 10–11 million tons per year (Bruce and Tackett, 2004). Mined gypsum will also experience a surplus supply as more synthetic gypsum is produced. According to the U.S. Geological Survey (USGS), some actual and planned mine closings already have been attributed to the substitution of synthetic gypsum (Founie, 2003).

The FGD gypsum market in Canada is not anticipated to influence U.S. demand. In Canada, SO_2 levels were cut by about 30% since 1990, and no further government targets have been set (Bruce and Tackett, 2004).

Because the gypsum industry tends to have a much more exaggerated cycle than other industries within the construction sector, the commitment of the gypsum supplier is critically important to encourage a partnership with consumers. Commitment is seen in numerous forms, including supply reliability, because building material production plants operate continuously, making supply interruptions difficult to manage; product quality to ensure impurities are controlled to acceptable levels; desirability of the local market region; and competitive advantage over competing materials (Berland et al., 2003).

3.4.2 Expected Value

Prices for gypsum in merchant markets are negotiated among buyers and sellers, and published figures are not always relevant. In 2003, the average values (FOB mine or plant) reported by U.S. producers were $6.90/ton for crude gypsum and about $20/ton for calcined gypsum. The average value for plaster reported by domestic producers during 2003 was $6.86/100 lb. The average value of uncalcined gypsum used in agriculture and cement production was about $17.40/ton (Founie, 2003). Raw FGD gypsum is expected to sell for $3–$5/ton at the power plant (Bruce and Tackkett, 2004). With regard to the specific applications outlined below, the price for gypsum used in cement production is consistently lower than agricultural gypsum and more in line with the price for gypsum in wallboard (Flaagan, 1998).

3.4.3 Existing Market Potential

3.4.3.1 Wallboard Manufacture

In the United States, the vast majority (90%) of FGD gypsum;produced is used to manufacture wallboard (ACAA, 2004), including regular wallboard, Type X, sheathing, soffit board, water-resistant gypsum, backing board, lath, veneer base, coreboard, gypsum liner board, predicated, foil-backed, and board for manufactured housing (Berland et al., 2003).

Synthetic gypsum used for wallboard manufacture must meet strict parameters. Parameters that are most important to product quality include free moisture, purity, soluble salts, pH, particle size, and surface area (Berland et al., 2003). Table 7 details the composition requirements for wallboard quality FGD gypsum (Flaagan, 1998). Assuming the synthetic gypsum meets particle-size requirements and does not contain any harmful impurities, a higher-purity synthetic gypsum will allow a lower-weight board to be produced without sacrificing strength. Soluble salt impurities are common in natural and synthetic gypsums. The four soluble salt ions typically tested for are magnesium, potassium, sodium, and chloride. Chloride is the most common contaminant in FGD gypsum. Soluble salts found in FGD gypsum can often be washed away (Berland et al., 2003).

FGD gypsum tends to be considerably finer (<0.2 mm) than natural gypsum; therefore, only limited quantities of FGD gypsum can be used to replace or supplement gypsum in older gypsum wallboard plants (Berland et al., 2003). In addition, many existing wallboard plants have their own gypsum mine that supplies consistent-quality gypsum, and regulations that require recycling of wallboard-waste gypsum back into the plant can impact the amount of synthetic gypsum that can be used at a plant designed to use rock gypsum. However, several new

wallboard plants have been built specifically to use FGD gypsum from a nearby coal-fired power plant and two new plants announced partnerships with utilities for startup in 2007 (BPB with Progress Energy and National Gypsum with Duke Power).

It is anticipated that the majority of existing wallboard plants already have secured a source for their gypsum supply, either mined or synthetic, and unless a cost-competitive product can be offered considering handling and transportation costs, the producer will not be able to enter the wallboard market. In addition, the estimated quantity of FGD gypsum produced from the supercritical unit will likely be too limited for use in gypsum manufacturing as wallboard manufacturers using FGD gypsum generally require ~600,000 tons per year.

Figure 2 shows all U.S. wallboard plants by source of gypsum (Gaynor, 2005). Table 8 identifies regional wallboard plants and their road distance from Virginia, Minnesota. Wallboard plants in excess of 1000 miles from Virginia, Minnesota, were not considered unless barging was an optional mode of transportation.

3.4.3.2 Cement Manufacture

In the United States, 8%, or 740,502 tons, of FGD gypsum is used in cement and concrete manufacture in 2004 (ACAA, 2004). Gypsum ground to a fine powder has long been used in portland cement manufacturing to help control the rate of setting. Added to portland cement clinker in the grinding process, gypsum typically makes up 3%–5% of the finished product. The primary issues associated with FGD gypsum use are cost, purity, and moisture content.

Transportation costs require that cement manufacture be close to the power plant for this use to be profitable. Major cement manufacturing companies supplying cement to Minnesota

Table 7. Composition Requirements for Wallboard-Quality FGD Gypsum

Property	Composition Requirements
$CaSO_4 \cdot 2H_2O$	95.0% min.
$CaSO_3$	0.5% max.
Free Moisture	10.0% max.
Fly Ash	1.0% max.
SiO_2	1.0% max.
$Ca/MgCO_3$	5.0% max.
Fe_2O_3	0.4% max.
Cl^-	100 ppm max.
Na	100 ppm max.
Mg	75 ppm max.
K	100 ppm max.
Total Soluble Salts	600 ppm max.
pH	6–8
Particle Size	20% max. <10 μm
Aspect Ratio	10 max.

include Holcim, Inc., Lafarge North America, and Lehigh Cement Company. Back-haul transportation arrangements with Minnesota cement suppliers may make it economical to transport FGD gypsum to the manufacturing facility. Cement manufacturing companies are listed in Table 9. Cement plants in excess of 1000 miles from Virginia, Minnesota, were not considered unless barging was an option.

Since the closest cement plant is more than 300 miles away from the proposed power plant, transportation costs may bar entry into this market.

3.4.3.3 Agriculture Applications

According to the ACAA (2004), 131,058 tons of FGD gypsum from forced-oxidized systems was used in agriculture applications in 2004. Gypsum has long been known to provide benefits in agricultural applications. It can be used as an amendment of sodic, saline, and sodic–saline soils to enhance crop production and to improve soil tilth. Gypsum can also be a fertilizer, providing calcium and sulfur to soils without increasing the alkalinity or pH.

Flaagan (1998) identified three nontraditional agriculture-related gypsum applications under development in North Dakota that may be applicable in Minnesota.

- Foliar feeding that incorporates gypsum with other chemicals can be used as a low-volume (4–5 lb/acre), high-value ($80–$160/ton) application.

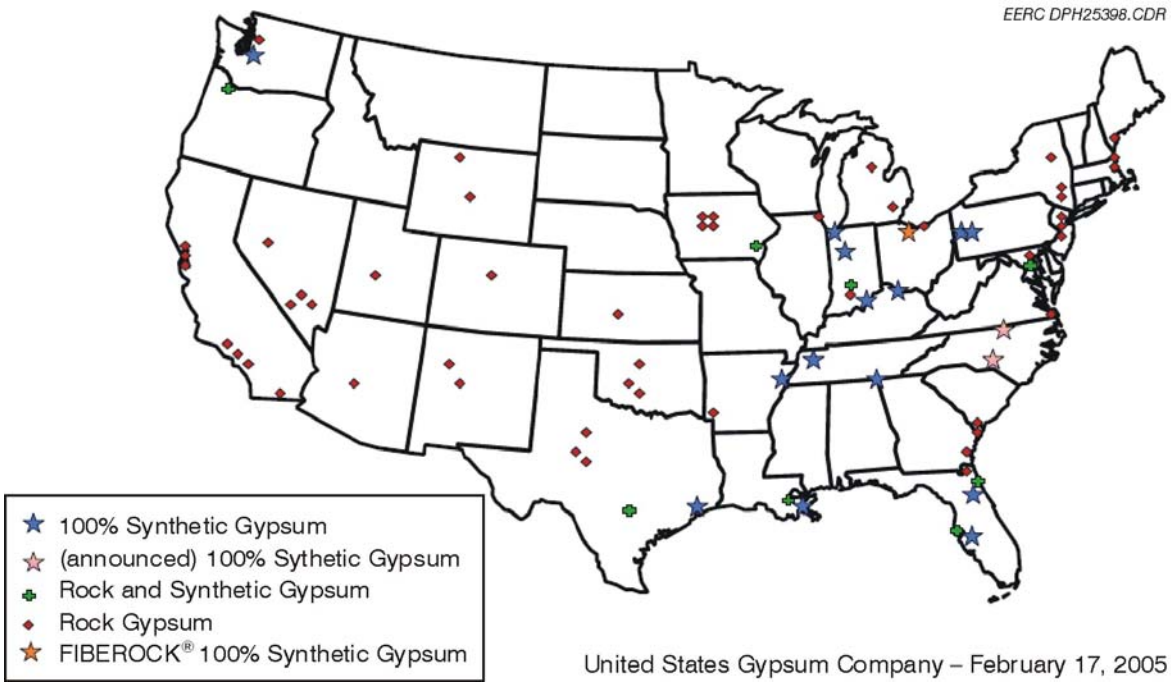

Figure 2. U.S. wallboard plants by source of gypsum (Gaynor, 2005).

Table 8. Regional Gypsum Wallboard Plants

Company	City	State/Prov.	Miles
BPB Canada, Inc.	Winnipeg	Manitoba	390
USG Corporation	Fort Dodge	Iowa	410
Georgia Pacific	Fort Dodge	Iowa	410
BPB America, Inc.	Fort Dodge	Iowa	410
National Gypsum Company	Fort Dodge	Iowa	410
BPB Manufacturing, Inc.	Plymouth	Wisconsin	490
USG Corporation	Sperry	Iowa	560
USG Corporation	East Chicago	Indiana	610
Georgia Pacific	Wheatfield	Indiana	660
USG Corporation	Detroit	Michigan	860
USG Corporation	Shoals	Indiana	880
National Gypsum Company	Shoals	Indiana	880
National Gypsum Company	Lorain	Ohio	904
CGC, Inc.	Hagersville	Ontario	1070*
Georgia Pacific	Caledonia	Ontario	1073*
BPB Canada, Inc.	Mississauga	Ontario	1098*

* Indicates barging would be the most cost-effective mode of transportation.

Table 9. Regional Cement Manufacturers

Company	City	State/Province	Miles
Holcim, Inc.	Mason City	Iowa	331
Lehigh Cement	Mason City	Iowa	331
Cemex	Charlevoix	Michigan	532*
Lafarge	Buffalo	Iowa	552
Lafarge	Alpena	Michigan	588
Lafarge	Sugar Creek	Montana	629
Lafarge	Fredonia	Kansas	782
Dakota Cement Company	Rapid City	South Dakota	802
Lafarge	Paulding	Ohio	805
Holcim, Inc.	Dundee	Michigan	843
Lehigh Cement	Mitchell	Indiana	852
Holcim, Inc.	Clarksville	Montana	862
Lafarge	Grand Chain	Illinois	915
Lafarge	Woodstock	Ontario	1026*
Lafarge	Stoney Creek	Ontario	1079*
St. Lawrence Cement	Mississauga	Ontario	1098*
Lafarge	Bath	Ontario	1256*

* Indicates barging would be the most cost-effective transportation.

- FGD gypsum can be used as a calcium supplement in animal feed for poultry, swine, and feedlot cattle.

- Gypsum is used in sugar beet processing to facilitate production of beet pulp pellets, which are marketed as cattle feed. It was estimated that 10,000 tons of FGD gypsum could be used in this market annually, providing food-grade quality requirements are met.

Gypsum can also be incorporated into lawn and garden or horticultural applications, where distributors advertise the effectiveness of gypsum for restoring yellow grass, and in animal control. Related applications are in composting and in the preparation of synthetic soil, both of which have numerous uses ranging in volume from very low for individual homeowners to very high for commercial producers (Flaagan, 1998).

It is anticipated that agriculture may be the best market for the proposed plant's gypsum material given its location in an agriculture-rich state. Cropland represents 40% of Minnesota's total land base, far in excess of the national ratio (Natural Resources Conservation Service, 2005). Most fertilizer manufacturers will consider a local gypsum source, providing the material meets quality specifications and is cost-competitive. Quality specifications for feed applications will be more stringent but will bring a higher price.

While the market potential is high for this application, it is difficult to estimate the annual market because of the large customer base consisting of individual farmers and multiple dealers/distributors. Flaagen (1998) made some preliminary assumptions on the ability of FGD gypsum to penetrate the agriculture market in North Dakota. He concluded that mines in Gilmore City and Harvey, Iowa, were supplying North Dakota's gypsum for approximately $60/ton. Shipping costs varied between $25 and $35/ton, with additional charges from the distributors or dealers, resulting in an end-user cost of $110–$130/ton. That cost was cited as being prohibitive for most farmers and the primary reason that gypsum application has only been used on a limited basis in North Dakota. If FGD gypsum is direct-marketed to farmers, MPCA may prohibit the materials use in certain applications. It may be more feasible to penetrate this market if the material were processed and packaged by a fertilizer dealer.

3.4.3.4 Plaster

FGD gypsum can be converted to plaster through a dehydration process, producing either beta or alpha hemihydrate plaster. Beta hemihydrate requires 60–80 mL of water per 100 grams of plaster, whereas alpha hemihydrate plaster typically requires 35–40 mL of water per 100 grams of dry plaster to get a pourable mix. To compare alpha and beta plasters, note that normal concrete made with cement has a compressive strength of about 3000 psi and a high-strength concrete would achieve about 6000 psi. A typical beta plaster achieves about 2000 psi but an alpha plaster gives a compressive strength of about 10,000 psi (Bruce and Tackett, 2004).

Alpha hemihydrate plaster is commonly used in applications that would be served by normal cement; however, the material needs to meet demanding specifications. The traditional wet process to produce alpha hemihydrate plaster costs about $100–$110/ton. It is also possible

to autoclave gypsum rocks to produce a lower-grade alpha hemihydrate at a lower cost of about $75–$85/ton. New processes under development offer the potential to manufacture the alpha hemihydrate at about $50–$60/ton. If credit can be given for the avoided disposal costs, ongoing environmental monitoring costs, and low-grade steam, then the incremental cost to produce alpha hemihydrate is about $35/ton (Bruce and Tackett, 2004).

Market potential for alpha hemihydrate plaster is variable. It is anticipated that the dental/food-grade market would yield a market price of $800/ton; however, this market is too small and expensive to service. Likewise, the fine china market would yield a market price of about $400/ton; but, again, the market is too small and expensive to service. There is potential for the material to be used in joint cements, simple casting plaster, floor screeds, and mining services (oil well cements, coal mine fire-stopping, subsidence control, gunnite) for about $250/ton (Bruce and Tackett, 2004). Although plaster applications yield a high market price, it is recommended to concentrate marketing efforts on the agriculture market first.

3.4.4 Recommended Approach to Market Entry

The most likely market for FGD gypsum produced from the proposed plant is in the agriculture market. Some utilities sell FGD gypsum direct to farmers; however, this approach is not recommended. A fertilizer dealer should be used to process, package, and sell the material to end users.

3.5 Ammonium Sulfate–Ammonium Nitrate Mixtures

3.5.1 Market Supply and Demand

Ammonium sulfate and ammonium nitrate are coproducts of the Powerspan technology using ECO. The liquid coproducts are substantially free of mercury and fly ash and may be used as a fertilizer in the liquid form or may be sent to a crystallizer in which moisture is driven off to produce crystals of well-defined size, strength, and composition. Once crystallized, the fertilizer may be usable in the form produced by the crystallizer, processed to further reduce the moisture of the crystals, or granulated (Powerspan, 2005).

The Andersons, Inc., formed an alliance with Powerspan to supply nitrogen reagents and market and distribute the coproducts from the technology. Wolfe (2005) stated that a 500-MW power plant burning a low-sulfur subbituminous coal would likely produce 80,000–100,000 tons of ammonium sulfate per year. This by-product would comprise about 21% nitrogen and 24% sulfur. Ammonium sulfate should be crystallized and granulated on-site or piped to a nearby location to produce a commercial-grade fertilizer (Wolfe, 2005). In Minnesota, ammonium sulfate is commonly blended with other pelletized fertilizers and used as a starter fertilizer for corn and wheat (Rehm, 2005). The ammonium nitrate coproduct is minimal, comprising about 2% of the waste stream. This material is kept in liquid form and used as a blending agent (Wolfe, 2005).

3.5.2 Expected Value

Green Markets (2004) did not report a price for ammonium sulfate in the Northern Plains (Minnesota, North Dakota, and South Dakota); however, it reported a price of $144–$155/ton in the Great Lakes Region (Michigan and Wisconsin) during March 2004. The Andersons, Inc., said it would sell the processed fertilizer for $170–$180/ton and believes that there is a ready-made fertilizer market in Minnesota given the state's rich agriculture economy (Wolfe, 2005). Green Markets (2004) reported a price for ammonium nitrate in the Midwestern Region (Ohio, Indiana, Illinois, Iowa, Missouri, and Nebraska) of $188–$192/ton.

3.5.3 Recommended Approach to Market Entry

The ammonium sulfate–nitrate by-product is being successfully traded in the Midwest fertilizer market. Based on the integrated design of the proposed plant, the EERC assumes that the by-product quality will be appropriate for use in the fertilizer market in Minnesota. It is recommended to use The Andersons, Inc., to market the material because of its expertise with the Powerspan technology and marketing its by-products.

3.6 IGCC By-Products

3.6.1 Sulfur

3.6.1.1 Market Supply and Demand

The United States was the world's leading sulfur producer in 2004 with 10.1 million metric tons (11.1 million short tons) (Ober, 2004); however, U.S. sulfur production was 5% lower in 2005 because of two hurricanes that caused major shutdowns of refining capacity in the Gulf Coast region (Ober, 2006). All elemental sulfur and by-product sulfuric acid (H_2SO_4) were produced as a result of efforts to meet environmental requirements that limit atmospheric emissions of sulfur dioxide (Ober, 2004). Sulfuric acid production is the major use for elemental sulfur, accounting for about 90% of sulfur consumption. In 2004, the USGS estimated that the United States produced about 37.5 million metric tons (41.3 million short tons) of sulfuric acid, which is equivalent to about 12.3 million metric tons (13.5 million short tons) of elemental sulfur (Ober, 2004). Similarly, the U.S. Census Bureau (2005) estimated U.S. sulfuric acid production to be 41.9 million short tons in 2004. Agriculture (primarily phosphate fertilizer production) is the leading sulfur-consuming industry at 62%; followed by petroleum refining, 29%; and metal mining, 3%. Other uses accounting for 6% of demand are widespread (Ober, 2006).

Sulfur differs from most other mineral commodities in that its primary use is as a chemical reagent rather than a component of a finished product. This use generally requires that sulfur be converted to an intermediate chemical (namely, sulfuric acid) prior to its initial use by industry (Ober, 2004).

Taking into account worldwide economics, the outlook for sulfur utilization in the United States is declining. The sulfur industry continues to increase production amidst slowing consumption, higher stocks, and expanded world trade. The USGS predicts that unless

nontraditional uses for elemental sulfur increase significantly and government mandates are adopted, large quantities of excess sulfur could accumulate in many areas of the world, including the United States (Ober, 2004).

3.6.1.2 Expected Value

The average value of shipments of elemental sulfur in 2005 was estimated to be $35.00/metric ton (f.o.b. mine and/or plant), which was 7% higher than 2004 and over three times the average in 2002 (Ober, 2006). This dramatic increase was a result of a strong U.S. economy, rising oil prices (through fuel surcharges imposed by freight carriers), and increased production at domestic phosphate fertilizer operations. It should be noted that sulfur prices vary significantly by region and fluctuate based on supply and demand. In 2004, prices in Florida reached $70.50/metric ton, whereas prices on the West Coast were once listed as $0/metric ton in 2003, although prices eventually rose to $12–$17/metric ton (Ober, 2003, 2004). These prices are comparable to prices provided by Green Markets (2004).

Historical (1997–2002) prices for virgin sulfuric acid ranged from $25 to $55 per short ton (The Innovation Group, 2006).

3.6.1.3 Existing Market Potential Pure Elemental Sulfur

3.6.1.3.1 Fertilizer

The primary market for sulfur is in fertilizer applications. Over 60% of all sulfur consumption is in the production of phosphate fertilizers (the sulfur is converted to sulfuric acid which is used to produce the phosphate fertilizer), and about 10% is used in other agriculture applications, including the production of nitrogenous fertilizers and plant nutrient sulfur. Sulfur can be applied directly as elemental sulfur, sulfur–bentonite mixes, ammonium sulfate, potassium sulfate, or superphosphates (Ober, 1999); however, sulfur is primarily used to make sulfuric acid, which is then used to produce phosphate fertilizer.

On a local scale, George Rehm (2005), a University of Minnesota Extension Service soil scientist, stated there was no demand for pure elemental sulfur for agriculture applications in the state. Rehm said there are approximately 32 million acres of cropland in Minnesota and about 20% of that land is sulfur-deficient. Sulfur-based fertilizer will only be used for corn and alfalfa crops, which is grown on approximately 1 million acres. A farmer would not likely use straight elemental sulfur as fertilizer, but it technically could be used for alfalfa crops, which only comprise 150,000 acres in Minnesota. Sulfur is applied once a year during the spring at about 12–25 lb/acre. If a producer were to capture 50% of the alfalfa market at an application rate of 20 lb/acre, 1.5 million lb (750 short tons) of sulfur would be used. Rehm further stated that a farmer is not likely to purchase sulfur directly from a power plant but would purchase it from a trusted fertilizer dealer.

The local horticulture market is another potential fertilizer market for elemental sulfur. Minnesota home owners use sulfur to lower soil pH to grow vegetation such as ornamental shrubs or blueberries (Rehm, 2005). Gertens, a Minnesota-based greenhouse garden center and

nursery, produces a private-label fertilizer specifically formulated for Minnesota lawns. Gertens' fertilizers use a blend of nitrogen, sulfur, iron, and potassium and are phosphate-free (Gertens, 2005).

Because the local fertilizer market does not have a great demand for pure elemental sulfur, elemental sulfur could be sold to phosphate fertilizer manufacturers, who would then convert it to sulfuric acid. In 2003, Iowa, Minnesota, Illinois, Nebraska, and California, in descending order, were the leading consumers of phosphate fertilizer (Terry and Kirby, 2003). Phosphate fertilizer typically reaches Minnesota by rail, and it is thought that manufacturers may be willing to fill railcars with a Minnesota source of sulfur to avoid deadheading railcars back to their manufacturing facilities. Table 10 is a list of U.S. phosphate fertilizer manufacturers. Please note that this list may not be exhaustive, and Canadian manufacturers should be considered. Mileage was calculated from Virginia, Minnesota.

3.6.1.3.2 Other Potential Low-Volume Applications

Other U.S. industrial applications for sulfur, listed in order of importance based on USGS historical demand patterns from 1970 to 1990, include petroleum refining, metal mining and processing, plastics and synthetic products, paper products, soaps, detergents and water treatment, paints, iron and steel production, storage batteries (acid), drugs and food products, and explosives. These applications are limited, requiring between 10 and 1000 tons of sulfur per year, depending on the application (Ober, 2005). Sulfur has also been used as binder replacement in petroleum asphalt and concrete, yielding sulfur-modified asphalt and concrete that meets or exceeds ASTM standards (Denney, 2005). This process is not widely used in the United States.

Table 10. U.S. Phosphate Fertilizer Manufacturers

Company	City	State	Miles
Agrifos	Pasadena	Texas	1436
Agrium	Conda	Idaho	1299
Cargill Fertilizer, Inc.	Bartow	Florida	1796
Cargill Fertilizer, Inc.	Riverview	Florida	1773
CF Industries	Plant City	Florida	1776
Honeywell	Hopewell	Virginia	1405
J.R. Simplot Corp.	Pocatello	Idaho	1235
J.R. Simplot Corp.	Rock Springs	Wyoming	1319
J.R. Simplot Corp.	Lathrop	California	2210
Mosaic Company	South Pierce	Florida	1736
Mosaic Company	Faustina	Louisiana	1519
Mosaic Company	Uncle Sam	Louisiana	1484
PotashCorp	Aurora	North Carolina	1607
PotashCorp	Geismar	Louisiana	1478
PotashCorp	White Springs	Florida	1581
SF Phosphates	Rock Springs	Wyoming	1319

3.6.2 Sulfuric Acid

3.6.2.1 Fertilizer

As previously mentioned, the manufacture of phosphate fertilizers is the predominate use for sulfuric acid worldwide. Phosphate fertilizers are produced by adding acid to ground or pulverized phosphate rock. Phosphate fertilizer manufacturers often have sulfuric acid and phosphoric acid production facilities. Sulfuric acid is produced by burning molten sulfur in air to produce sulfur dioxide, which is then catalytically converted to sulfur trioxide for absorption. Phosphoric acid is manufactured by adding sulfuric acid to phosphate rock (World Bank Group, 1998). The purity of the sulfur is very important in production of sulfuric acid from sulfur, and even trace levels of some contaminants may limit the use of some sulfur.

Fertilizer plants typically have internal production for sulfuric acid and also receive material from the merchant market. The low-quality demands of sulfuric acid in this market allow the fertilizer industry to consume low-grade and by-product acid (Akzo Nobel, 2006). Refer to Table 10 for a list of U.S. phosphate fertilizer manufacturers, noting that there are no local phosphate fertilizer manufacturers. The sulfuric acid produced from the proposed power plant will likely yield a higher-quality grade than required for fertilizer manufacture.

3.6.2.2 Petroleum Refining

Sulfuric acid has been used in the petroleum industry for treating lubricating oil fractions (to improve color, odor, and other characteristics) and for producing high-quality, high-octane gasoline components by the alkylation of olefins (principally butylenes and propylene) with isobutene (OSHA, 2006).

The top ten states with petroleum refining based on total value of shipments are Alabama, Texas, Louisiana, California, Illinois, Pennsylvania, New Jersey, Ohio, Washington, and Oklahoma, respectively (U.S. Census, 2004). The petroleum refining industry is not centralized in northeastern Minnesota; therefore, there is minimum potential to sell sulfuric acid to the local petroleum refining industry.

3.6.2.3 Metal Mining

Sulfuric acid is used in metal mining as a flotation agent and leaching solvent. As a flotation agent, sulfuric acid is used to make a chemical reagent that causes one or a group of minerals to adhere to air bubbles for collection. As a leaching solvent, sulfuric acid is used to extract a soluble metallic compound from ore (EPA, 1995).

According to the Minnesota Department of Employment and Economic Development (MN DEED) (2006), iron ore mining makes up less than 4% of the jobs in northeastern Minnesota and has continued to experience significant job losses since 2002. Nonetheless, it still has been a long-standing economic force in that region. It further noted, however, that several northeastern Minnesota taconite mining operations are moving forward with planned expansions and

increasing investment opportunities. Minnesota iron ore/taconite mines are listed in Table 11. These local mines are a potential market for sulfuric acid.

Table 11. Iron Ore/Taconite Mines in Minnesota

Company	City	State
Northshore Mining Company (Cleveland-Cliffs Inc.)	Silver Bay	MN
Hibbing Taconite Company (Cleveland-Cliffs Inc.)	Hibbing	MN
Minntac Plant (United States Steel Corporation)	Mt. Iron	MN
Keewatin Taconite (United States Steel Corporation)	Keewatin	MN
United Taconite Company (Cleveland-Cliffs Inc.)	Eveleth	MN
Great Northern Iron Ore Properties	St. Paul	MN
Mittal Steel USA – Minorca Mine	Virginia	MN

3.6.2.4 Paper and Pulp Manufacture

Sulfuric acid is used in the pulp and paper industry for pH adjustment and for the production of chlorine dioxide, which is used in pulp bleaching (Akzo Nobel, 2006).

Paper and paper product manufacturing is a major industry for northeastern Minnesota, with three companies (Boise Cascade, Sappi Fine Paper, and UPM Blandin Paper Mill) making the list of the top 15 employers in northeastern Minnesota in 2006 (MN DEED, 2006). It should be noted, however, that paper manufacturing has continued to experience significant job losses since 2002 (MN DEED, 2006). Table 12 lists Minnesota paper and pulp manufacturers. These companies represent a potential local market for sulfuric acid.

Table 12. Paper and Pulp Manufacturers in Minnesota

Company	City	State
Blandin Paper Mill (UPM)	Grand Rapids	MN
Sartell Mill (International Paper)	Sartell	MN
Liberty Paper Inc.	Becker	MN
Potlatch Corporation	Bemidji	MN
Stora Enso Duluth Paper Mill	Duluth	MN
Boise Paper (Boise Cascade, LLC)	International Falls	MN
Cloquet Mill (Sappi Fine Paper)	Cloquet	MN

3.6.3 Recommended Approach to Market Entry

The local demand for pure elemental sulfur is minimal. Considerable effort would be required to enter the local agriculture markets, and even if marketing efforts were successful, the demand would not meet supply. Phosphate fertilizer manufacturers should be contacted to determine if they would be interested in obtaining sulfur from Minnesota. Because Minnesota is the second leading consumer of phosphate fertilizer in the United States, it is thought that manufacturers may be willing to back-haul sulfur in railcars from Minnesota to avoid deadheading railcars back to their manufacturing facilities. If a contract with a phosphate fertilizer manufacturer cannot be secured, the elemental sulfur may need to be landfilled.

One practical approach might be to consider converting the elemental sulfur to sulfuric acid on-site, as did TECO's IGCC Polk Station. Based on discussions with Polk Station representatives, it is assumed that it does not use a by-product marketer but direct-markets its materials to customers. For its sulfuric acid stream, it elected to produce H_2SO_4 instead of elemental sulfur because it has a better market and is easier to handle. There are markets for 99.99% pure sulfur, but TECO selected a small (250 ton/day) H_2SO_4 plant. The plant initially produced 98% H_2SO_4 for Florida mining applications. When that market dissolved, it started producing 92% H_2SO_4 and is currently marketing its entire supply to municipal water treatment facilities and is making a profit of nearly $2 million/year on that by-product stream (Wolfe, 2005).

Should a producer elect not to produce sulfuric acid on-site, it may want to consider selling its pure elemental sulfur to a manufacturer of sulfuric acid. Table 13 lists several regional manufacturers of sulfuric acid. Please note this list may not be exhaustive, and manufacturers in Canada should be considered. Mileage was calculated from Virginia, Minnesota. In addition, a producer could potentially sell its pure elemental sulfur to the local iron/taconite or paper industry.

Table 13. U.S. Manufacturers of Sulfuric Acid

Company	City	State	Miles
AK Steel Corporation	Middletown	Ohio	829
ASARCO Incorporated	East Helena	Montana	1197
Big River Zinc Corporation	Sauget	Illinois	746
Cyprus Climax Metals Company	Fort Madison	Iowa	579
DuPont	North Bend	Ohio	819
J.R. Simplot Co.	Pocatello	Idaho	1362
Koch Materials Company	Rosemount	Minnesota	211
Ohio Edison Company	Niles	Ohio	931
PVS Chemicals, Inc.	Chicago	Illinois	533
Rhodia, Inc.	Hammond	Indiana	560

3.7 IGCC Slag

3.7.1 Market Supply and Demand

Slag production and use statistics from specifically IGCC plants are not reported by ACAA. Boiler slag has a high utilization percentage of 89.61%, utilizing 1,973,385 tons in 2004 (ACAA, 2004). Two U.S. power plants, TECO's Polk Station and the SG Solutions, LLC, Wabash River plant, produce IGCC slag.

3.7.2 Expected Value

Slag's delivered price is highly dependent on haul distance and application. If local markets are found for the material, a profit may be realized.

3.7.3 Existing Market Potential

IGCC slags exhibit physical and chemical properties similar to boiler slag and bottom ash, which are utilized in engineering or manufacturing applications (Pflughoeft-Hassett, 1997). It is anticipated that IGCC slag will exhibit properties similar to boiler slag and may be used in these applications.

Utilization options noted in the literature based on characteristics of bench- and pilot-scale generated IGCC slags included cement and concrete production, aggregate applications, fill applications, and soil amendments (Pflughoeft-Hassett, 1997). A more extensive list of IGCC slag uses noted in IEA Coal Research (Clarke, 1991) also included ceramics, lime bricks, and abrasive grit as potential uses. As reported by IEA Coal Research (Clarke, 1992), several processes and patents have been developed for the utilization of IGCC slag.

3.7.3.1 Blasting Grit and Roofing Granules

Over 88% of boiler slags are used in the manufacture of blasting grit or as roofing shingle granules (ACAA, 2004). Based on discussions with Wabash River Plant representatives, the IGCC slag produced from the proposed power plant will be suitable for blasting grit and roofing granule applications. A Minnesota-based slag dealer, ATI–Black Diamond (ATI–BD), has recycled boiler slag from surrounding coal-fired power plants for over 20 years. Bruce Haslerud, chief financial officer of ATI–BD, said his company could acquire an additional 20,000–30,000 tons of slag per year. However, he noted that one of his suppliers is switching from coal to gas and will no longer produce a slag material. In addition, the rail cost for one of his North Dakota suppliers is high and it may be more economical for him to take the slag from the proposed plant. Considering these two variables, ATI–BD may be able to take an additional 30,000–40,000 tons/year, making this local market potential between 50,000–70,000 tons/year. ATI–BD said it pays $0.50–$11/ton depending on product quality and freight costs. Back-haul freight arrangements will likely be required to make this an economical venture for both parties. Once the material is received, it is washed, separated using a wet process, dried, and sized. ATI-BD sells the resulting material for about $27/ton (Haslerud, 2005). Abrasives, Inc., a North Dakota-based slag dealer, was also contacted. A company representative said two North Dakota

power plants supply more than enough material, and it currently does not have the capacity to take more material (Abrasives, Inc., 2005). However, other regional slag dealers may have a demand for more material.

3.7.3.2 Cement and Concrete

In 2003, 63,273 tons of boiler slag was used in cement and concrete applications in the United States. Like boiler slag, IGCC slag can be used in a variety of cement and concrete applications (Clarke, 1991), such as the following:

- Cement manufacture – In the production of portland cement, slag can be used as a raw material in clinker production or ground into the clinker to produce portland cement. A representative from Lehigh Cement (Stillwagon, 2005) indicated that Lehigh Cement would consider using the slag produced from the proposed plant in its Iowa manufacturing facilities. If the slag chemistry is appropriate, it can be interground to produce a blended cement.

- Aggregate – Slag can be used in concrete as a replacement for natural sand or fine aggregate. If only slag is used as the aggregate, it is typically blended with sand or other well-graded fine aggregate to produce an aggregate with suitable particle-size distribution. In addition, mortar and grouts used in bricklaying and masonry work can use IGCC slag as a replacement for natural fine aggregates.

- Manufacture of concrete products – Cement-based building products such as building blocks, pipes, and other precast structures could incorporate slag as a fine aggregate.

3.7.3.3 Asphalt Aggregate

Boiler slag can be used as fine aggregate in hot-mix asphalt. ACAA (2004) reports that in 2004, 39,942 tons of boiler slag was used as mineral filler in asphalt. The material's characteristics—superior hardness, affinity for asphalt, and dust-free surface—aid in asphalt adhesion and resistance to stripping. Since boiler slag exhibits a uniform particle size, it is commonly blended with other aggregates for use in asphalt mixtures. It is anticipated that the IGCC slag produced will perform similarly to boiler slag and be acceptable in asphalt applications.

3.7.3.4 Recommended Approach to Market Entry

The blasting grit and roofing granules market is the largest and most profitable market for IGCC slag. The local slag dealer contacted does not have the capacity to take all of the proposed plant's material, but other regional slag dealers may exist that could use the remainder of the material. Cement and concrete and asphalt applications have limited market potential, although if a local company were found to use the material, the remainder of the material may be used. Temporary storage options should be considered until these partnerships can be formed.

4.0 TRANSPORTATION

4.1 Special Handling Requirements

The following is a summary of special handling requirements needed during transportation of by-products.

4.1.1 Fly Ash

Fly ash is a fine powder very similar in appearance to cement and has many of the same handling characteristics. Fly ash does, however, have several different characteristics from cement that can affect its handling. The particle size of fly ash is finer than cement, with less than 25%–30% being retained on a 325-mesh screen and a Blaine fineness of at least 6500. As a result, aerated fly ash will flow where neither water nor cement will. Fly ash also has some very fine, hard particles, mostly carbon and iron compounds, that can give it an abrasive quality, similar to that of sandblasting grit. These two properties can cause problems if there are tiny leaks in either storage or transportation equipment. In addition, fly ash is hygroscopic, meaning it will absorb moisture (Pflughoeft-Hassett, 1995). Because of these properties, pneumatic trucking is recommended for transporting this material.

4.1.2 Bottom Ash

Bottom ash is a coarse, granular, incombustible by-product. It is coarser than fly ash, with grain sizes spanning from fine sand to fine gravel. The material can be handled, stored, or transported using the same methods and equipment that are normally used for conventional aggregates.

4.1.3 FGD Gypsum

Transporting FGD gypsum can be difficult because the material is abrasive, sticky, compressible, and considerably finer than natural gypsum (Berland et al., 2003). Given these conditions, a moisture content of 10% is recommended to transport the material to market. A high moisture content makes the material difficult to handle and adds transportation cost. Pelletizing the gypsum using a binder prior to shipping may be a good option if a profitable market is developed.

4.1.4 Ammonium Sulfate–Ammonium Nitrate

Ammonium sulfate should be crystallized and granulated on-site or piped to a nearby location to produce a commercial-grade fertilizer. Ammonium nitrate should be transferred in its liquid form because it is extremely combustible when dry.

4.1.5 Sulfur

To transfer elemental sulfur, it must remain in its molten state. If the material cools, it will harden and be impossible to remove from the transportation container unless costly measures are taken to return the material to its molten state. Therefore, heated containers must be used, which makes the economics of transporting the material more difficult. To transfer sulfuric acid, steel (generally carbon steel) tanks should be used. Although sulfuric acid is not flammable, it should not be stored near organic materials, nitrates, carbides, chlorates, and metal powders. Contact of sulfuric acid with these materials may cause ignition.

4.1.6 Slag

IGCC slag is a coarse, granular, incombustible by-product. It is coarser than fly ash, with grain sizes spanning from fine sand to fine gravel. The material can be handled, stored, or transported using the same methods and equipment that are normally used for conventional aggregates.

4.2 Transportation Options

The following is a list of transportation options for northeast Minnesota.

- Truck Lines: Four interstate regular route, heavy specialized carriers, and freight companies have terminals in northeastern Minnesota. Delivery times to the major metropolitan centers around the United States are only days. Numerous back-haul opportunities, rates that are now very flexible, along with fast delivery time makes shipping by truck much more desirable (City of Virginia, 2006).

- Rail Service: As a direct result of the region's wood products and iron ore industries, along with grain shipments to the Port of Duluth-Superior, most of the communities in northeastern Minnesota are served by four rail carriers: Burlington Northern/Santa Fe, Canadian National, Canadian Pacific, and Union Pacific/Wisconsin Central (Iron Range Resources, 2006). In Virginia, Minnesota, rail service is provided by Duluth, Winnipeg, and Pacific Railway; Duluth, Missabe, and Iron Range Railway; and Burlington Northern (City of Virginia, 2006).

- Highways: Most major northeastern Minnesota communities are connected by a four-lane highway system and have easy access to state and federal roads, making travel and truck transportation more efficient. Highways 2, 53, and 169 are major routes for U.S. and Canadian trucking companies that move wood products, agricultural products, and other goods. These roads are part of a well-established highway network that provides access from the Canadian border to Duluth, Minneapolis/St. Paul, Wisconsin, North Dakota, and the rest of the country (Iron Range Resources, 2006).

- Port of Duluth-Superior: For over 35 years, manufacturing in northeastern Minnesota has taken advantage of the Port of Duluth to ship materials to the metropolitan areas of the eastern United States as well as overseas. During an average shipping season that

usually begins in late March and continues until mid-January, approximately forty million metric tons of industrial cargo and manufactured goods travel through the Port of Duluth (City of Virginia, 2006). Outbound ships carry more than 17 million tons of taconite pellets and iron ore from Minnesota annually, along with millions of tons of other commodities destined for eastern U.S. markets and foreign ports via the Great Lakes and the St. Lawrence Seaway (Iron Range Resources, 2006).

4.3 Transportation Costs

Estimated transportation costs are located in the market sections of this report. These estimates are based on historical data and do not consider the nation's current rising fuel prices. Once a plant location is determined and markets are selected for each by-product, it is recommended that the producer perform a more in-depth transportation cost analysis. For many of the proposed market opportunities, back-haul transportation arrangements may make the difference between a profitable venture and one that will not produce revenue.

5.0 CONCLUSIONS AND RECOMMENDATIONS

All potential markets identified in this report are based on assumed by-product composition and environmental and engineering performance. These assumptions were based on anticipated fuel and combustion technology provided by Excelsior. Tables 14 and 15 provide a summary of markets based on by-product type. Markets are listed in order of highest to lowest potential, based on the research performed for this report.

Many of the markets identified will require information on the composition and performance of by-products to be produced. For several market options, this testing needs to include the environmental performance of individual by-products. The environmental performance testing will be required for any market that needs approval through MPCA. In order to get a preliminary understanding of the characteristics of the by-products to be produced, the EERC recommends pilot-scale testing using the fuel and combustion technology selected. The by-products produced from the pilot-scale test, although not exact replicas of a full-scale demonstration, will produce a more accurate assessment of what type of by-products Excelsior can expect to produce which will lead to a more focused by-product management plan.

Excelsior expressed a strong desire to identify current regional markets for its by-products. The "Recommended Approach to Market Entry" sections of this report summarize the EERC's recommended markets and entry strategies for each by-product. The EERC cautions that once Excelsior enters into negotiations with potential buyers for its by-products, the expected value and transportation costs assessments may change significantly, even though efforts were made to reasonably predict these dollar amounts based on past experience.

For fly ash and ammonium sulfate-ammonium nitrate mixtures, a current regional market was identified that would use all of the material expected to be produced. However, bottom ash,

Table 14. Markets for By-Products from a Supercritical pc-Fired Power Plant Located in Becker or Virginia, Minnesota

By-Product	Market	Market Entry Approach
Fly Ash	Concrete	Evaluate fly ash quality; use established marketing company; consider constructing storage to accommodate the seasonal nature of the market.
	Soil stabilization	Evaluate fly ash quality; use established marketing company; potentially, construct storage to accommodate the seasonal nature of the market.
Bottom Ash	Aggregate	Further evaluate market need for aggregate in location close to the plant.
	Mine filling	Follow regulatory guidance for mine filling.
FGD Gypsum	Agricultural applications	Seek fertilizer company as partner; potentially process/pelletize FGD gypsum at plant site.
	Cement manufacture	Maintain awareness of regional cement manufacturing needs for continuing assessment of this market.
	Wallboard manufacture	Maintain awareness of regional wallboard manufacturing plants for continuing assessment of this market.
	Plaster	Follow regional and local developments to assess this market for future potential.
Ammonium Sulfate – Ammonium Nitrate Mixtures	Fertilizer	Partner with experienced group to process and market fertilizer streams.

FGD material, slag, and sulfur may require further market analysis to secure markets that will use all of the material and avoid disposal. Short-term storage will likely be required for these by-products until markets can be secured.

Table 15. Markets for By-Products from an IGCC Power Plant Located in Becker, Minnesota

By-Product	Market	Market Entry Approach
IGCC Slag	Blasting grit Roofing granules	Develop partnership with local slag dealer.
	Cement manufacture	Maintain awareness of regional cement manufacturing needs for continuing assessment of this market.
	Aggregate for concrete, concrete products, or asphaltic concrete	Assess local markets regularly for this market.
Elemental Sulfur	Fertilizer	Seek partner in phosphate fertilizer manufacturing to determine potential to back-haul sulfur to manufacturing facility.
Sulfuric Acid	Metal mining Paper and pulp manufacture	Contact local manufactures to determine product quality and quantities needs.
	Petroleum refining Fertilizer	Investigate these as second-tier options if the metal mining and paper and pulp manufactures markets are unsuccessful.

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APPENDIX A

APPROVED FLY ASH SOURCES IN MINNESOTA

Mn/DOT CERTIFIED FLY ASH SOURCES
(4/20/2004)

Fly Ash Distributor	Power Plant	Class	Mn/DOT Standard Abbreviation
Enduracon Technologies P.O. Box 14372 2103 Wabash St. St. Paul, MN 55114	Poz NS @ Silver Bay, MN Poz AC @ Alma, WI	C C	POZSBMN POZALWI
Environmental Resource Corp. 2978 Center Court Eagan, MN 55121	Big Stone @ Big Stone, SD	C	BSTBSSD
Holcim Inc. Pozzolanic Materials Division Suite 100 3221 McKelvey Road St. Louis, MO 63044	Union Electric @ Labadie, MO	C	UNELAMO
ISG Resources 21778 Highview Ave Lakeville, MN 55044	Coal Creek @ Underwood, ND	C/F	COCUNND
ISG Resources, Inc. 2310 Hawkeye Drive P.O. Box 3557 Sioux City, IA 51102	Council Bluffs #3 @ Council Bluffs, IA Lansing, IA Ottumwa, IA Port Neal #3 @ Sioux City, IA Port Neal #4 @ Sioux City, IA	C C C C C	CB3CBIA LANLAIA OTTOTIA PN3SCIA PN4SCIA
Lafarge North America 855 Apollo Road Eagan, MN 55121	NSP @ Eagan, MN NSP @ Riverside, St. Paul, MN Pleasant Prairie @ Kenosha, WI Columbia Generating Stations @ Portage, WI Weston Unit #1 @ Wausau, WI Weston Unit #2 @ Wausau, WI Weston Unit #3 @ Wausau, WI Edgewater Unit #5 @ Sheyboygan, WI	C C C C C C C C	NSPEAMN NSPSPMN PLPKEWI CGSPOWI WU1WAWI WU2WAWI WU3WAWI EU5SHWI