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## **Characterization of Feed Streams and Emissions from Biomass Gasification/Combustion at Fuel Ethanol Plants**

**R. Vance Morey, Professor**

Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, MN

**Dennis L. Hatfield, Ethanol Team Leader**

RMT, Inc., Madison, WI

**Rod Sears, Energy Team Leader**

RMT, Inc., Madison, WI

**Douglas G. Tiffany, Research Fellow**

Applied Economics, University of Minnesota, St. Paul, MN

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**Abstract.** *Fuel and emission characteristics of co-products of the ethanol dry-grind process [distillers wet grains (DWG), concentrated distillers solubles (referred to as “syrup”), and distillers dried grains with solubles (DDGS)], and corn stover are evaluated. Biomass co-products from the dry-grind ethanol production process, particularly DDGS, are good sources for the electrical and thermal energy needed to operate the plant, and even contain sufficient energy to produce excess power that can be sold. However, the number of subsequent process steps required to reduce emissions to compliance levels, particularly nitrogen oxide, will be important in determining the economic viability of using biomass co-products from dry grind ethanol plants for energy production. The alkali metal content (potassium and sodium) of the ash is high (22 to 34 %) for co-products and corn stover. Such high levels of alkali metals can lead to ash fouling in combustion and steam generation units, and to potential agglomeration of bed material in fluidized bed systems.*

**Keywords.** Biomass, Fuel, Emissions, Process heat, Combined heat and Power

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## **Introduction**

Dry-grind ethanol process co-products and/or corn stover can be used to provide electricity (both for the plant and sale to the grid) and process heat. These biomass fuels can reduce costs, increase the renewable energy balance, and reduce greenhouse gas emissions for fuel ethanol production (Morey et al., 2005).

Rising natural gas costs and decreasing prices for the biomass co-products of the dry-grind process [distillers wet grains (DWG), concentrated distillers solubles (referred to as “syrup”), and distillers dried grains with solubles (DDGS)] suggest that there is significant potential for energy cost savings/returns over a range of operating conditions by using co-products as fuels at ethanol plants. However, to determine the overall economic feasibility of using the biomass co-products as fuel, the chemical and physical characteristics of these feed streams, air emissions, options for combustion/gasification to produce heat, electric generation system technologies, and associated capital and operating costs must be determined. This paper focuses on characterization of the biomass feed streams and potential air emissions.

Distillers grains are normally marketed as livestock feed. DWG and syrup are separated wet forms of the co-product which contain 60 to 70% moisture. They have a short shelf life (a week or less in warm weather). Syrup is pumpable unless the viscosity gets too high because of process factors or low temperature. DWG can be handled with loaders, high solids conveyors, or special pumps, but handling can become problematic at below-freezing temperatures. DDGS is created by drying the DWG and syrup together. Drying the DWG alone without adding back the syrup produces a product called distillers dried grains (DDG). DDG and DDGS have a typical moisture content of 10%-13%, and may be used as fuel as-is. They have a long shelf life and can be readily stored and transported by conventional solids handling systems.

Some have proposed using DWG or syrup as fuels so that the drying step for DDGS production can be eliminated. However; the high moisture content of DWG and syrup requires that these products either be mixed with some type of dry biomass, that their combustion be supplemented with fossil energy, or that some process other than drying be used to recover energy in the combustion or gasification unit exhaust stream to preheat combustion or gasification air in order to sustain the energy generation process.

The advantages of using the co-products, or some portion of them, as fuel for the ethanol production process, are that these materials are available at the plant, they are produced in sufficient quantity to meet process heat and electricity needs (Morey et al., 2005), and during periods of low co-product prices the task of marketing them is reduced or eliminated.

Corn stover is also a potential biomass source to provide energy at ethanol plants. Since ethanol plants are usually located in corn growing areas, the corn stover is available in close proximity. However, since under current production practices, most corn stover is left in the field, there are costs associated with collection, transportation, storage, and pre-processing to make the material into a convenient fuel. The cost of the corn stover per unit of energy is probably higher than the ethanol co-products at current co-product prices (Sokhansanj and Turhollow, 2004; Morey et al., 2005).

In reviewing the literature, we found significant amounts of information about DDGS and other forms of co-products in terms of their characteristics as animal feeds. Some of this information is applicable to characterizing the co-products as fuels. However, much of the necessary fuel information was missing, so we decided to collect co-product samples from five dry-grind ethanol plants and to analyze the samples for a range of fuel characteristics. The literature contained somewhat more fuel characteristic data for corn stover, but we had one corn stover sample analyzed for completeness and to compare literature data with current analyses.

### **Sample Collection and Analysis**

Feed streams were sampled at five cooperating dry-grind ethanol plants. Feed streams included distillers dried grains with solubles (DDGS) – 4 plants, distillers dried grains (DDG) – 1 plant, distillers wet grains (DWG) – 5 plants, and syrup – 5 plants. Sample and shipping containers with sampling instructions were sent to each of the five plants. Plant personnel obtained the samples, and then called a delivery service to transport the samples to the laboratory. Three commercial laboratories were used for the various analyses. The laboratories used standard ASTM procedures or related standard industry procedures for the analyses. Analyses for fuel properties included proximate, ultimate, ash characteristics and metals, energy content, and handling properties (bulk density, viscosity, particle size distribution).

A sample of corn stover was obtained from the Agricultural Utilization Research Institute (AURI), Waseca, Minnesota and submitted for analysis.

### **Results**

Fuel characteristics for ethanol plant coproducts and corn stover are summarized in Table 1. Most results are presented on a moisture free basis for ease of comparison. Since only one plant produced DDG, detailed results are not presented here because we agreed not to identify results from specific plants. However, the DDG results on a moisture free basis are consistent with the DWG results on a moisture free basis from the five plants.

DWG and syrup have mean moisture contents of about 65% and 67%, respectively, as received (Table 1) and higher heating values of approximately 7.79 MJ/kg (3349 Btu/lb) and 6.43 MJ/kg (2765 Btu/lb) respectively at these moisture contents. As discussed further below, based on the mathematical modeling done as part of this project, and on empirical experience, these moisture contents are too high to sustain gasification/combustion without augmentation with some other fuel or drying of the material before use as a fuel. In addition, modeling and empirical experience indicated that combustion of the DWG or syrup in a standard combustion unit (as compared to a fluidized bed unit) without further drying is impractical or essentially infeasible, owing to predicted flame instability and system fouling, even with reasonable levels of fossil fuel augmentation.

For other characteristics, results are more easily compared on a moisture free basis. Measured ash contents and higher heating values for co-products and corn stover (Table 1) are comparable to the results in Table 2 from other studies. Ultimate analysis for corn stover (Table 1) appears to be consistent with the results in Table 2.

Nitrogen and sulfur occur in significant quantities in the three ethanol co-products (Table 1) and the patterns among products are similar to those shown in Tables 2 and 3. Nitrogen and sulfur results for DDGS, although somewhat variable, are consistent across the studies represented in Tables 1 and 3.

We did not analyze for phosphorus and potassium because a significant amount of information on these two elements is available from other analyses of ethanol co-products. Table 3 shows results from the other research for phosphorus and potassium, along with other elements that are important for co-products when used as livestock feed. Potassium and phosphorus trends in the three ethanol co-products are demonstrated from the results of Belyea et al. (2004). Potassium and phosphorus results for DDGS are consistent across the studies presented in Table 3.

Ash characteristics of the co-products are presented in Table 4. Ash analyses were run for either two or three plants. The alkali metal content (potassium and sodium) of the ash is high (22 to 34 %) for co-products and corn stover. Such high levels of alkali metals can lead to ash fouling in combustion and steam generation units, and to potential agglomeration of bed material in fluidized bed systems.

Thermogravimetric analyses are presented in Figures 1 through 4 for selected samples. These figures show how these biomass fuels volatilize as a function of temperature.

### **Modeling of Combustion and Emissions**

We used a computational fluid dynamics approach to model combustion and gasification. Major components of the models were developed by RMT and are proprietary; however, results of the modeling using fuel characteristics of ethanol coproducts and corn stover are presented.

As discussed above, once co-product analyses applicable to combustion were available, modeling indicated that combustion of the DWG or syrup in a standard combustion unit (as compared to a fluidized bed unit) without further drying is impractical or essentially infeasible, owing to predicted flame instability and system fouling. In addition, a standard combustion unit would likely not be able to cope with the levels of sulfur and nitrogen in the co-products streams, which could result in unacceptable levels of emissions of sulfur oxides and nitrogen oxides. Based on these conclusions, evaluation of standard combustion units (devices designed for liquid or gaseous fuels or pulverized coal) for direct firing of the biomass co-products was discontinued, and the project concentrated on fluidized bed combustion and on gasification (either fluidize bed or fixed bed, updraft). A standard combustion unit could be used for combustion of the syngas from a gasification unit, if the sulfur and nitrogen can be satisfactorily addressed.

Modeling indicated that both fluidized bed combustion and gasification are feasible for the biomass co-products. For optimal performance and consistent achievement of regulatory requirements, careful system design and operation are critical. This is especially true if a variety of biomass materials are intended to be used.

Modeling showed that the single most critical factor for efficient and effective utilization of the biomass co-products is the moisture content of the feed stream. As discussed above, exclusive

use of DWG or syrup as-is, while perhaps technically feasible in a carefully designed fluidized bed, will probably not produce consistent, cost-effective results for powering an ethanol plant. The use of DDG or DDGS is predicted to produce excellent, cost-effective results, but with the added complexity and cost of drying the DWG and syrup (about 70% moisture) to the moisture content of DDG or DDGS (about 10% moisture). A key element of designing an overall co-products energy system that is efficient, reliable, and cost-effective is balancing the benefits of drier biomass fuel with the cost and complexity of drying the co-products to any given moisture content. The co-products have sufficient energy content for both drying and power production; effective and cost-effective system design is the key to operational and financial success.

A drier feed stream can be achieved not only by drying a wetter feed stream, but also by mixing the wetter stream with an intrinsically drier stream, such as corn stover. This has its own additional complexity and cost, and must be factored into the analysis for any particular plant.

Using the analytical results for the biomass feed streams, the modeling can also predict the emissions of the key pollutants carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and unburned carbon. Our modeling indicates that the primary emission of concern will be NO<sub>x</sub>. CO can usually be controlled by adjustments to the combustion or gasification conditions, or at the stack by catalytic oxidation. SO<sub>2</sub> can be controlled by adding a chemical (usually limestone) to the combustion or gasification unit; this technology is widely used in industry. VOCs can usually be controlled by adjustments to the combustion or gasification conditions. Since fluidized beds promote very complete combustion, emission of VOCs is not predicted to be a major concern.

NO<sub>x</sub> can be a greater control challenge, since NO<sub>x</sub> arises not only from the combustion air, but also from the fuel. The ethanol co-products (DDGS, DWG, syrup) have high levels of nitrogen (2.6 to 5.4 % dry weight basis, Table 1) compared to fossil fuels or even corn stover, and so have a high potential for generation of NO<sub>x</sub>. NO<sub>x</sub> from the air (thermal NO<sub>x</sub>) increases as the temperature of the combustion unit increases; for this reason, gasification, which operates at a lower temperature than combustion, is attractive for minimizing NO<sub>x</sub> emissions. NO<sub>x</sub> from fuel nitrogen is also decreased by operating in a reducing atmosphere, which further suggests an advantage for gasification.

Technologies are available for NO<sub>x</sub> reduction at the stack, if acceptable NO<sub>x</sub> levels cannot be achieved from the combustion or gasification process. An example is selective catalytic reduction which involves injecting urea in stack gases to react with the NO<sub>x</sub> to produce nitrogen gas (N<sub>2</sub>), carbon dioxide, and water. Our modeling indicates that fairly aggressive NO<sub>x</sub> control may need to be applied to the co-products for the combustion mode.

Reducing the nitrogen in the fuel is another potential approach. Preprocessing (fractionation) of the corn before grinding and fermentation to separate the high protein (high nitrogen) component into a material that has higher value for feed rather than using it as fuel is one possibility. The modified co-product that remains after processing would have less nitrogen, thus reducing the potential for forming NO<sub>x</sub> if it were used for fuel.

We have not attempted to model the emissions of particulate matter, for three primary reasons. First, most of the particulates generated in a fluidized bed appear in the exhaust gas stream, so reasonable assumptions regarding the mass of emissions can be made based on the ash content and chemical composition of the feed streams. Second, highly effective particulate control technologies, able to meet essentially any desired level of emissions to the atmosphere, are widely applied throughout industry. Third, all combustion and gasification units will require a particulate control system, whereas other pollutants may be addressed via process modifications or chemical additions.

### **Summary and Conclusions**

Our initial evaluation indicates that the biomass co-products from the dry-grind ethanol production process, particularly DDGS, are good sources for the electrical and thermal energy needed to operate the plant, and even contain sufficient energy to produce excess power that can be sold. However, the number of subsequent process steps required to reduce emissions to compliance levels, particularly NO<sub>x</sub>, will be important in determining the economic viability of using biomass co-products from dry grind ethanol plants for energy production.

The alkali metal content (potassium and sodium) of the ash is high (22 to 34 %) for co-products and corn stover. Such high levels of alkali metals can lead to ash fouling in combustion and steam generation units, and to potential agglomeration of bed material in fluidized bed systems.

We have developed a detailed analytical program to provide a good data set for completion of other project elements, and for subsequent quantification of the financial impact of using the co-products for energy production at the ethanol plant.

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### **References**

- AURI. 2005. Agricultural renewable solid fuels data. Agricultural Utilization Research Institute Fuels Initiative. Online: [www.auri.org/research/fuels/downloads.asp](http://www.auri.org/research/fuels/downloads.asp).
- Belyea, R.L., K.D. Rausch, and M.E. Tumbleson. 2004. Composition of corn and distillers dried grains with solubles from dry grind ethanol processing. *Bioresource Technology* 94:293-298.
- Brown, Robert C. 2003. Biorenewable Resources. Iowa State Press. Table 3.3, page 67.
- Ebeling, J.M., and B.M. Jenkins. 1985. Physical and chemical properties of biomass fuels. *Transactions of the ASAE* 28(3): 898-902.
- Dakota Gold. 2005. Dakota Gold Marketing – Enhanced nutrition distillers products. Online: [www.dakotagoldmarketing.com](http://www.dakotagoldmarketing.com).

Morey, R.V., D.G. Tiffany, and D.L. Hatfield. 2005. Biomass for electricity and process heat at ethanol plants. ASAE Paper No. 056131. St. Joseph, Mich: ASAE.

National Renewable Energy Laboratory. 1998. Corn stover data. Golden, Colorado. Online: <http://www.ecn.nl/phyllis/DataTable.asp>.

Sokhansanj, S. and A.F. Turhollow. 2004. Biomass densification – cubing operations and costs for corn stover. *Applied Engineering in Agriculture* 20(4): 495-499.

University of Minnesota. 2005. The value and use of distillers dried grains with solubles (DDGS) in livestock and poultry feeds. Online: [www.ddgs.umn.edu](http://www.ddgs.umn.edu).

Table 1. Characteristics of ethanol co-products and corn stover as fuels.

Parameter	DDGS	DWG	Syrup	Corn Stover <sup>7</sup>
<b>As received</b>				
Moisture, %	10.12 (1.38) <sup>1</sup>	64.46 (6.13) <sup>5</sup>	67.29 (6.80) <sup>5</sup>	6.15
Ash, %	3.41 (0.27) <sup>1</sup>	0.97 (0.68) <sup>5</sup>	2.31 (0.77) <sup>5</sup>	6.31
Higher heating value, MJ/kg [Btu/lb]	19.46 (0.39) <sup>1</sup> 8368 (168) <sup>1</sup>	7.79 (1.32) <sup>5</sup> 3349 (567) <sup>5</sup>	6.43 (0.97) <sup>5</sup> 2765 (418) <sup>5</sup>	16.83 7235
<b>Moisture Free</b>				
Ash, %	3.89 (0.29) <sup>2</sup>	2.58 (1.25) <sup>5</sup>	7.02 (1.47) <sup>5</sup>	6.73
Higher heating value, MJ/kg [Btu/lb]	21.75 (0.20) <sup>2</sup> [9349 (88) <sup>2</sup> ]	21.95 (0.26) <sup>5</sup> [9438 (110) <sup>5</sup> ]	19.73 (1.45) <sup>5</sup> [8482 (623) <sup>5</sup> ]	17.93 7709
Lower heating value, MJ/kg [Btu/lb]	20.24 <sup>8</sup> [8703 <sup>8</sup> ]	20.51 <sup>8</sup> [8819 <sup>8</sup> ]	18.19 <sup>8</sup> [7819 <sup>8</sup> ]	16.73 <sup>8</sup> [7192 <sup>8</sup> ]
<u>Proximate</u>				
Volatile matter, %	82.50 (1.32) <sup>2</sup>	83.18 (2.09) <sup>5</sup>	81.71 (0.92) <sup>5</sup>	66.58
Fixed Carbon, %	12.84 (1.61) <sup>2</sup>	13.58 (1.75) <sup>5</sup>	10.32 (1.58) <sup>5</sup>	26.65
Chlorine, µg/g	1757 (89) <sup>3</sup>	1673 (1543) <sup>1</sup>	3459 (807) <sup>1</sup>	984
Mercury, µg/g	<0.010 <sup>4</sup>	<0.10 <sup>6</sup>	<0.012 <sup>6</sup>	<0.010
<u>Ultimate</u>				
Carbon, %	50.24 (0.31) <sup>2</sup>	52.53 (3.24) <sup>5</sup>	43.12 (4.29) <sup>5</sup>	45.48
Hydrogen, %	6.89 (0.05) <sup>2</sup>	6.60 (0.34) <sup>5</sup>	7.07 (0.24) <sup>5</sup>	5.52
Nitrogen, %	4.79 (0.34) <sup>2</sup>	5.35 (0.35) <sup>5</sup>	2.63 (0.59) <sup>5</sup>	0.69
Oxygen, %	33.42 (1.11) <sup>2</sup>	32.28 (2.87) <sup>5</sup>	39.21 (4.31) <sup>5</sup>	41.52
Sulfur, %	0.77 (0.18) <sup>2</sup>	0.66 (0.11) <sup>5</sup>	0.96 (0.31) <sup>5</sup>	0.04
<u>Metals, mg/kg</u>				
Arsenic	<3.20 <sup>4</sup>	<3.10 <sup>6</sup>	<3.20 <sup>6</sup>	2.50
Beryllium	<0.093 <sup>4</sup>	<0.093 <sup>6</sup>	<0.11 <sup>6</sup>	<0.089
Cadmium	<0.046 <sup>4</sup>	<0.50 <sup>6</sup>	<0.53 <sup>6</sup>	<0.45
Chromium	0.50 (0.05) <sup>3</sup>	<0.79 <sup>6</sup>	0.75 (0.20) <sup>1</sup>	<0.45
Lead	<0.046 <sup>4</sup>	<0.50 <sup>6</sup>	<0.53 <sup>6</sup>	0.46
Manganese	15.95 (1.63) <sup>3</sup>	12.05 (4.45) <sup>1</sup>	34.93 (10.63) <sup>1</sup>	23.4
Nickel	0.87 (0.06) <sup>3</sup>	<1.20 <sup>6</sup>	1.97 (0.45) <sup>1</sup>	<0.45
Phosphorus	-	-	-	-
Potassium	-	-	-	-
Selenium	1.80 (0.00) <sup>3</sup>	<1.80 <sup>6</sup>	<1.60 <sup>6</sup>	<1.30

<sup>1</sup> mean (standard deviation) of samples from 3 plants

<sup>2</sup> mean (standard deviation) of samples from 4 plants

<sup>3</sup> mean (standard deviation) of samples from 2 plants

<sup>4</sup> samples from 2 plants

<sup>5</sup> mean (standard deviation) of samples from 5 plants

<sup>6</sup> samples from 3 plants

<sup>7</sup> one sample

<sup>8</sup> calculated using mean higher heating value and mean ultimate analysis

Table 2. Comparisons for ethanol co-products and corn stover on a moisture free basis.

<b>Parameter</b>	<b>DDGS<sup>1</sup></b>	<b>DDG w/o solubles<sup>1</sup></b>	<b>Corn Stover<sup>1</sup></b>	<b>Corn Stover<sup>2</sup></b>	<b>Corn Stover<sup>3</sup></b>
Ash, %	4.59	2.24	7.64	5.58	5.1
Higher heating value, MJ/kg (Btu/lb)	21.91 (9422)	22.91 (9848)	18.07 (7768)	17.65 (7588)	18.23 (7836)
<b>Proximate</b>					
Volatile matter, %	-	-	-	75.17	80.9
Fixed Carbon, %	-	-	-	19.25	-
Chlorine, µg/g	-	-	600	984	-
<b>Ultimate</b>					
Carbon, %	-	-	-	43.65	46.8
Hydrogen, %	-	-	-	5.56	5.74
Nitrogen, %	-	-	-	0.61	0.66
Oxygen, %	-	-	-	43.31	41.4
Sulfur, %	0.45	0.4	0.04	0.01	0.11

<sup>1</sup> AURI. 2005. Agricultural renewable solid fuels data. Agricultural Utilization Research Institute Fuels Initiative. Online: [www.auri.org/research/fuels/downloads.asp](http://www.auri.org/research/fuels/downloads.asp)

<sup>2</sup> Brown, Robert C. 2003. Biorenewable Resources. Iowa State Press. Table 3.3, page 67. (Source: Ebeling, J.M., and B.M. Jenkins. 1985. Physical and chemical properties of biomass fuels. *Transactions of the ASAE* 28(3): 898-902.)

<sup>3</sup> National Renewable Energy Laboratory. 1998. Golden, Colorado.

Table 3. Comparison of elements in ethanol co-products (% of dry matter).

<i>Element</i>	<i>DWG</i> <sup>1</sup>	<i>Syrup</i> <sup>1</sup>	<i>DDGS</i> <sup>1</sup>	<i>DDGS</i> <sup>2</sup>	<i>DDGS</i> <sup>3</sup>
Nitrogen	5.4 5.1 – 5.8	3.2 2.2 – 4.8	5.1 4.8 – 5.3	4.9 4.5 – 5.4	4.7
Sulfur	0.48 0.40 – 0.58	0.74 0.20 – 1.32	0.58 0.36 – 0.84	0.61 0.31 – 1.05	0.84
Phosphorus	0.54 0.50 – 0.59	1.52 1.35 – 1.85	0.86 0.70 – 0.95	0.76 0.42 – 0.99	0.83
Potassium	0.59	2.32 2.0 – 2.6	1.12	1.00 0.45 – 1.33	1.19
Sodium	0.45	0.024	0.13	0.17 0.01 – 0.52	0.19
Magnesium	0.18	0.69	0.35	0.30 0.14 – 0.38	0.36
Calcium	0.019	0.045	0.028	0.07 0.02 – 0.51	0.04
Iron	0.010	0.014	-0.010	-	-
Zinc	0.011	0.013	0.011	-	-

<sup>1</sup> Belyea, R.L., K.D. Rausch, and M.E. Tumbleson. 2004. Composition of corn and distillers dried grains with solubles from dry grind ethanol processing. *Bioresource Technology* 94:293-298. (data from nine dry-grind plants)

<sup>2</sup> University of Minnesota. 2005. The value and use of distillers dried grains with solubles (DDGS) in livestock and poultry feeds. Online: [www.ddgs.umn.edu](http://www.ddgs.umn.edu). (Data are for 32 plants in 11 states for all quantities except chloride, which is for 16 plants in 8 states.)

<sup>3</sup> Dakota Gold. 2005. Dakota Gold Marketing – Enhanced nutrition distillers products. Online: [www.dakotagoldmarketing.com](http://www.dakotagoldmarketing.com)

Table 4. Ash characteristics of ethanol co-products and corn stover.

Parameter	DDGS	DWG	Syrup	Corn Stover <sup>3</sup>
<b>Ash Fusion – Oxidizing Atmosphere</b>				
Initial Deformation, °C [°F]	583 (53) <sup>1</sup> [1081 (96) <sup>1</sup> ]	711 (56) <sup>2</sup> [1312 (91) <sup>2</sup> ]	1044 (873) <sup>2</sup> [1912 (1572) <sup>2</sup> ]	1054 [1930]
Softening, °C [°F]	593 (56) <sup>1</sup> [1099 (100) <sup>1</sup> ]	749 (65) <sup>2</sup> [1381 (117) <sup>2</sup> ]	1197 (456) <sup>2</sup> [2186 (820) <sup>2</sup> ]	1084 [1984]
Hemispherical, °C [°F]	705 (5) <sup>1</sup> [1301 (9) <sup>1</sup> ]	786 (68) <sup>2</sup> [1446 (122) <sup>2</sup> ]	1424 (81) <sup>2</sup> [2595 (146) <sup>2</sup> ]	1149 [2100]
Fluid, °C [°F]	1108 (447) <sup>1</sup> [2027 (805) <sup>1</sup> ]	1116 (321) <sup>1</sup> [2041 (578) <sup>2</sup> ]	1479 (18) <sup>2</sup> [2695 (33) <sup>2</sup> ]	1207 [2205]
<b>Ash Fusion – Reducing Atmosphere</b>				
Initial Deformation, °C [°F]	690 (25) <sup>1</sup> [1274 (45) <sup>1</sup> ]	719 (49) <sup>2</sup> [1327 (89) <sup>2</sup> ]	1037 (209) <sup>2</sup> [1898 (377) <sup>2</sup> ]	884 [1624]
Softening, °C [°F]	751 (68) <sup>1</sup> [1384 (123) <sup>1</sup> ]	797 (82) <sup>2</sup> [1467 (148) <sup>2</sup> ]	1191 (242) <sup>2</sup> [2176 (436) <sup>2</sup> ]	937 [1718]
Hemispherical, °C [°F]	812 (128) <sup>1</sup> [1493 (231) <sup>1</sup> ]	863 (112) <sup>2</sup> [1586 (201) <sup>2</sup> ]	1253 (203) <sup>2</sup> [2287 (366) <sup>2</sup> ]	1043 [1909]
Fluid, °C [°F]	1411 (12) <sup>1</sup> [2573 (21) <sup>1</sup> ]	1081 (29) <sup>2</sup> [1978 (62) <sup>2</sup> ]	1458 (8) <sup>2</sup> [2657 (15) <sup>2</sup> ]	1201 [2194]
<b>Mineral Analysis, %</b>				
Silicon dioxide	2.89 (0.22) <sup>1</sup>	4.37 (2.16) <sup>2</sup>	<2.42 <sup>5</sup>	54.12
Aluminum oxide	<0.38 <sup>4</sup>	<0.38 <sup>5</sup>	<0.38 <sup>5</sup>	0.78
Titanium dioxide	<0.03 <sup>4</sup>	<0.03 <sup>5</sup>	<0.03 <sup>5</sup>	0.04
Iron oxide	<0.32 <sup>4</sup>	<0.29 <sup>5</sup>	<0.93 <sup>5</sup>	0.45
Calcium oxide	<1.4 <sup>4</sup>	<0.1.4 <sup>5</sup>	<0.1.4 <sup>5</sup>	5.61
Magnesium oxide	13.31 (1.61) <sup>1</sup>	8.85 (1.89) <sup>2</sup>	10.81 (2.71) <sup>2</sup>	4.22
Potassium oxide	30.04 (0.88) <sup>1</sup>	22.40 (6.10) <sup>2</sup>	27.03 (5.66) <sup>2</sup>	20.22
Sodium oxide	3.65 (1.88) <sup>1</sup>	3.05 (1.78) <sup>2</sup>	3.18 (1.01) <sup>2</sup>	1.47
Sulfur trioxide	1.57 (0.35) <sup>1</sup>	2.03 (2.16) <sup>2</sup>	5.87 (1.59) <sup>2</sup>	12.75
Phosphorus pentoxide	43.24 (3.19) <sup>1</sup>	34.77 (5.44) <sup>2</sup>	30.15 (3.59) <sup>2</sup>	1.97
Strontium oxide	<0.02 <sup>4</sup>	<0.02 <sup>5</sup>	<0.02 <sup>5</sup>	<0.02
Barium oxide	<0.02 <sup>4</sup>	<0.02 <sup>5</sup>	<0.02 <sup>5</sup>	0.02
Manganese dioxide	0.06 (0.01) <sup>1</sup>	0.05 (0.02) <sup>2</sup>	0.05 (0.02) <sup>2</sup>	0.06
Nitrogen	2.44 (1.77) <sup>1</sup>	2.35 (1.20) <sup>2</sup>	1.55 (0.64) <sup>2</sup>	-

<sup>1</sup> mean (standard deviation) of samples from 2 plants

<sup>2</sup> mean (standard deviation) of samples from 3 plants

<sup>3</sup> one sample

<sup>4</sup> samples from 2 plants

<sup>5</sup> samples from 3 plants

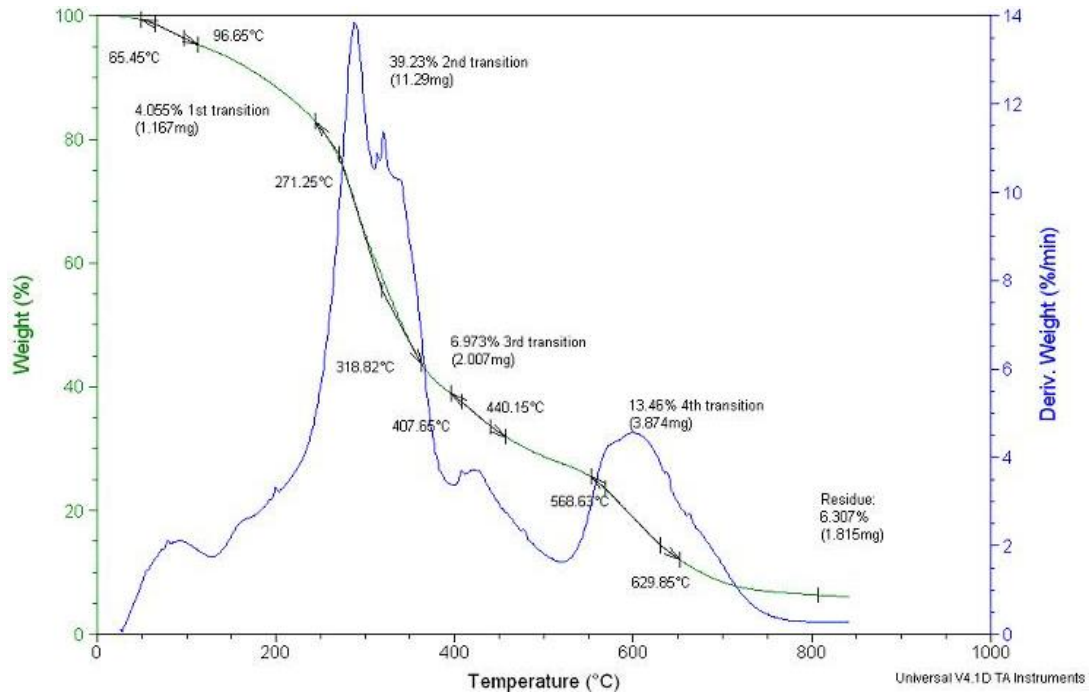


Figure 1. Thermogravimetric analysis for a DDGS sample (9 to 12 % moisture).

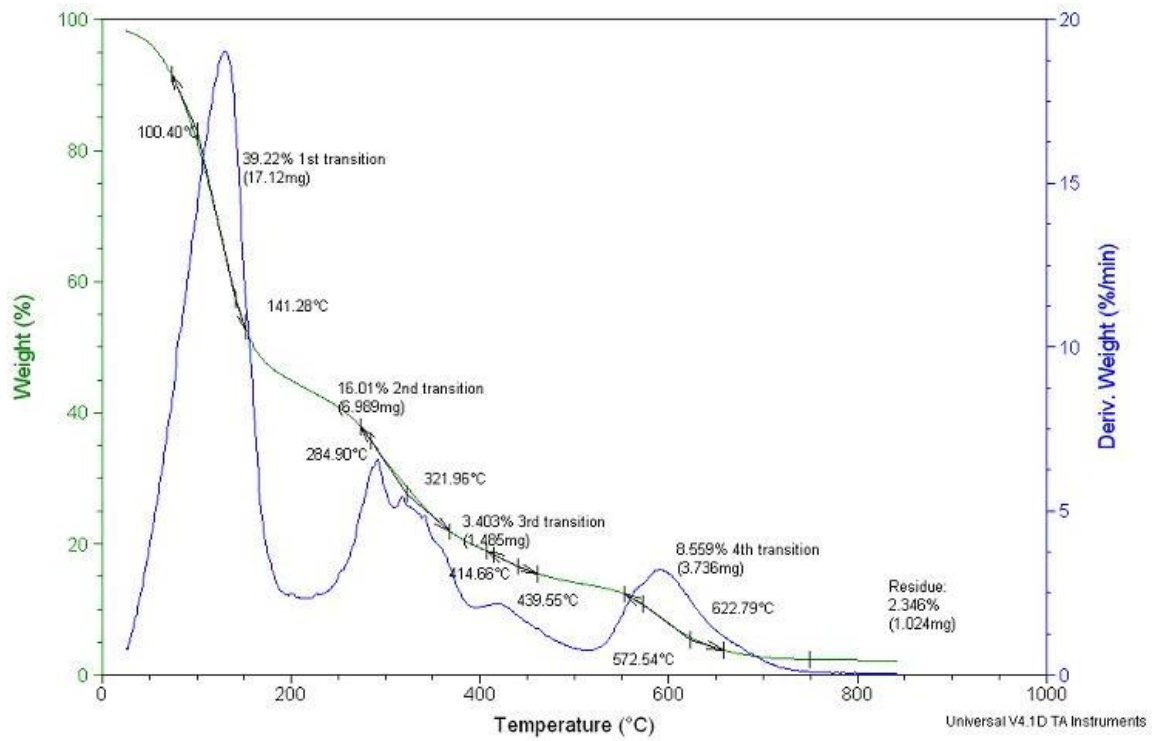


Figure 2. Thermogravimetric analysis for a DWG sample (55 to 70% moisture).

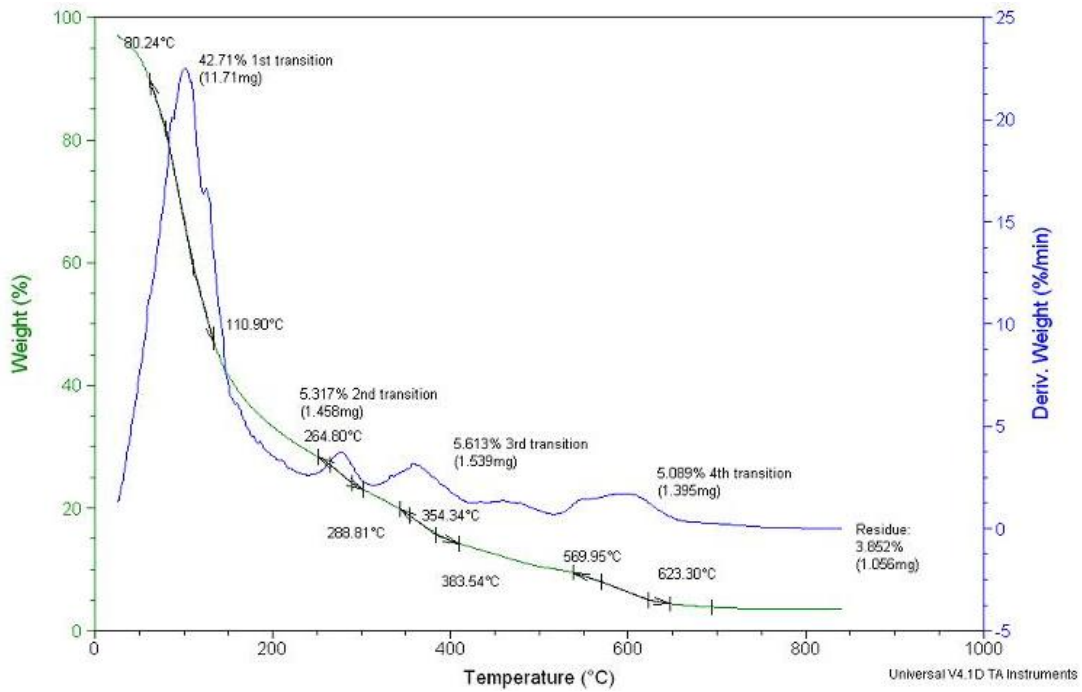


Figure 3. Thermogravimetric analysis for a syrup sample (58 to 77% moisture).

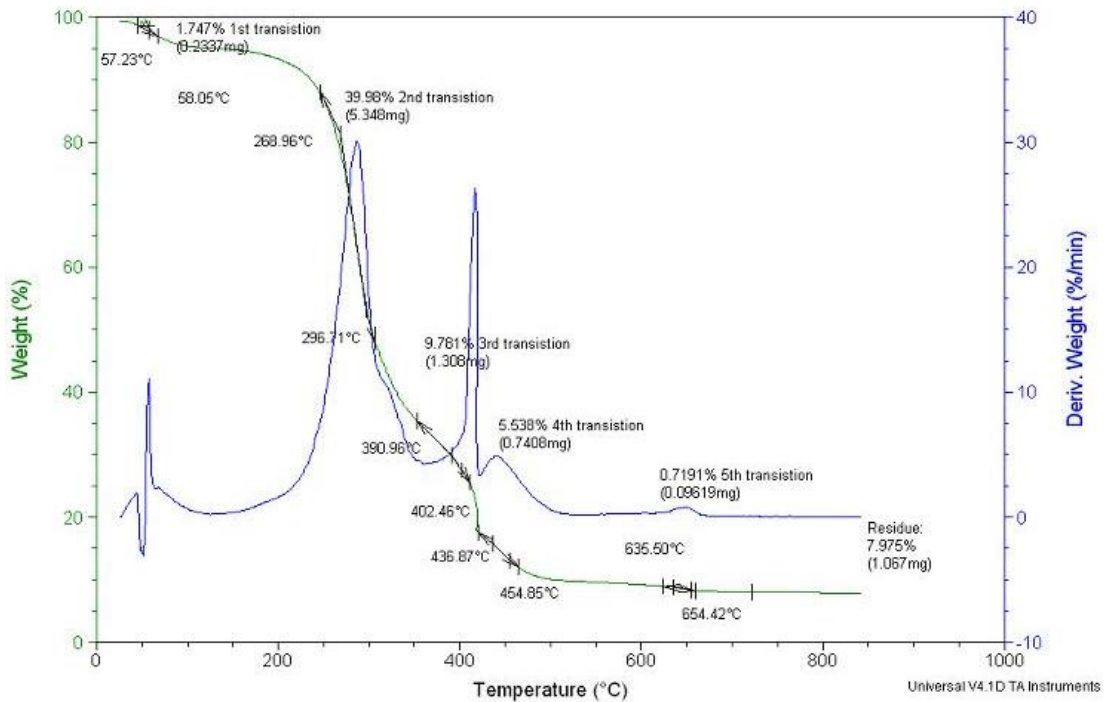


Figure 4. Thermogravimetric analysis for a corn stover sample (6.15% moisture).