

Final Report

Xcel Renewable Development Fund Project (RD-56)

Generating Electricity with Biomass Fuels at Ethanol Plants

Chapter/Task 9 – Ash Characterization and Evaluation

This chapter describes characteristics and potential uses of ash that arises from the combustion of ethanol co-products as fuels. It was primarily prepared by project participants at RMT Inc.

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RD56: Generating Electricity With Biomass Fuels at Ethanol Plants Report for Task 9, “Ash Characterization and Evaluation”

Background of the Task

Combustion of any of the biomass co-product feed streams evaluated in this project, by any of the combustion methods evaluated, will result in the production of ash. This project examined the quantities of ash produced in the combustion of the biomass fuels, the mineral composition of the ash, the chemical and physical characteristics of the ash, the fusion temperature of the ash, the equipment needed to handle the ash, the ash disposal options, and the potential for beneficial use of the ash or the ash components.

The ash content of the co-product streams (DWG, syrup, DDG, and DDGS) and corn stover were determined through laboratory testing of the samples obtained at the partner ethanol plants. Samples were ashed in laboratory furnaces at a maximum temperature of 1,382°F (750°C) for 2 hours. The ash was weighed and then subjected to chemical and physical analyses. This procedure yielded valid data for most purposes; but, for the physical and handling characteristics of ash from a fluidized bed unit, ash samples were obtained and tested from an operating fluidized bed burning syrup.

Quantities of Ash

The ash content of the co-products ranges from less than 2% to over 8%, while the ash content of corn stover is typically around 6% to 7%. One datum for corn stover ash, 21.6%, is regarded by this project as an outlier, and is not included in the further evaluation of corn stover ash. Data from the analyses performed as part of this project and data from the literature are listed in Table Ash-1.

The maximum total quantity of ash that an ethanol plant could produce can be estimated from the ash content of the dried distillers grains with syrup (DDGS), since the DDGS contains the solid components of both the syrup and the distillers wet grains (DWG) without syrup. Some of the ash will come directly from the combustion process, while the remainder will have been captured in the emission control system. We assume that emissions of particulate to the atmosphere will be negligible. An ethanol plant with a nominal capacity of 40 million gallons per year (mgy) (150 million liters per year) of ethanol is usually estimated to produce about 130,000 tons (118,000 metric tons) per year of DDGS. Assuming that the DDGS is 10% moisture, this amounts to about 120,000 tons (109,000 metric tons) of DDGS per year on a moisture-free basis. Using the project data and the range of values in the literature for the ash content of DDGS, 3.50% to 6.00%, this calculates to an annual ash production of 4,200 tons to 7,200 tons (3,810 to 6,530 metric tons).

As a crosscheck, we can calculate the maximum potential ash based on the feed material (corn) and on the literature values for the ash content of the corn, approximately 1.4%. We assume here that negligible ash-forming material (such as neutralizing acid) is added during the production process, and that negligible ash-forming components are present in the ethanol. However, substantial amounts of ash-forming materials may come into the process from the process water, especially since the process water is often well water. Therefore, the calculation of ash based on the input corn is expected to be low. A 40 million gallon (150 million liter) per year fuel ethanol plant will use about 15 million bushels of corn annually. At 56 pounds (25 kg) per bushel, this is 420,000 tons (381,000 metric tons) of corn per year. At 1.4% ash in the corn, the maximum ash production is calculated to be 5,900 tons (5,350 metric tons) per year.

These estimates of ash quantity do not include materials, such as limestone for SO₂ suppression, that may be added to the combustion process. Data are not publicly available regarding the exact identification or quantities of such materials, but they may be expected to contribute significantly to the quantity of ash produced.

Ash Mineral Analysis

Ash samples from syrup, DWG, DDG, DDGS, and corn stover were subjected to a standard analysis (in oxidizing environment per ASTM D 3682-01) of mineral content. Results, as shown in Table Ash-2, are expressed in terms of the mineral oxides. The ash mineral analyses are used in evaluating the behavior of the ash in the combustion unit, the disposal alternatives and costs, and the potential for beneficial reuse of the ash. The ash mineral analyses of the individual feed streams are discussed below.

For corn stover, results from the literature were compared with the sample analyzed as part of this project. The dominant component from both sources is silicon, comprising about 54% of the ash in both sources. There was good agreement between the sources for the alkaline metals, comprising about 27.3 % of the project sample and 29.6% of the literature source. The dominant metal is potassium at about 20%, with calcium at about 7%, and sodium at about 1%. The literature source had no data for sulfur, while the project sample showed sulfur at about 12%. Magnesium was at about 5% in both sources, and aluminum was at about 1%. The figures for phosphorus differ substantially, with the literature value at 8.7% and the project sample value at 1.97%. Overall, considering the inherent expected variability in corn stover from different areas and different soil types, and subject to different applications of chemicals, and also considering the inherent inconsistent nature of corn stover samples (especially when the corn stover has been collected off the ground), good comparability was found between the literature data and the project sample data.

Literature data were not available for ash analysis of the co-product streams, so all data are from project samples. The ash mineral composition of the co-product streams differs

substantially from that of the corn stover. The dominant metal is phosphorus, the content of which is very much higher than in the corn stover, with a mean of about 35%. The silicon content is much lower, ranging from less than 2.14% to 6.87%, with a mean of less than 3%. For the alkaline metals, while the total content, at about 30%, was similar to corn stover, the distribution of the alkaline metals is substantially different, with calcium consistently below the level of quantification (1.4%); potassium ranging from about 15% to about 31%, with a mean of about 26%; and sodium ranging from about 1% to nearly 4%, with a mean of about 3%. The magnesium content is substantially higher than in the corn stover, with a mean of about 10.7%. The aluminum content is consistently below the level of quantification (0.38%). Sulfur is much lower, with a mean of about 3.4%.

These ash analyses do not include materials, such as limestone for SO₂ suppression, that may be added to the combustion process. Data are not publicly available regarding the exact identification or quantities of such materials, but they may be expected to significantly affect the ash chemical composition of operating ash combustion or gasification units.

Physical Characteristics of the Ash

Ash samples from an operating fluidized bed combusting syrup were analyzed for physical characteristics, including sieve distribution, bulk density, and specific gravity. These values are not included in this report, but are generally discussed further. The ash used for physical characteristics analyses includes materials that are be added to the combustion process. Data are not publicly available regarding the exact identification or quantities of such materials, but they may be expected to contribute significantly to the physical characteristics of the ash produced. The literature indicates that limestone is added to the combustor for SO₂ suppression. The project team believes that the ash sample characterized for this project is representative of ash that will be produced by combusting any of the biomass co-products, and that will require management for reuse or disposal.

The sieve distribution indicates that the ash particle size is very fine, with all particles passing the #40 sieve or <425 µm. The bulk density of the ash is similar to that of the co-products except syrup.

Literature data were not available for the physical characteristics of ash. However, publicly-available documents from the operating fluidized bed combusting syrup indicate that the physical characteristics are similar to typical dry fertilizers applied to cropland.

Ash Fusion Characteristics

The ash fusion characteristics are critical to the proper design and operation of a combustion system. Because this project evaluates both biomass combustion (operating in an oxidizing atmosphere) and biomass gasification (operating in an oxygen-starved atmosphere), ash fusions

for the various feed streams were evaluated (ASTM D 1857-04) under both oxidizing and reducing conditions. The data are presented in Table Ash-3, and are depicted graphically on Figures Ash-1 and Ash-2.

For the oxidizing atmosphere, the ash fusion temperatures differed widely among partner ethanol plants and among co-product feed streams. However, examination of the data allow for certain preliminary conclusions to be drawn regarding the use of these feed streams for combined heat and power (CHP) purposes. For DWG and DDGS, although two of the samples exhibited a sharp rise in the temperature needed to progress from a hemispherical stage to a fluid stage, overall, the temperature at which ash handling in the combustion unit becomes problematic is generally quite low. Combustion systems, especially those designed for CHP applications, need to be operated at as high a temperature as possible to promote both fuel efficiency and generation of the energy density needed for the CHP process. These temperatures are usually well above the approximately 1,200°F-1,500°F (650°C-815°C) at which the tested ash samples demonstrated problematic behavior. This may result in material buildup or fouling of the combustion system components and the ash handling equipment. These issues need to be addressed in the design of the combustion and ash handling systems.

The situation is different for the syrup samples. With the exception of the softening temperature at one partner ethanol plant, the temperatures at which the syrup ash would become problematic are above those needed for either gasification or combustion. Although no literature data were found regarding syrup ash fusion temperatures under oxidizing conditions, one of the project partner ethanol plants is combusting its syrup to generate process steam, thus verifying the conclusions drawn from the data from this project.

For reducing conditions, the temperatures at which the ash from all of the feed streams becomes problematic are well above those required for efficient operation of a gasification system, which typically generates combustible gasses in the 800°F-1,200°F (427°C-650°C) range. The temperature in the non-oxygen-starved portion of the bed, where the fixed carbon is completely oxidized, will be somewhat higher, but can be maintained at a level below which the ash may become problematic. This will be less of a concern for syrup, for which ash fusion temperatures are typically several hundred degrees higher than the other feed streams.

These data on ash fusion characteristics do not include materials, such as limestone for SO₂ suppression, that may be added to the combustion process. Data are not publicly available regarding the exact identification or quantities of such materials, but they may be expected to substantially impact the ash behavior in an operating system.

Chemical Characteristics of Ash

Ash samples from a fluidized bed burning syrup were analyzed for pH, calcium, and TCLP metals to provide additional information regarding the chemical characteristics of ash. These

values are not included in this report, but are generally discussed further. The results indicate that significant fluidized bed material (limestone) is mixed with the ash, affecting both physical and chemical characteristics. Information is not publicly available on what, if any, additional materials may be added to the combustor. However, the project team believes that the sample is representative of ash that will be produced by combustion of biomass co-products, and that will require management for reuse or disposal.

The laboratory results indicate very little potential for metals to leach from the ash. Also, both the calcium concentration and the pH are elevated due to the limestone portion of the ash.

Literature data were not available for the chemical characteristics of ash. However, publicly-available data for the chemical characteristics of fluidized bed ash from the combustion of syrup were reviewed. The following is a summary of those results:

- No PAHs were detected.
- Various inorganic compounds were detected in the ash sample. However, the concentrations do not appear to be at significant levels.
- The MPCA Tier 1 Generic Soil Reference Value (SRV) for copper (11 mg/kg) was compared and exceeded, but the copper concentration was well below the Tier 2 industrial SRV. These exceedences are not expected to prohibit the reuse of ash. However, specific restrictions on the reuse of ash are expected.
- The MPCA Tier 1 Generic Soil Leaching Values (SLVs) for molybdenum (6.0 mg/kg), selenium (1.5 mg/kg), and silver (3.9 mg/kg) were compared and exceeded. However, the co-products themselves typically contain greater than 1.5 mg/kg selenium. These exceedences are not expected to prohibit the reuse of ash. However, specific restrictions on the reuse of ash are expected.

Ash Beneficial Reuse

Co-products from dry grind ethanol production contain about 3-7 percent ash. If all co-products were to be used as fuel, a 40 mgy (150 million liters per year) ethanol plant would produce about 4,000-7,000 tons (3,630-6,350 metric tons) of ash annually, while a 100 mgy (375 million liters per year) plant would produce about 2 ½ times as much. Co-product ash can potentially be put to multiple productive uses in civil engineering, manufactured products, and agricultural applications in ways that are technically sound, environmentally benign, and commercially competitive. Both Minnesota and Wisconsin have active state-sponsored programs to reuse combustion ash and to avoid disposal in landfills (except for use as daily cover). The Wisconsin Department of Administration reported that 72 percent of coal combustion ash and slag was beneficially used in the year 2000. The primary beneficial uses of the ash from the industrial and institutional coal boilers were as an unbonded surface course for roads, as a cold weather road abrasive, as a confined structural fill, and as a daily cover at landfills.

Ethanol co-product ash has the potential for beneficial reuse in several ways. Based on known applications for coal ashes from like combustion technologies and the results of laboratory analyses of co-product ash composition and physical characteristics, the potential applications include the following:

- Agricultural applications, including liming, soil amendment, and nutrient recovery
- Construction applications, including cement substitute, concrete products production, and soil stabilizer
- Self-cementing ash for oil field grouting
- Selected roadbase and subbase applications, including as a component of structural fill and synthetic aggregates
- Waste stabilization, including acidic waste, sludge, and heavy metals
- Landfill daily cover

Ash chemical composition varies somewhat by co-product burned, although for all of the co-products, the ash retains a high mineral content with 30 to 45% phosphorus (in the form of pentoxide) by weight. Potassium oxide is 20 to 30% by weight, while magnesium oxide is about 10% and silica is about 2%. Co-products contain about 0.5 to 1% sulfur by weight, with the highest measured sulfur level found in syrup.

Federal and state regulations place stringent limits on the amounts of pollutants that can be emitted from combustion processes. For combustion of ethanol plant co-products, the most potentially problematic emissions will likely be SO₂ and NO_x. SO₂ is usually controlled by material that reacts with the sulfur oxide and produces nongaseous sulfur compounds that remain with the ash. The most commonly used material is limestone, which reacts with the SO₂ to form gypsum (CaSO₄). In a typical application, about 25-30 percent excess limestone is added, which results in a strongly alkaline ash. The addition of the limestone changes both the chemical and physical nature of the ash. The high alkaline content and very small particle size necessitate careful management of the ash and the use of appropriate personal protective equipment for personnel involved in ash management. Particular care will need to be taken if the ash is handled by individuals who have not had applicable training in handling such material, and who may not possess applicable personal protective equipment. If corn stover is part of the feed material, the high silica content of the resultant ash will also need to be taken into account in ash management.

Unlike ash from coal combustion, which may contain heavy metals of several types, the ash from combustion of the ethanol plant co-products is low in mercury and other heavy metals of concern. Biomass ash is intrinsically more environmentally benign than coal ash, and may be beneficially reused in additional ways.

Ash Use As Fertilizer and Soil Amendment

Co-product ash may be suitable to improve soil chemical and physical properties. An evaluation of the soil is needed to determine crop requirements, and how the character of the ash may improve soil. The evaluation would include application rates to meet crop needs.

Studies have shown that combustion ash added to topsoil mixtures improves porosity, increases seed germination rates, and improves plant yields for a variety of crops.

Co-product ash can be used to treat soil pH and provide soil nutrients. The unreacted lime present in the ash will raise the pH of acidic soil, while the reacted lime (gypsum) is a source of calcium. Magnesium, phosphorus, potassium, and other minerals are also added to soil. The ash also improves physical soil properties, such as soil porosity, which improves aeration and water penetration for acidic soil, and increases moisture retention.

When used as agricultural liming materials, uncontaminated co-product limes can be distributed in accordance with Minnesota Statutes, sections 18C.531 to 18C.575, and Wisconsin Statutes, sections 94.65 to 94.66. Greenhouse studies demonstrated that ash-amended soil resulted in higher plant productivity than typical ag-lime-amended soil. These results possibly are due to pH and nutritional issues, but root penetration due to improved soil porosity was also probably a factor. Application rates for byproduct limes must be based on the lime recommendations of the University of Minnesota Extension Service and cannot cause the soil pH to exceed 7.1 after application. Site-specific application rates for byproduct lime must be determined by an individual, such as a crop consultant, who has a background and understanding of crop nutrient management. Recommended rates for lime can be obtained from the University of Minnesota Extension Service publication "Fertilizer Recommendations for Agronomic Crops in Minnesota" BU-06240-S, and the Minnesota Department of Agriculture publication "Ag-Lime Recommendations in Pounds ENP per acre" available on their Web site (www.mda.state.mn.us/lime). Similar recommendations for Wisconsin can be found at the University of Wisconsin-Extension Web site (learningstore.uwex.edu/Soil-Fertility).

Co-product ash is high in phosphorus, a nutrient commonly added to soil to increase crop yields. The addition of phosphorus to the soil depends on the total phosphorus already present and the amount of organic and inorganic acid extractables available in the ash. The rate of organic phosphorus is applied based on the soil nitrogen content. New regulations may limit the rate of ash co-product application based on the phosphorus soil test and runoff risk, the phosphorus content of co-product ash, and the phosphorus removal rate of the crop.

Co-product ash also contains significant amounts of potassium, calcium, magnesium, and sulfur. Most potassium in the ash is considered available, while the other mineral cations are available to varying degrees. High levels of sulfate may leach in the soil.

Trace metals such as boron, copper, zinc, iron, manganese, and molybdenum are present in the ash and serve as micronutrients, low amounts of which are required for plant growth.

Some sodium is present in the ash, which is detrimental to soil structure, as high levels of sodium are toxic to plants.

In the past (1940s through about 1980), agricultural research raised some concern about the proper soil calcium to magnesium ratio. The popular thinking was that high levels of magnesium cause soil to be “hard,” with a drop in crop yields. More recent research, as highlighted on the Minnesota Extension Web site, has demonstrated that neither magnesium soil nor the calcium/magnesium ratio has any effect on crop growth and production. The calcium to magnesium ratio is an outdated concept and should be not used in making fertilizer recommendations.

A case-specific beneficial use determination (CSBUD) was made by the MPCA for the use of ash generated from the project partner ethanol plant combusting syrup. The ash is land-applied as a fertilizer or an alternative liming agent. The ash is bundled, stored, tested, and reused according to the requirements of the CSBUD. Specific reporting and record keeping also apply. Soil testing is completed to verify the site suitability and application rates.

The very fine particle size of the co-products ash from fluidized bed combustion, combined with the chemical composition of the ash, pose handling and application challenges for agricultural reuse. Slurrying is likely impractical owing to the chemical nature of the ash, the large amount of weight added to the ash, the high pH of the slurry, and the need for ongoing agitation to avoid settling or plugging of piping or nozzles. The literature reports that pelletization is being tested. Pelletization would avoid the problems associated with slurrying, and makes the ash amenable to use in standard agricultural equipment, albeit likely with some minor modifications to equipment and/or procedures. Cost data for pelletization are not available.

Little information is available regarding detailed, long-term field experience with the agricultural reuse of ash generated from combustion of dry grind co-products, although such reuse is ongoing. Specific studies on the ash from the gasification of alfalfa stems indicate the following:

- Potassium concentrations increased and magnesium concentrations decreased significantly in corn.
- Little effect was noted for phosphorus or other trace elements.
- Ash application significantly increased salinity chlorine, extractable phosphorus, exchangeable potassium, calcium, magnesium, and sodium in soil.

- Although some PAH compounds were detected in ash, its application will not cause a major environmental concern when applied at reasonable agronomic rates.

Ash Use in Construction

Coal ash is used as structural fill material in constructing highway embankments and road bases. Marketable uses for bottom ash include replacements for sand, gravel, and crushed stone; aggregate for concrete products; soil amendments; structural fills; base and sub-base pavements; anti-skid material for roads; roofing shingle granules; chip seal road topping; blasting grit; and material for snow and ice removal.

When ash is present with free lime, it reacts chemically to form cementitious materials, the type of which depends on the properties of the ash. Pulverized coal units, which are the most common type of coal combustion technology, produce both a bottom ash and a fly ash, which differ in chemical composition and physical properties. Bottom ash is coarser than fly ash due to larger fuel particle size and increased combustion residence time. Fly ash has properties that are acceptable for use as a high-strength concrete (Portland cement), while bottom ash has use as described above. The free lime, carbon content, and sulfate content of co-product ashes can limit their utilization to moderate-strength concrete products production, as free lime in ash will form water-soluble calcium hydroxide, resulting in some weakening of the concrete from contact with moisture. Such materials may not be preferred for heavy construction applications. When used as an aggregate, the bottom ash product has a lower unit weight than many naturally occurring aggregates, thus reducing the weight of the finished product.

Coal ash can be used either mixed with or in the place of conventional backfill materials, such as soil, sand, or gravel, and to alleviate problems and restrictions generally associated with the placement of these materials. As the result is more cement-like, less compaction is required.

Data are not available regarding the use of dry grind ethanol co-products ash as compared with coal ash for construction applications. Coal ash has been used in large quantities for many years, with a great deal of research and established market channels, while dry grind ethanol co-products ash is relatively new in the marketplace, has limited available applications research, and limited local marketing channels. Construction applications for dry grind co-products ash will likely be minimal until additional research is performed, and the performance of applications and products incorporating the ash withstand the test of time.

Ash for Treatment of Certain Waste Streams; Landfill Disposal

Co-product ash can likely be used to stabilize certain waste streams from both industrial processing operations and municipal sludge. The ash may help to solidify certain waste

materials for landfilling and to neutralize acidic wastes. For each of these applications, the suitability of co-product ash is enhanced by its free lime content.

In the case that a practical beneficial use is not found for the ash, landfill disposal is an option, based on the nontoxic characteristics of the ash. The primary challenge for landfill disposal is the potential for the ash to become airborne during unloading and spreading. The ash may be suitable for use as daily cover for other landfilled materials. It may also be possible to send the ash to a monofill. Ash monofills generally have a lower tipping price than regular landfills, as the ash can be retrieved at a later date for use in road building, etc. Considerations for ash monofill disposal include the location of the monofill, whether some amount of ash will be stored on-site prior to pickup, and dust handling.

Regulatory Beneficial Use Determination

States regulate beneficial reuse of solid waste. For Minnesota, beneficial use determination (BUD) has been made for specific solid waste, including coal combustion slag for the manufacture of roofing shingles, ceiling tiles or asphalt products; coal combustion slag for use as a sand blast abrasive; coal combustion fly ash when used as a pozzolan or cement replacement; coal combustion fly ash for aggregate in concrete; and uncontaminated byproduct lime used as agricultural liming material. The co-product ash will require a case-specific BUD prior to its reuse. In Wisconsin, similar beneficial use requirements apply to industrial byproducts.

Economic Value

In addition to the avoided cost of ash disposal, there is an economic value to the beneficial reuse of co-product ash. The chemical and physical composition of co-product ash, its (and its potential user's) market location, and seasonal aspects all contribute to determining the value of co-product ash. These market factors and pricing are explored below.

Chemical and Physical Composition of Co-product Ash

If the quality of the co-product ash meets engineering standards, its use can lower the costs of construction. For example, the substitution of ash as a cementing agent reduces the cost of the finished product. If the co-product ash can be used as a synthetic gypsum for use in wallboard, then the processing required of natural mined gypsum is avoided.

Ash used to stabilize soil or waste makes this process less expensive.

Market Location

The marketplace in which the co-product ash is produced has a substantial impact on its value. The co-product ash may be competing with large quantities of coal ash from

utilities' plants. The most economically attractive reuse applications may be geographically remote. Transportation distance and method (truck, rail, barge, ship) are major factors in the cost of using co-product ash. Loading and unloading methods impact the cost of handling, which is reflected in the transportation price. Local and state regulations regarding transportation of the ash, permitting of the application, reporting, and possibly waste fees may have a significant impact on the desire and ability of a potential buyer to use the ash.

Seasonal Factors

The time of year may also contribute to pricing, depending on the application. In the Midwest, the production of coal ash is highest during both the coldest and hottest months of the year, during the heating and cooling seasons. These same periods of the year may represent the slowest times for construction and other applications that beneficially use the ash. This sort of imbalance in the production and demand for ash can contribute to highs and lows in pricing. Many utilities and ash marketing firms work to overcome this seasonal imbalance by using storage silos and sometimes large distribution networks. A dry grind ethanol plant seeking to beneficially reuse co-products ash will need to take these factors into account for its particular ash, location, and potential ash buyer.

Per the American Coal Ash Association (www.aaa-usa.org), some of the typical 2003 price ranges found for various coal combustion ash products are as follows.⁽²⁾ These prices will likely change over time and, considering the differences of the dry grind ethanol co-products ash and the coal ash, may not be comparable to the former.

- Concrete quality ash - \$20 to \$45 a ton (\$22 to \$49 metric ton)
- Self-cementing ash for soil stabilization - \$10 to \$20 a ton (\$11 to \$22 metric ton)
- Snow and ice control - \$3 to \$6 a ton (\$3 to \$7 metric ton)
- Flowable fill - \$1 a ton and up
- Road base - \$4 to \$8 a ton (\$4 to \$9 metric ton)
- Self-cementing ash for oil field grouting or waste stabilization - \$15 to \$25 a ton (\$16 to \$22 a metric ton)

⁽²⁾ American Coal Ash Association, "Frequently Asked Questions," www.aaa-usa.org.

Tables

Table Ash-1
Summary of Ash Content From Laboratory Results and Literature Values

SOURCE/ REFERENCE	AS RECEIVED		MOISTURE FREE
	% ASH	% MOISTURE	% ASH
Corn Stover			
LAB	6.31	6.15	6.73
C	4.7	6.1	5.1
D	20.3	5.9	21.6
E	6.81	9.14	7.64
N	--	--	5.58
DDG			
E	1.96	13.35	2.24
DDGS			
1	3.51	8.79	3.85
2	3.10	11.55	3.50
3	3.62	10.03	4.02
4*	1.68	59.80	4.17
5	--	--	--
A	4.90	9.00	--
B	5.35	10.78	--
E	4.16	9.27	4.13
J	4.00	11.70	--
L	--	--	6.00
M	--	--	4.2
P	--	--	5.80
DWG			
1	0.78	65.98	2.28
2	0.72	64.67	2.05
3	2.18	54.26	4.77
4	0.64	70.70	2.17
5	0.54	66.71	1.61
Syrup			
1	1.39	77.17	6.09
2	2.64	66.71	7.94
3	3.33	58.55	8.03
4	2.50	69.32	8.16
5	1.71	64.70	4.86

Notes:

-- = not available/analyzed.

1, 2, 3, 4, and 5 = samples collected from partner ethanol plant.

Lab = laboratory analysis of sample collected.

* The DDGS results from Partner Ethanol Plant #4 appear to be at odds with other DDGS values.

References:

A = Typical values. Distillers Grain Technology Council. 2005. Louisville, Kentucky.

B = Average of 34 samples. Converted from 100% dry matter basis. University of Minnesota. 2006. Nutrient profiles.

C = Single corn stover analysis. National Renewable Energy Laboratory. 1998. Golden, Colorado.

D = Single corn stover analysis. Evans, R.J., A.R. Knight, M. Onischak, and S.P. Babu. 1988. Development of biomass gasification to produce substitute fuels. Richland, Washington, USA. Pacific Northwest Laboratory (PNL). PNL--6518, 14 p.

E = Average of multiple samples. Number of samples not reported. Agricultural Utilization Research Institute. Fuels initiative. Waseca, Minnesota.

J = Average of 20 samples. Noll, S.L., C. Parsons, C. Abe, and J. Brannon. 2002. Nutrient composition of corn distiller dried grain with solubles. University of Minnesota and Illinois.

L = Average of 32 plants. The value and use of distillers dried grains with solubles (DDGS) in livestock and poultry feeds. University of Minnesota. 2005.

M = Dakota Gold Marketing - Enhanced nutrition distillers products. Dakota Gold. 2005.

P = Mean value of 118 samples. Spiels, M.J., M.H. Whitney, and G.C. Shurson. 2002. Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. University of Minnesota.

Table Ash-2
Results for Ash Mineral Analysis

MINERAL	CORN STOVER		DDGS						DWG			SYRUP		
	LAB	C	1	2	3	4	4*	5	3	4	5	3	4	5
Silicon dioxide (wt%)	54.12	54	<2.14	<2.14	2.73	3.04	<2.14	--	3.09	3.16	6.87	<2.14	2.42	<2.14
Aluminum oxide (wt%)	0.78	2	<0.38	<0.38	<0.38	<0.38	<0.38	--	<0.38	<0.38	<0.38	<0.38	<0.38	<0.38
Titanium dioxide (wt%)	0.04	--	<0.03	<0.03	<0.03	<0.03	<0.03	--	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Iron oxide (wt%)	0.45	--	<0.29	0.33	0.32	0.30	0.40	--	0.29	<0.29	<0.29	0.93	<0.29	0.90
Calcium oxide (wt%)	5.61	8.7	<1.4	<1.4	<1.4	<1.4	<1.4	--	<1.4	<1.4	<1.4	<1.4	<1.4	<1.4
Magnesium oxide (wt%)	4.22	6.1	11.92	11.45	12.17	14.45	13.20	--	10.25	6.70	9.60	9.97	13.84	8.61
Potassium oxide (wt%)	20.22	20.7	28.37	26.50	29.41	30.66	30.07	--	26.72	15.42	25.07	29.32	31.19	20.59
Sodium oxide (wt%)	1.47	0.2	1.32	2.35	4.98	2.32	3.01	--	3.82	1.01	4.31	4.11	2.11	3.31
Sulfur trioxide (wt%)	12.75	--	0.62	1.65	1.82	1.32	1.02	--	1.10	0.50	4.50	6.02	7.38	4.22
Phosphorus pentoxide (wt%)	1.97	8.7	44.76	36.32	40.98	45.49	42.85	--	41.04	31.93	31.34	32.04	32.41	26.01
Strontium oxide (wt%)	<0.02	--	<0.02	<0.02	<0.02	<0.02	<0.02	--	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Barium oxide (wt%)	0.02	--	<0.02	<0.02	<0.02	<0.02	<0.02	--	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Manganese dioxide (wt%)	0.06	--	0.05	0.05	0.06	0.05	0.05	--	0.07	0.03	0.04	0.04	0.05	0.07
Nitrogen (wt%)	<0.20	--	--	--	1.18	3.69	--	--	1.38	3.69	1.99	1.45	0.96	2.23

Notes:

Lab = laboratory analysis of sample collected.

1, 2, 3, 4, and 5 = samples collected from partner ethanol plant.

* = resampled to confirm previous results.

-- = not available/analyzed.

Reference:

C = Single corn stover analysis. National Renewable Energy Laboratory. 1998. Golden, Colorado.

Table Ash-3
Summary of Laboratory Results and Literature Values for Ash Fusion Temperature

PARAMETER	OXIDIZING ATMOSPHERE																REDUCING ATMOSPHERE																	
	CORN STOVER	DDGS							DWG				SYRUP					CORN STOVER	DDGS							DWG				SYRUP				
		1	2	3	4	4*	5	AVG	3	4	5	AVG	3	4	5	AVG	1		2	3	4	4*	5	AVG	3	4	5	AVG	3	4	5	AVG		
Initial deformation (°F)	1,930	1,510	1,423	1,149	1,013	1,407	--	1,300	1,226	1,304	1,407	1,312	1,214	2,708	1,814	1,912	1,624	1,350	1,316	1,242	1,306	1,390	--	1,321	1,238	1,327	1,415	1,327	1,544	2,295	1,855	1,898		
Softening (°F)	1,984	1,514	1,443	1,169	1,028	1,546	--	1,340	1,249	1,432	1,466	1,382	1,242	2,715	2,602	2,186	1,718	1,386	1,425	1,297	1,471	1,580	--	1,432	1,297	1,572	1,531	1,467	1,690	2,305	2,532	2,176		
Hemispherical (°F)	2,100	1,543	1,555	1,294	1,307	2,414	--	1,623	1,309	1,486	1,544	1,446	2,435	2,722	2,629	2,595	1,909	1,476	1,566	1,329	1,656	2,516	--	1,709	1,358	1,737	1,662	1,586	1,909	2,313	2,639	2,287		
Fluid (°F)	2,205	1,747	2,044	2,596	1,458	2,639	--	2,097	1,583	2,691	1,849	2,041	2,682	2,733	2,671	2,695	2,194	1,742	2,603	2,558	2,588	2,707	--	2,440	1,912	2,034	1,989	1,978	2,641	2,671	2,660	2,657		

Notes:
1, 2, 3, 4, and 5 = samples collected from partner ethanol plant.
* = resampled to confirm previous results.
-- = not analyzed.

Figures

Figure Ash-1
Ash Fusion Temperatures by Co-Product, Oxidizing Atmosphere

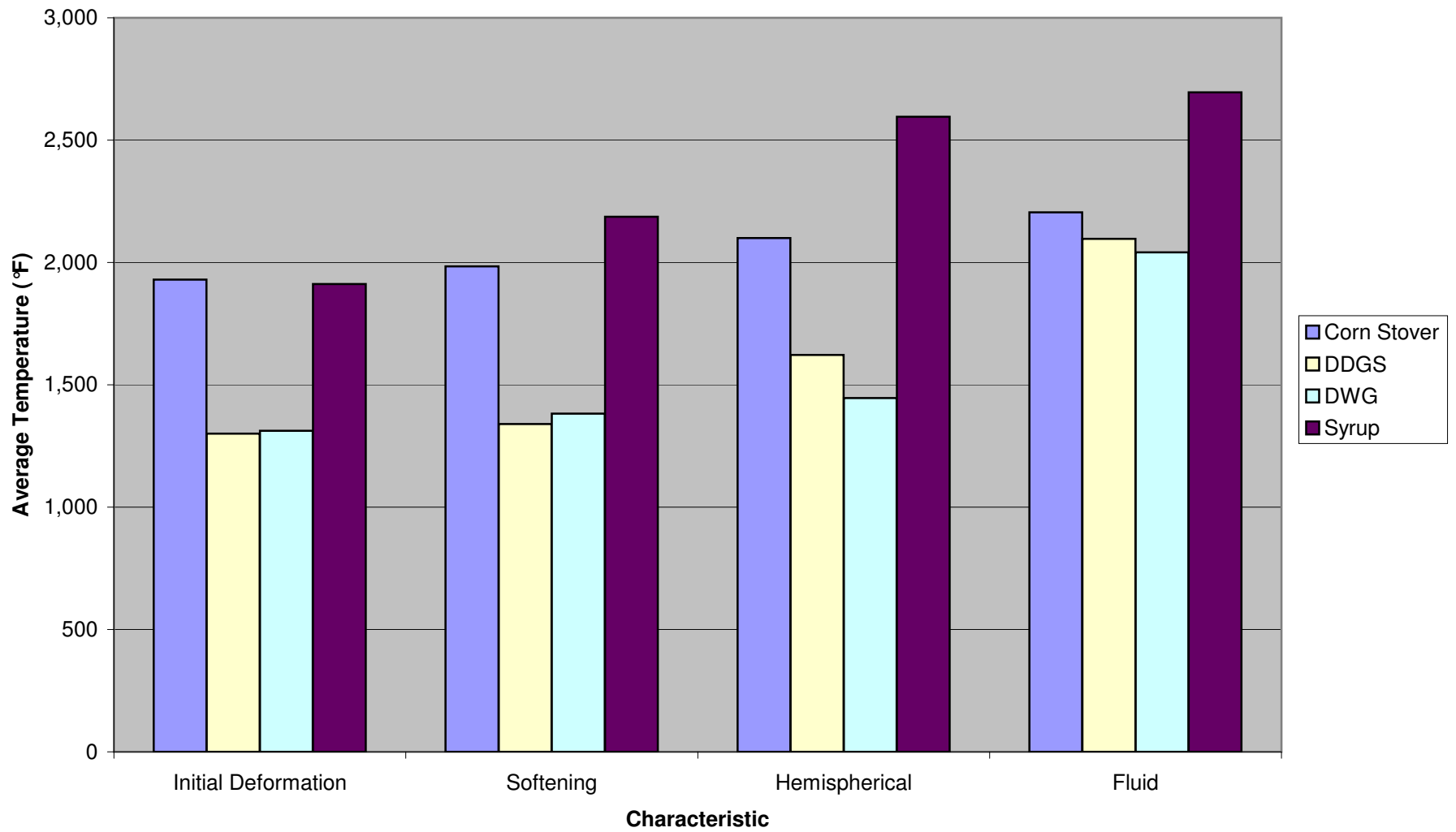


Figure Ash-2
Ash Fusion Temperatures by Co-Product, Reducing Atmosphere

