Project Title: **Evaluating Energy Efficient Strategies and Product Quality for Distillers’ Dried Grains with Solubles (DDGS) in Dry-Grind Ethanol Plants**

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**Period of Proposed Project Date:**

Beginning: __January 1, 2008__                    Ending: __December 31, 2009__

**Amount Requested**

Year 1: _$25,000_                                     Year 2: _$25,000_
Problem Identification and Related Research

The amount of corn used for ethanol production has increased 17-fold during the past 20 years, to more than 600 millions bu/year. This has resulted in 4.9 billion gallons of ethanol valued at $10.8 billion and 12 million metric tons of distillers grains valued at $1.6 billion in 2006 (RFA 2005a). Much of the fuel ethanol production capacity in the United States is concentrated in NC-213 states. Wet milling and dry grinding are used to produce ethanol from corn. Wet milling involves soaking the corn kernel in water (steeping) to soften it and fractionating it into its chemical components. Fractionation separates the starch, protein, fiber, and germ, and allows these components to be processed separately. The three major coproducts of wet-mill ethanol production are animal feed products, i.e., corn gluten meal (high protein, 40%) and corn gluten feed (low protein, 28%), and corn germ, which may be further processed into corn oil. In dry grinding, the corn kernel is physically broken apart and not fractionated, which results in one primary coproduct, i.e., distillers dried grains with solubles (DDGS). The marketing of coproducts represents approximately 10-20% of the product value from a dry grind ethanol plant, and thus is an important income stream to offset ethanol processing costs (Rausch and Belyea, 2006). This is especially important because dry-grind ethanol plants account for 70% of ethanol production in the U.S. and DDGS are the only coproduct available (RFA, 2005b).

The fermentation and distillation steps have undergone many technological improvements, which have increased energy efficiency of ethanol production by 67% since the 1970s (Shapouri et al., 2003). However, not much attention has been paid to address the issues of energy efficiency and quality of coproducts. For example, DDGS are affected by high concentrations of fiber and phosphorous, variability in composition, and high cost of water removal (Rausch and Belyea, 2006). Variability in composition and moisture reduces quality and hence marketability. Also, the high drying cost of DDGS decrease coproduct margins. As ethanol margins shrink, the dry-grind ethanol industry will be forced to strive for increased product quality and drying process efficiency. In order to correctly implement energy saving and quality improving strategies during the DDGS drying operation, fluid-solid transport modeling and process optimization coupled with on-line performance monitoring of rotary dryers in dry-grind ethanol processing plants is proposed in this project.

Dry-Grind Corn-to-Ethanol Processing

The basic steps in dry-grind corn-to-ethanol processing are grinding, cooking, liquefaction, saccharification, fermentation, distillation and recovery (Figure 1). After fermentation is completed, the resulting material (beer) consists of liquid (8-12% ethanol by weight) and non-fermentable solids. The ethanol is separated from the water part using distillation columns. The residual water is then removed using molecular sieves that selectively adsorb the water from the ethanol/water vapor mixture, resulting in nearly pure ethanol (>99%) (Mosier and Ileleji, 2006). The whole stillage is withdrawn from the bottom of the distillation unit and is then centrifuged to produce wet grains and thin stillage. Some of the thin stillage is recycled to the beginning of the dry-grind process to conserve the water used by the facility. The remaining thin stillage passes through evaporators and is concentrated to produce condensed distillers solubles (syrup; CDS). This syrup is then mixed with distillers wet grains (DWG) at 60-65% moisture content.
and dried in a sequence of two rotary drum dryers to produce DDGS around 10-12% moisture content. The costs of removing water in this process are substantial. The initial water to be removed by dewatering (pressing and centrifuging) requires about 0.5–10 Btu per pound of water removed; the remaining water to be removed by drying requires 300-1590 Btu per pound of water removed from coproduct (Rausch and Belyea, 2006). The total energy required to produce ethanol using the dry-grind processing is about 48,772 Btu per gallon (Shapouri et al., 2002). This translates to $5.36 \times 10^5$ million Btu for the 110 million gallon ethanol plant operated by The Andersons in Clymers, IN. Since DDGS drying utilizes about 30% of the total energy required for dry-grind corn processing (Lurgi, 2007), a 5-10% increase in drying process efficiency would save about 80,400-160,800 million Btu, or about $482,400-$964,800 annually at a natural gas cost of $6 per million Btu. This shows that improving rotary drum dryer efficiency could have significant impact on the economics of the dry-grind corn-to-ethanol process.

**Drying Process in Rotary Drum Dryer**

A rotary drum dryer is a slightly inclined and rotating cylinder in which the distillers’ wet grains (DWG) are tumbled or mechanically turned and flow in the same (concurrent) or opposite (counter current) direction as the hot drying air. DWG cascading from the flights are transported axially down (towards the discharge) the length of the dryer due to gravity. This forward motion is influenced by drag from the hot drying air stream. The DWG may also roll and bounce axially along the base of the dryer and in the flights. The flights inside the dryer promote direct contact between the mixed DWG and the hot air causing the solids to undergo drying (Figure 2). Therefore, the drying process in a rotary drum dryer involves not only heat and mass transfer between the hot air stream and the particles but also complicated movement of particles within the dryer due to gravitational, rotational and centrifugal forces. The final DDGS moisture content depends on the condition of the drying air (temperature and relative humidity), and the residence time. The solids mean residence time is influenced by dryer dimensions (length and diameter), dryer rotational speed and angle of inclination, airflow rate, solids feed rate, and solids feed moisture content (Renaud et al., 2001). High residence time means high cost of drying per production rate. Hence, an optimized solution is required between the production rate and the residence time required to reduce the product final moisture content to values safe for quality preservation and marketing.

**Recycling of DDGS in Rotary Drum Dryers**

The total amounts of heat and mass transferred during the passage of solids through the dryer largely depend on the surface area and the time of contact between the solid and gas phases (Kelly, 1995). The feed moisture content of the mixed DWG affects their movement in the rotary drum dryer, the adhesion of the particles, and the drying rate (and residence time). Partly recycling DDGS and mixing them with DWG and distillers solubles is one of the techniques employed for reducing the initial feed moisture content, which affects the mean residence time (Figure 1). This has a strong impact on DDGS quality and the drying process efficiency. The influence of the amount of recycled DDGS (recycle ratio) on the quality of the final DDGS produced has not been investigated and appears to be unknown in the ethanol industry (Mike Myrick, The Andersons, Personal Communication). Therefore, this proposed investigation - process simulation coupled with online performance monitoring of the drying process - will help identify the optimal
value of the recycle ratio, and thus should improve energy efficiency without compromising DDGS quality.

**Simulation Models for Rotary Drum Dryers**

Effective control of drying is not intuitive as the drying process in rotary dryers involves three main transport phenomena occurring simultaneously: transportation of moist solids, heat exchange between the gas and the solids, and moisture transfer from the solids to the gas. The need for thorough assessment of the capacity limitation of rotary drum dryers and the development of effective control schemes has led to a recent emphasis on the development of dryer simulation models as an effective control and management tool (Sheehan et al., 2005). Shahhosseini et al. (2001) reviewed different rotary drum dryer modeling approaches. The literature review revealed that extensive research has been undertaken to develop simulation models for optimization of rotary dryer operation and design of control systems. These approaches vary from black box to neural network to fully mechanistic systems. Neural network and black box models for the simulation of flighted rotary dryers require exhaustive industrial experimental data for model training, which is generally difficult to obtain. Empirical models are simpler to use but lack accuracy. However, mechanistic models are often used because it is possible to predict outside of nominal operating conditions with reasonable accuracy (Sheehan et al., 2005). The complicated transport phenomena in the dryer involves heat and mass transfer between the hot air stream and the particles, movement of particles within the dryer due to gravitational, rotational and centrifugal forces. A thorough understanding of the transport phenomena in the rotary dryer is needed as they affect moisture content, particle size distribution and color of the final DDGS. This calls for a sophisticated mechanistic modeling approach such as Computation Fluid Dynamics (CFD), which provides detailed information on heat and mass transfer within the dryer, and solids transport and interaction with hot drying air.

In this project, the numerical methodology underlying the FLUENT™ CFD solver will be employed. The simulation will provide detailed information on the effect of DDGS recycle ratio on stresses in a granular medium, particle velocities, temperature distribution, moisture content and residence time, which are important parameters required for studying what-if scenarios and possible energy efficient strategies. Such strategies are expected to reduce energy consumption of the drying process without compromising the DDGS quality. Therefore, the detailed information obtained from CFD simulation will be used to optimize the drying operation for a range of process conditions. This calls for development of process optimization model. The detailed data obtained from CFD simulation and MATLAB optimization toolbox will be employed for searching optimal energy efficient strategy for good DDGS quality for different DWG inlet and DDGS outlet conditions (temperature, moisture content), air stream conditions (temperature, relative humidity, velocity), rotational speed and incline angle (residence time), and DDGS recycle ratios. The process optimization model can further be used to develop a model-based control system for the rotary dryer, which could be incorporated into the existing plant automation system.

**Advantages of the CFD-Process Optimization modeling Approach**

CFD modeling and process optimization coupled with on-line performance monitoring of rotary dryers in dry-grind ethanol processing plants is proposed in this
project. Given that much work has already been done in developing simulation models for rotary dryers for applications such as sugar and fertilizer processing, the CFD models developed by Witt (2003) for rotary dryer simulation and by Huang et al. (2005) for three-dimensional simulation of a spray dryer will be used as a basis to develop a CFD model for DDGS drying application. The advantage of the CFD approach is that on-line monitoring is done for specific conditions, and the validated CFD model will help in predicting ranges of process conditions, which reduces the requirement of exhaustive on-line measurement. The CFD model provides virtually any information whereas in experiments only very limited information is usually available on the dynamics of the particle flow. Since the CFD simulation provides generally information of the drying process, optimal values of the process variables should be identified. This can be done using the CFD simulation data for calibrating a process optimization model. Hence, the proposed approach exploits the synergy between CFD and on-line monitoring.

Objectives

This proposed project is part of a larger, multi-disciplinary research and extension effort at Purdue University involving faculty, staff and graduate students from Agricultural & Biological Engineering, Animal Sciences, Agricultural Economics and Agronomy to improve the processing, handling and utilization of DDGS from dry-grind ethanol plants in Indiana and surrounding states. Beyond the current effort with its primary focus on animal digestibility and performance, feedback from stakeholders indicated that the effect of drying and recirculating DDGS on energy efficiency and coproduct quality is a major concern of dry-grind ethanol plant operators and needs to be addressed. Therefore, this effort leverages existing expertise at Purdue and collaboration with industry, and is targeted at providing practical guidelines for the energy efficient production of high quality DDGS. To that end, two primary objectives will be pursued:

1. Conduct on-line monitoring of rotary dryer performance for different DWG inlet and DDGS outlet conditions (temperature, moisture content), air stream conditions (temperature, relative humidity), residence time, DDGS recycle ratios, and solubles addition, and generate a data set for the validation of the rotary dryer and process simulation models proposed in Objective 2. (Year 1)

2. Adapt and validate an available CFD-based computer simulation model of the rotary dryer, and apply the model to calibrate process optimization model that can be utilized to formulate operator guidelines and has the potential for automated, on-line process control to maintain optimal operating conditions. (Years 1 & 2)

The objectives to be pursued in this project will address Objective A (Develop practices and technologies to support quality management systems for production, distribution, processing, utilization of quality grains and oilseeds) and Objective C (Create and disseminate scientific knowledge that will enhance public confidence in market-driven quality management systems for grains) of NC-213.

Procedures

Objective 1. Conduct on-line monitoring of rotary dryer performance for different DWG inlet and DDGS outlet conditions (temperature, moisture content), air stream conditions (temperature, relative humidity), residence time, DDGS recycle ratios, and
solubles addition and generate a data set for the validation of the rotary dryer and process simulation models proposed in Objective 2.

The on-line drying process monitoring will be conducted at the dry-grind ethanol plant of The Andersons in Clymers, IN. This 110-million gallon ethanol plant has two parallel DDGS processing lines with two rotary drum dryers used for drying approximately 45,000 lb/h of DDGS each and a third rotary unit used for cooling DDGS before final storage (Figure 3). A mixture of DWG, Condensed Distillers Solubles (CDS) (metered in gallons/minute) and recycled DDGS from Dryer A (DDGS-RA) enter one of the two process lines at a combined moisture content of 60-65%. Dryer A dries this mixture to a moisture content of about 30-35% using heated air around 900°F, which results in a product exit temperature of about 220°F. A smaller portion of the DDGS (typically less than 25%) is recycled to the inlet of Dryer A while the majority will be mixed with CDS (metered in gallons/minute) and recycled DDGS from Dryer B (DDGS–RB) and enters into Dryer B. Dryer B dries this mixture to a moisture content of about 10-12% using heated air around 850°F, which results in a product exit temperature of about 225°F. A smaller portion of the DDGS (typically less than 25%) is recycled into the inlet of Dryer B while the majority continues into the rotary cooler where additional 1-2 points of moisture are removed while DDGS are cooled with ambient air to within about 40°F of ambient air temperature.

On-line process monitoring will be done using the AIChE’s (American Institute of Chemical Engineers) testing procedure for continuous direct-heat rotary dryers outlined in AIChE (2005). A copy of AIChE procedures is included in Appendix A. The procedure applies to the rotary dryers at the dry-grind ethanol plant of The Andersons in Clymers, IN, in which both hot air and material flow are from end-to-end of the dryer cylinder, and in which heat is transferred primarily by convection from the hot drying air to the wet material. Table 1 lists the process variable that will be measured during on-line monitoring for both dryer A and B and for the following energy efficiency improving strategies:

- **Strategy 1**: Base line case (current plant operation)
- **Strategy 2**: 0% CDS, 100% DWG mixed with recycled DDGS (current plant recycle ratio)
- **Strategy 3**: 15-20% CDS, 80-85% DWG mixed with recycled DDGS (current plant recycle ratio)
- **Strategy 4**: 30-40% CDS, 60-70% DWG mixed with recycled DDGS (current plant recycle ratio)
- **Strategy 5**: 25% recycled DDGS mixed with base line CDS and DWG
- **Strategy 6**: 40% recycled DDGS mixed with base line CDS and DWG
- **Strategy 7**: 60% recycled DDGS mixed with base line CDS and DWG

In addition to the sensors listed in Table 1, which will be calibrated at Purdue University and installed to measure the mentioned process parameters, we will also have access to the data collected by the automated process monitoring and control system in the plant. The product quality will be tested in an off-campus laboratory. Moreover, the proposed project will benefit from the expertise of the current multi-disciplinary research on DDGS composition and quality studies at Purdue University in which the PIs (Klein Ileleji and Dirk Maier) are involved.
To account for the influence and variability of different batches of corn and weather conditions on the drying process and product quality, a Purdue University graduate student will collect performance data and product samples for 3-5-day periods on a monthly basis between January and December 2008. During that same period of time, the graduate student will analyze the data collected on an on-going basis, which may result in some adjustment and fine-tuning of the procedures outlined above. All experimental results will be analyzed for statistical significance using standard statistical procedures. The performance results obtained during this 12-month period will be summarized in a project report that the PIs will use to develop an initial set of process improvement recommendations. The data set obtained will also be used to validate and calibrate the process optimization model to be developed under Objective 2.

Table 1

<table>
<thead>
<tr>
<th>Monitored Parameter</th>
<th>Monitoring Point</th>
<th>Sensors/Method</th>
<th>Purpose</th>
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<tbody>
<tr>
<td>Feed Inlet and product outlet Temperature</td>
<td>Material inlet and outlet ports</td>
<td>Thermocouples</td>
<td>Treatment control/material and energy balance</td>
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<tr>
<td>Feed Inlet and product outlet moisture content</td>
<td>Material inlet and outlet ports</td>
<td>Putting a representative sample in a closed, insulated container with thermocouple immersed in the material</td>
<td>Treatment control/material and energy balance</td>
</tr>
<tr>
<td>Feed, product, recycled DDGS, DWG and CDS flow rate</td>
<td>Material inlet and outlet ports</td>
<td>Collecting the feed and product for a measured time period and weighing the amount collected and using the plant’s automated measuring system</td>
<td>Treatment control/calculate the blend and recycle ratio/material and energy balance</td>
</tr>
<tr>
<td>Drying air inlet and outlet temperature</td>
<td>Drying air Inlet and outlet ports</td>
<td>Thermocouples</td>
<td>Treatment control/material and energy balance</td>
</tr>
<tr>
<td>Drying air inlet and outlet relative humidity</td>
<td>Drying air Inlet and outlet ports</td>
<td>Hygrometer</td>
<td>Treatment control/material and energy balance</td>
</tr>
<tr>
<td>Drying air inlet and outlet flow rate</td>
<td>Drying air Inlet and outlet ports</td>
<td>Using hot-wire anemometer or Pitot tube/plant’s automated measuring system</td>
<td>Treatment control/material and energy balance</td>
</tr>
<tr>
<td>Residence time</td>
<td>Material inlet and outlet ports</td>
<td>Introducing a tracer into the feed</td>
<td>Treatment control/product quality/material and energy consumption</td>
</tr>
<tr>
<td>Temperature of dryer cylinder</td>
<td>Dryer cylinder surface</td>
<td>Using radiation gages and surface thermocouples</td>
<td>Energy balance/energy loss</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>Fuel port</td>
<td>using the plant’s automated measuring system</td>
<td>Energy efficiency</td>
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</table>
Previous work by one of the PIs (Ileleji, not published) showed that quality measures such as color and particle size correlate to the ratios of DWG and CDS in the final product mixture of DDGS. Another physical property of interest is the particle density which directly correlates to the bulk density and is a measure of the mass of material in a given volume. We will evaluate the final DDGS product quality based on their physical properties (color, particle size and distribution, particle density) and proximate analysis (moisture, crude fat, crude protein, crude fiber, and ash). For each sample produced by the various strategies investigated, physical and chemical properties will be measured on three replicate sub-samples. Particle size and distribution will be determined using a RO-Tap shaker and a set of U.S. standard sieves. Results will be expressed using the procedure specified in ANSI/ASAE Standard S319.3 for determining and expressing fineness of feed materials by sieving (ASAE Standard, 2006). Data of the L, a and b values will be collected from sample treatments using the HunterLab Model LSXE Colorimeter. L* values represent the light(+)/dark(-) spectrum, a* values represent the red(+)/green(-) spectrum and b* values represent the yellow(+)/blue(-) spectrum. These values describe the darkness/brightness of colors and have been used to differentiate the colors of various DDGS samples by Rosentrater (2006) and others. A gas multipycnometer (Quantachrome Corporation, Boynton Beach, FL) will be used to determine the particle density of DDGS particles produced by the various drying strategies tested. The analysis for crude protein, crude fat, and crude fiber will obtain the basic chemical profile of DDGS produced by the various strategies investigated. The chemical compositional analysis will be contracted to an accredited laboratory for DDGS analysis using Association of Official Analytical Chemist (AOAC) standard methods. We will use PROC GLM analysis of variance (ANOVA) to determine if there are differences the physical properties and chemical composition of DDGS sampled from the various drying strategies investigated. In addition, we will investigate the correlation between particle physical properties and their chemical composition and also their correlation to the drying processes investigated.

Objective 2. Develop and validate an available CFD-based computer simulation model of the rotary dryer, and apply the model to calibrate a process optimization model that can be utilized to formulate operator guidelines and has the potential for automated, on-line process control to maintain optimal operating conditions.

**CFD (Computational Fluid Dynamics) Model:**

CFD model will be developed to simulate and analyze the drying process in a rotary dryer. FLUENT™, a computational fluid dynamics (CFD) software capable of modeling different types of heat, mass and momentum transfer problems will be employed. The dryer modeling steps will involve building a simulated replicate model of the rotary dryer, meshing, applying the appropriate initial, boundary and transient conditions to the system and implementing the correct solution solving scheme.

**Geometric Modeling and Mesh Generation:** The geometry will includes only the rotary dryer itself. The details of the dryer will be obtained from the ethanol plant. The geometry will be created in GAMBIT™ and meshed using unstructured tetrahedral/hexahedra, taking care to resolve regions of high gradient.
**Mathematical Model:** A variety of physics must be resolved in order to correctly predict the particle flow, heat and mass transfer. These include the unsteady computation of fluid-particle flow and heat transfer in the presence of turbulence and natural convection, water-vapor transport.

- **Governing Conservation Equations for Continuous Phase (Drying air):**

  - Continuity:
    \[
    \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \tag{1}
    \]

  - i-Direction Momentum:
    \[
    \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \tag{2}
    \]

  - Energy:
    \[
    \frac{\partial}{\partial t} (\rho h) + \frac{\partial}{\partial x_j} (\rho u_i h) = \frac{\partial}{\partial x_j} \left( (k + k_i) \frac{\partial T}{\partial x_j} \right) + S_p \tag{3}
    \]

  Where, $t$ is time, $\rho$ is the air density, $u_i$ is the air velocity, $p$ the pressure, $g_i$ the acceleration due to gravity, $h$ the air sensible enthalpy, $k$ the thermal conductivity, $S_p$ is the source of heat. For laminar flow, the stress tensor $\tau_{ij}$ is the Newtonian stress tensor. For turbulent flow, we plan to use the Reynolds-averaged Navier-Stokes (RANS) equations, whereby the molecular viscosity is augmented by a turbulent viscosity computed using the RNG k-\(\varepsilon\) turbulence model. Similarly, turbulent transport of heat is modeled using the turbulent thermal conductivity $k_i$.

- **Governing Equations for the Dispersed Phase (Particle):** Based on the solution obtained for the flow field of the continuous phase, Euler-Lagrangian approach obtains the particle trajectories by solving the force balance of the particles considering the discrete phase inertia, aerodynamic drag, gravity, $g_i$ and further optional user-defined forces, $F_{xi}$ such as cohesive, normal and tangential forces,

  \[
  \frac{du_{pi}}{dt} = C_D \frac{18 \mu}{\rho_p d_p^2} \frac{Re(u_i - u_{pi})}{24} + g_i \frac{\rho_p - \rho}{\rho_p} + F_{xi} \tag{4}
  \]

  The relative Reynolds number, $Re$ is computed as

  \[
  Re = \frac{\rho d_p (u_p - u)}{\mu} \tag{5}
  \]

  Where, $u_p$ is the particle velocity, $C_D$ is the drag coefficient, $d_p$ is the particle diameter, $\mu$ is the air viscosity, $\rho_p$ is particle density.

- **Heat and Mass Transfer Between the Two Phases (air and particle):**

  The rate of vaporization

  \[
  N_i = h_i (C_{i,s} - C_{i,\infty}) \tag{6}
  \]

  The heat transfer between the particle and the hot air

  \[
  m_p c_p \frac{dT_p}{dt} = h A_p (T_\infty - T_p) + \frac{dm_p}{dt} h_{fg} \tag{7}
  \]
Where, $N_i$ is the molar flux of vapor, $h_c$ is the mass transfer coefficient, $C_{i,s}$ and $C_{i,\infty}$ are the vapor concentration at the particle surface and in the hot air, $m_p$ is the mass of the particle, $c_p$ is the specific heat capacity of the particle, $T_p$ is the temperature of the particle, $h$ is the heat transfer coefficient, $A_p$ is the surface area of the particle, $T_{\infty}$ is the drying air temperature, $h_{fg}$ is the latent heat of vaporization.

**Numerical Method:** An unstructured solution-adaptive finite volume scheme will be used to solve the governing equations. The domain is discretized in convex unstructured polyhedral control volumes. The governing equations are integrated over the control volume and yield a balance of convective and diffusive fluxes, storage and generation. Second-order discretization schemes are used for both temporal and spatial discretization. The resulting (nominally) linear set of algebraic equations is solved using an algebraic multigrid scheme.

**CFD Model Simulation Experiments and Validation:**
CFD modeling will provide a detailed description of the transport processes (heat, mass, momentum). CFD model will be developed by the graduate student beginning in June 2008 with assistance from a Purdue University post-doctoral research assistant (Teshome Jiru) to provide quantitative information of the DDGS drying process in rotary drum dryers. Completion and verification of the model is expected by December 2008. Validation utilizing the extensive data set obtained for the seven monitoring strategies under Objective 1 will be completed by March 2009. Extensive simulation experiment using a broad range in process conditions for which experimental performance data was not available will be undertaken between April and June 2009. The simulation experiment will be done for three drying air temperature ranges: normal 800–900°F, low 650-750°F and high 950 -1050°F.

**Process Optimization:**
The CFD simulation date provides generally information of the drying process. Optimal values of the process variables should be identified, which can be accomplished by using an optimization function. The detailed data obtained from CFD simulation will be used to produce optimization function using the response surface method (RSM). RSM is combination of statistical and mathematical technique used in study of the relationships and optimization in which large number of variables influence a dependent variable or response (Myers and Montgomery, 1995). RSM allows finding optimal process conditions by combining a smaller number of input variables, $X_i$ on which the output variable $Y$ depends. The functional relationship between the response and the levels of inputs can be written as:

$$Y = f(X_1,\ldots ,X_n)$$  \hspace*{1cm} (8)

The functional relationship is not easy to establish, hence first or second order polynomial approximations are usually adapted (Pelegrina et al. 2002):

$$Y = b_0 + \sum_{i=1}^n b_i X_i + \sum_{i=1}^n b_{ii} X_i^2 + \sum_{i=1}^n \sum_{j=i+1}^n b_{ij} X_i X_j$$  \hspace*{1cm} (9)

The DDGS moisture content is affected by drying air condition (temperature, $T$, velocity, $v$, relative humidity, $H$), feed moisture content, $MC_f$ (affected by the amount of
DDGS, CDS, DWG in the feed), dryer rotational speed, $\omega$ and drying time, $\tau$. For a given strategy only $T$, $H$, and $\tau$ are varied, the other variables being kept constant, and $n = 3$. To find the optimal strategy among the seven strategies, $MC$, $\tau$, will vary and the other variables will be kept constant, and $n = 2$.

The optimization model will be developed by the graduate student beginning in July 2009 to find optimal operating conditions based on the key process variables. The optimization model of the rotary drum dryer has the potential to become a process control model. Once calibrated using output from the validated CFD model, it will be employed in August through October 2009 to produce optimal values of drying air temperature, humidity and residence time, DDGS recycle ratio, and to develop a model-based control system for the dryer. The control system can be incorporated into current automated monitoring system. The simulation results obtained during this period will be summarized in a final project report that the PIs will use to develop a final set of process improvement recommendations. The PIs will also explore and discuss with the plant manager and company engineers the possibility of incorporation of the process optimization model into the existing process automation and control system of The Andersons Clymers Ethanol Plant. Collaboration

We will be working closely with staff of The Andersons Clymers Ethanol Plant at Chalmers, IN during the entire project (see enclosed letter of cooperation and support). Their willingness to collaborate and provide access to the plant for performance monitoring and sample collection is absolutely unique and will result in benefiting the U.S. ethanol industry as-a-whole.

**Anticipated Results**

The primary anticipated results from this project are two-fold: (1) a set of practical process improvement recommendations regarding energy efficiency and coproduct quality for dry-grind ethanol plants; (2) a DDGS rotary dryer process optimization model that can be used by plant operators and engineers to evaluate possible combinations of key process parameters; and (3) a DDGS rotary dryer process optimization model that could potentially be incorporated into the existing process automation and control system of a dry-grind ethanol plant. These anticipated results would benefit the dry-grind ethanol industry in the NC-213 states by improving DDGS quality, increasing energy savings, and lowering drying costs.

**Time Table**

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<tr>
<th>Objective</th>
<th>Task</th>
<th>Time Frame</th>
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Literature Cited


## Budget Narrative

The funds requested will primarily be used to support a half-time graduate student with a stipend of $19000 per year and tuition of $6000 per year for the two years of this project. This project will be leveraged by 10% of the time of a post-doctoral research assistant (Teshome Jiru) who is currently a staff at Purdue University on a separately funded project. He will work closely together with the graduate student. This project will be further leveraged by materials and supplies that are currently available through the college-wide DDGS project at Purdue University. Leverage funds are estimated to be valued at $25000 for the duration of this project.

### Budget

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Figure 1. Process flow diagram for a typical dry-grind corn-to-ethanol plant (Rausch and Belyea, 2006).
Figure 2. Inside view of a rotary drum dryer showing the arrangement of the flights (top) and the cascading of product due to the flighting (bottom) (Savaresi et al. 2001).
Maier, Ileleji and Jiru. 2007. Evaluating Energy Efficient Strategies and Product Quality for DDGS in Dry-Grind Ethanol Plants

**Key:**
- DWG - Distillers Wet Grains;
- CDS - Condensed Distillers Solubles;
- DDGS - Distillers Dried Grains with Solubles;
- -RB - Recycle from Dryer B
- MC - Moisture Content
- R - Ratio of product in blend
- -RA - Recycle from Dryer A

Figure 3. Sample coproduct flow through a typical series of two rotary dryers in a dry-grind corn-to-ethanol plan.
APPENDIX A
Continuous Direct-Heat Rotary Dryers

100.0 PURPOSE AND SCOPE

101.0 Purpose

The purpose of this procedure is to suggest a method for conducting performance tests on continuous direct-heat rotary dryers.

101.2 Reasons for conducting performance tests on commercial-size dryers may be:

- To measure the performance of the dryer under typical operating conditions;
- To determine optimum dryer capacity under existing operating conditions;
- To study alternative operating conditions for increasing dryer capacity and performance;
- To provide a record for future troubleshooting;
- To gather data for design of new dryers of different capacities, or dryers for similar products;
- To study specific dryer characteristics that may affect product quality, e.g., speed, slope, rotation, temperature profile, active loading, and calculated factors, such as the volumetric heat transfer coefficients;
- To determine a desirable operating range for routine control of the dryer and the thermal sensitivity of materials;
- To determine the optimum operating conditions for cost-effectiveness, fuel conservation, and minimum environmental impact, and
- To study the specific drying characteristics that determine product quality, e.g., residence time, temperature profile, etc.

101.3 Although this procedure could be used as a guide for designing tests to demonstrate dryer capacity under manufacturers' performance guarantee conditions, it is not intended for this purpose, nor is this procedure adequate to serve as a basis for a performance guarantee. For example:

1) This procedure does not set limits or acceptable deviations between pilot plant test results or manufacturers' predictions and commercial results.
2) It does not address material handling questions, nor feed properties and uniformity, other than those of feed rate and moisture content.
3) It does not set standards for fabrication quality and mechanical performance.
4) Moreover, for any specific product, there may be particular temperature or moisture measurements, sampling techniques, and quality requirements other than dryness which should be included in performance specifications.
AIChe Equipment Testing Procedure

102.0 Scope
This procedure applies to continuous direct-heat rotary dryers (see Section 202.8) in which a wet material being dried is conveyed by slope and rotation of an essentially horizontal cylinder. Material movement is also either slightly enhanced or impeded by a stream of gas flowing through the cylinder, depending on the material and the flow direction of the gas stream. The gas stream is usually the sole external source of thermal energy for material heating and liquid vaporization, and is also the carrier gas for removing evolved vapors from the cylinder. Gas flow direction may be either co-current with, or counter-current to, material flow. This procedure excludes situations in which fuel enters with the material and is burned, i.e., the de-oiling of metal chips, turnings, and borings. It also excludes coating operations and special situations, such as drying of sugars and other materials that may change chemical characteristics on being heated. Schematically, the flows are as indicated in Figure 1.

102.2 This procedure is primarily intended for continuous direct-heat rotary dryers in which both gas and material flow are end-to-end of the dryer cylinder, and in which heat is transferred primarily by convection from hot gases to wet materials.

102.3 This procedure is not intended for any form of indirect-heat rotary dryers, or other types of dryers, such as flash dryers, freeze dryers, vacuum pan dryers, paddle dryers, or high temperature calciners and kilns, where radiation is the primary heat transfer mode.
200.0 DEFINITIONS AND DESCRIPTIONS OF TERMS

201.0 Dryer Description (see Figure 1)

Figure 1: Counter-Flow Rotary Dryer

201.1 A continuous direct-heat rotary dryer consists of a rotating cylinder, which may be slightly inclined to the horizontal to promote or retard material flow. The inside of the cylinder may be fitted with material conveying flights and lifting flights of various forms designed to lift and shower the material through the gas stream as both material and gases move through the cylinder, thus enhancing intimate gas-solids contact. The ends of the rotating cylinder are joined to stationary breechings that connect to the gas supply and exit gas ducts, the material feed, and product conveyors. The annular clearances between the ends of the rotating cylinder and stationary breechings are enclosed by fabric, friction, or labyrinth rotary seals in order to minimize the effect of air leakage on the operating conditions. Figure 1 is an illustration of a typical continuous direct-heat rotary dryer. A sketch of a typical dryer system is shown in Figure 2.
202.0 Description of Terms

202.1 Cylinder material fillage is a ratio of volume of material in the dryer to the total volume of the dryer. See paragraph 404.4 for discussion of the application of this ratio.

202.2 Drying is an operation in which a liquid is separated from a solid or a semi-solid material by vaporization of the liquid.

202.3 Dehydration refers to the drying of vegetable and animal products to less than their natural moisture contents, and to the removal of water of crystallization from chemical compounds. The following terminology is commonly employed for various drying and dehydration processes.

202.4 Bound moisture is liquid held by a material in such a mechanism that the liquid exerts a lower than normal vapor pressure at the same temperature. Liquid may be bound by solution in cell or fiber walls, homogeneous solution throughout the material, and by chemical or physical adsorption on solid surfaces. The fraction of bound moisture that can be removed depends on the specific conditions of humidity, temperature in the external surroundings, gas flow rate, and residence time in the dryer.

202.5 Capillary flow is flow of liquid through the interstices and over the surfaces of a solid, caused by liquid surface tension resulting from liquid-solid molecular attraction.

202.6 Constant-rate period is the drying period during which the rate of liquid removal per unit of material surface, and per unit of time, is constant.

202.7 Critical moisture content is the moisture content at which the constant-rate period ends and the falling-rate period begins.

202.8 Direct-heat dryer is one type of drying equipment in which heat is transferred to the material being dried by direct contact with the heating medium. Usually, the heating medium is a hot gas and the heat transfer mechanism is convection.

202.9 Dry basis expresses the moisture content of a wet material as the weight of moisture per unit weight of dry material. The advantage of using this basis is that the moisture change per unit weight of dry material is obtained simply by subtracting the moisture content before and after drying.

202.10 Dryer efficiency is the fraction of the supplied thermal energy used to heat the material and liquid to evaporation temperature, to vaporize the liquid, and to heat the vapor and the material to their dryer exit temperature.

202.11 Equilibrium moisture content is the ultimate moisture content to which a given material can be dried under specific conditions of gas temperature, constant gas flow, and humidity.
Continuous Direct-Heat Rotary Dryers

202.12 Leoporous efficiency of the gas stream flowing through a direct-heat dryer compares the amount of evaporation actually obtained to the amount which would be obtained if the gas stream were saturated adiabatically before leaving the dryer.

202.13 Falling-rate period is a drying period during which the drying rate per unit of material surface continually decreases. It can also be thought of as the condition where the diffusion rate of moisture within the solid particle towards the surface is less than the evaporation rate at the surface. See Figure 3 below for a graphic representation of these drying phases.

![Diagram](image)

Figure 3: Drying Rate as a Function of Drying Time

202.14 Fiber saturation point is the measure of bound moisture content of a cellular material, such as wood, at which the cell walls are completely saturated, while the intercellular spaces remain liquid free. It is the equilibrium moisture content occurring when the humidity of the surrounding atmosphere approaches saturation.

202.15 Flash dryer is one in which the material to be dried is carried pneumatically in a hot gas stream through the body of the dryer. The product is in contact with the gas stream for only a short time but this feature makes it possible to situate the dryer close to the rest of the process equipment.

202.16 Free moisture content is the measure of liquid content that is removable at a given temperature and humidity. Free moisture may include both bound and unbound moisture, and is equal to the total average moisture content of the material minus the equilibrium moisture content for the prevailing conditions of drying.
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202.17 Funicular state is the condition that occurs while drying a porous body when capillary action causes air to be drawn into the pores to replace evaporated moisture.

202.18 Humidity denotes the amount of condensable vapor present in a non-condensable gas, and is usually expressed as weight of condensable vapor per unit weight of dry gas.

202.19 Indirect-heat dryer is one type of drying equipment in which heat is transferred primarily by conduction and radiation, and the heating medium is physically separated by a wall from the material being dried.

202.20 Internal diffusion occurs in a material during drying when liquid or vapor flow appears to obey the fundamental laws of diffusion.

202.21 Material retention time is a measure of the time it takes for product to flow through the dryer. See Section 404.4 for the measurement procedure.

202.22 Moisture content of a material is the moisture quantity per unit weight of dry or wet solid.

202.23 Moisture gradient refers to the moisture profile of a material at a given moment during a drying process. The nature of the moisture gradient depends on the mechanism of moisture flow inside the material.

202.24 Penultimate state is the state of liquid in a porous body when a continuous film of liquid no longer exists around and between discrete particles, so that flow by capillarity cannot occur. This state follows the funicular state in a drying process.

202.25 Percent saturation of a gas containing a condensable vapor is the ratio of the partial pressure of the condensable vapor to the vapor pressure of the pure vapor at the same temperature, expressed as a percentage. For water in air, this is also called percent relative humidity.

202.26 Unaccomplished moisture change refers to the ratio of free moisture present at any time to that initially present.

202.27 Unbound moisture in a hygroscopic material is the moisture in excess of the equilibrium moisture content corresponding to saturation humidity in the surrounding atmosphere. All water in a non-hygroscopic material is unbound moisture.

202.28 Volumetric heat transfer is a parameter used to assess heat transfer efficiency of the dryer. See Section 702.0 for a discussion of this parameter.

202.29 Wet basis expresses the moisture content of a wet material as the ratio of moisture to the weight of moisture and dry solids.
Continuous Direct-Heat Rotary Dryers

300.0 TEST PLANNING

301.0 Conditions

301.1 Safety
Any equipment testing must conform to the latest requirements of all applicable safety standards. These include, but are not limited to, plant, industry, local, state, and federal regulations. It is recommended that all testing be conducted under the supervision of personnel fully experienced in plant and equipment operating practices.

During test planning stages, a thorough safety hazards review of the test program and procedures should be completed, and all necessary steps carried out to ensure safe equipment operation, and the safety of all personnel involved, or that could potentially be exposed. Special care and study must be given to tests and equipment involving flammable vapors and/or flammable or explosive dust.

301.2 Environmental
The test procedure must conform to the latest requirements of all applicable environmental standards, including plant, industry, local, state and federal regulations. Environmental standards that apply to the equipment in normal operation should also apply during testing.

301.3 Liability
See statement on the copyright page at the front of this book.

302.0 Dryer Material and Heat Balances

302.1 The performance capability of a continuous direct-heat rotary dryer can be demonstrated only under conditions of steady-state flow of material and gas. For steady-state conditions, the feed material rate, moisture content and temperature, gas velocities, temperatures, and humidities in and out of the dryer cylinder; and product rate, moisture content, and temperature must remain essentially constant during the test period. Cylinder rotation speed and cylinder slope must also remain constant during the test.

302.2 During the test, gas and material temperatures, moisture contents, flow rates, total heat input to the dryer, and heat losses from the dryer cylinder and breechings must be measured. It is necessary to record the quantity of dust, and its temperature and moisture content, separately from the cylinder product because the temperature of dust conveyed to the dust recovery or off-gas treatment equipment is usually the same as the cylinder exhaust gas temperature, but may be different from the temperature of the cylinder discharge product. There may also be a difference in material moisture contents. Without an accounting of material division, a material balance on moisture content, and an accurate accounting of heat consumed as sensible heat in the material, is not possible.
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302.3 Particle size distribution analyses should be made of the feed, product, and entrained dust materials, so that a reasonable gas velocity, and thus heat input, can be established for the dryer test. If the velocity is too high, too much product may be carried out of the dryer as dust into the dust recovery equipment. This product may or may not be fully dry, and thus may not be suitable for mixing with the main cylinder product. If the gas velocity is too low, dryer performance will be negatively affected, since the feed rate will have to be adjusted to match the incoming heat. Thus, knowing the size distribution of the incoming feed material will enable an adjustment and prediction of the gas velocity and the amount of dust which will be blown to the collectors.

302.4 In order to evaluate a dryer thoroughly, all systems, including the feed, air heater, dust collection, and instrumentation should be inspected as part of the test preparations, and verification should be made that each system is working correctly and according to its respective specification.

302.5 Because most measurements made on commercial size, continuous direct-heat rotary dryers are susceptible to human, instrument, and analytical errors, and because small but uncontrollable variations usually occur in material flow, gas flow, temperature and moisture contents during the performance test, heat and material balances should be compared to assure that results are consistent among themselves. The balances to be obtained are as follows:

302.5.1 Moisture Balance:

\[
\text{(feed moisture content)} - \text{(product moisture content)} + \text{(dust moisture content)} = \text{(evaporation)}
\]

[measure moisture on these materials by usual methods]

302.5.2 Solids Balance:

\[
\text{(dry material flow in)} = \text{(dry material flow out), i.e., the sum of dryer product discharge + dust recovery + hang-up in the dryer, if any} + \text{leaves from system} \pm \text{back-spillage}
\]

[calculate a solids material balance around dryer system after weighing product, dust recovered, any hang-up in the dryer, and total dry feed material put into the dryer, using measured moisture contents. Dryer hang-up can be any material stuck or wedged somewhere in the dryer, between the lifting flights, in the spiral flights, etc., because it is sticky, wet, or fused, and has not broken loose to mingle with the rest of the material progressing through the dryer. Such hang-up should be physically removed and weighed. Back-spillage is feed material that spills back out over the retaining dam of the dryer cylinder at the feed point due to overfeeding, overloading, and sticking]
Continuous Direct-Heat Rotary Dryers

302.5.3 Dry Gas Balance:
(dry gas flow in) = (dry gas flow out)
[measure gas velocity and humidity of in/out gases]

302.5.4 Humidity Balance:
(evaporation) + (moisture from fuel combustion) =
(gas stream humidity gain)

302.5.5 Heat Balance:
(heat gained by the gas through the heater) = (heat provided by fuel burned or from other heat source)
[use weight or volume of fuel burned and calorific value]

302.5.6 Dryer Gas Heat Balance:
(heat lost by gas through the dryer) = (material sensible heat gain) +
(vapor sensible heat gain) + (heat of evaporation) + (dryer heat losses)
[measure product and dust temperatures, solids balance, calculate total evaporation, and estimate heat losses by calculating from dryer breeching/duct surface temperatures and areas]

302.6 In order to complete these balances, all of the following data should be obtained during the test. Data units cited are SI, but any consistent system may be employed. See Figures 1 and 2:

- Dry feed rate [kg/s]
- Cylinder product rate [kg/s]
- Recovered dust rate [kg/s]
- Feed moisture content [kg/kg] (dry basis)
- Product moisture content [kg/kg] (dry basis)
- Dust moisture content [kg/kg] (dry basis)
- Feed temperature [K]
- Product temperature [K]
- Recovered dust temperature [K]
- Inlet gas flow [m³/s]
- Inlet gas temperature (ambient) [K]
- Inlet gas humidity [kg/kg]
- Heated gas temperature [K]
- Fuel consumption [kg/s]
- Fuel heating value [kJ/kg]
- Fuel carbon/hydrogen content [kg/kg]
- Alternative steam or electricity used [kg/s] or [kW]
- Alternative steam latent heat value [kJ/kg]
- Cylinder, breechings, ducts, and cyclone surface temperatures [K]
- Cylinder exit gas temperature [K]
- Cyclone exit gas temperature [K]
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- Exhaust fan temperature [K]
- Exhaust fan humidity [kg/kg]
- Exhaust fan flow [m³/s]
- Exhaust fan speed [s⁻¹]
- Exhaust fan static pressure [Pa]
- Exhaust fan power consumed [kW]
- Supply fan temperature [K]
- Supply fan humidity [kg/kg]
- Supply fan volume [m³/s]
- Supply fan speed [s⁻¹]
- Supply fan static pressure [Pa]
- Supply fan power consumed [kW]
- Cylinder rotational speed [s⁻¹]
- Cylinder slope in material direction [±m/m]
- Cylinder drive power used [kW]
- Feed breeching static pressure [Pa]
- Feed breeching leakage rate [m³/s]
- Product breeching static pressure [Pa]
- Product breeching gas leakage rate [m³/s]
- Material retention time [s]
- Cylinder material fillage [kg]
- Feed bulk density [kg/m³]
- Product bulk density [kg/m³]
- Cyclone pressure drop [Pa]
- Entrained dust bulk density [kg/m³]

Figure 4 shows a sample test data sheet.
### Continuous Direct-Heat Rotary Dryers

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### Surface Temperatures:
- Cylinder: °C
- Exhaust Ducts: °C
- Cyclone: °C
- Feed Breeding: °C
- Discharge Breeding: °C
- Exit Gas Temperature: °C
- Cyclone Exit Gas Temperature: °C
- Exhaust Fan Temperature: °C
- Exhaust Fan Humidity: kg/kg
- Exhaust Fan Volume: m³/s
- Exhaust Fan Static Pressure: Pa
- Exhaust Fan Power Consumption: kW

Figure 4: Rotary Dryer Test Data Sheet (continued on next page)
## AlChE Equipment Testing Procedure

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<td>m³/s</td>
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<td>Product Breach, Static Pressure</td>
<td>Pa</td>
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<td>Retention Time</td>
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<tr>
<td>Product Bulk Density</td>
<td>kg/m³</td>
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<tr>
<td>Cyclone Dust Bulk Density</td>
<td>kg/m³</td>
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<tr>
<td>Cyclone Pressure Drop</td>
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*Figure 4: Rotary Dryer Test Data Sheet (Continued)*
LETTER OF SUPPORT
Fax Transmission

To: Dirk Maier

Fax #: ______________________________

Phone #: ______________________________

From: Mike Myrick

Date: 8-30-07

Number of pages including this one: 2

If you do not receive all pages, please contact:

The Andersons
3324 S. 325 W.
Logansport, IN 46947

Phone #: 574-722-2627
Fax #: 574-732-1916

Subject: ______________________________

Special Instructions: ______________________________
To: Dr. Dirk E. Maier, Director  
Post-Harvest Education & Research Center  
Purdue University  

Re: Evaluating Energy Efficiency Strategies and Product Quality for Distillers' Dried Grains with Solubles (DDGS) in Dry-Grind Ethanol Plants

Our company, The Andersons, supports the goal of Purdue University faculty to evaluate energy saving and quality improving strategies during the DDGS drying operation, fluid-solid transport modeling and process optimization coupled with on-line performance monitoring of rotary dryers in dry-grind ethanol processing plants. We are interested and willing to have researchers conduct on-line monitoring of and sample collection from the rotary drum dryers in our Clymers ethanol plant.

Our company currently operates two dry-grind corn-to-ethanol plants (Albion, Michigan; Clymers, Indiana) and is in the process of constructing a third one in Greenville, Ohio. Our grain handling, ethanol processing and plant nutrient distribution plants are in NC-213 states (Ohio, Michigan, Indiana and Illinois).

Therefore, we are excited about the potential findings of this proposed research especially if it will lead to energy savings in the DDGS drying process and potentially result in optimized process control for our and other dry-grind corn-to-ethanol plants. We look forward to our collaboration with Purdue’s Post-Harvest Education & Research Center.

Sincerely,

Mike Myrick, Plant Manager  
The Andersons Clymers Ethanol Plant