ANNOUNCEMENT

PART I: STI PRODUCT DESCRIPTION (To be completed by Recipient/Contractor)

A. STI Product Identifiers

1. REPORT/PRODUCT NUMBER(s)
DOEGO11037-1

2. DOE AWARD/CONTRACT NUMBER(s)
DE – FG36 – 01GO11037

3. OTHER IDENTIFYING NUMBER(s)

B. Recipient/Contractor

Shivvers, Inc. Corydon, Iowa

C. STI Product Title

Development of a Energy Saving Grain Drying Invention

D. Author(s)

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E. STI Product Issue Date/Date of Publication

9/30/2005 (mm/dd/yyyy)

F. STI Product Type (Select only one)

- ☒ 1. TECHNICAL REPORT
☒ Final ☐ Other (specify) _____
- ☐ 2. CONFERENCE PAPER/PROCEEDINGS
Conference Information (title, location, dates)

- ☐ 3. JOURNAL ARTICLE
a. TYPE: ☐ Announcement Citation Only
☐ Preprint ☐ Postprint
b. JOURNAL NAME

c. VOLUME _____ d. ISSUE _____
e. SERIAL IDENTIFIER (e.g. ISSN or CODEN)

☐ OTHER, SPECIFY

G. STI Product Reporting Period (mm/dd/yyyy)

4/01/2001 Thru 7/31/2005

H. Sponsoring DOE Program Office

Golden Field Office

I. Subject Categories (list primary one first)

Energy Conservation, Consumption & Utilization

Keywords: Grain Drying, Energy Saving

J. Description/Abstract

Please see attached document

K. Intellectual Property/Distribution Limitations

(must select at least one; if uncertain contact your Contracting Officer (CO))

- ☒ 1. UNLIMITED ANNOUNCEMENT (available to U.S. and non-U.S. public; the Government assumes no liability for disclosure of such data)
- ☐ 2. COPYRIGHTED MATERIAL: Are there any restrictions based on copyright? ☐ Yes ☐ No
If yes, list the restrictions as retained in your contract
- ☐ 3. PATENTABLE MATERIAL: THERE IS PATENTABLE MATERIAL IN THE DOCUMENT
INVENTION DISCLOSURE SUBMITTED TO DOE:
DOE Docket Number: S-
(Sections are marked as restricted distribution pursuant to 35 USC 205)
- ☐ 4. PROTECTED DATA: ☐ CRADA ☐ Other
If other, specify
Release date (mm/dd/yyyy) _____
- ☐ 5. SMALL BUSINESS INNOVATION RESEARCH (SBIR) DATA
Release date (Required, _____
(No more than 4 years from date listed in part 1.E above)
- ☐ 6. SMALL BUSINESS TRANSFER (STTR) DATA
Release date (Required, _____
No more than 4 years from date listed in part 1.E above)
- ☐ 7. OFFICE OF NUCLEAR ENERGY APPLIED TECHNOLOGY

L. Recipient/Contractor Point of Contact Contact

for additional information (contact or organization name to be included in published citations and who would receive any external questions about the content of the STI Product or the research contained therein)

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ANNOUNCEMENT

PART II: STI PRODUCT MEDIA/FORMAT and LOCATION/TRANSMISSION

(To be completed by Recipient/Contractor)

A. Media/Format Information:

1. MEDIUM OF STI PRODUCT IS:
☒ Electronic Document ☐ Computer medium
☐ Audiovisual material ☐ Paper ☐ No full-text
2. SIZE OF STI PRODUCT 13 pages
3. SPECIFY FILE FORMAT OF ELECTRONIC
DOCUMENT BEING TRANSMITTED, INDICATE:
☐ SGML ☐ HTML ☐ XML ☒ PDF Normal ☐ PDF Image
☐ WP-Indicate Version (5.0 or greater) _____
Platform/operating system _____
☐ MS-Indicate Version (5.0 or greater) _____
Platform/operating system _____
☐ Postscript _____
4. IF COMPUTER MEDIUM OR AUDIOVISUAL
 - a. Quantity/type (*specify*) _____
 - b. Machine compatibility (*specify*) _____
 - c. Other information about product format a user
needs to know: _____

B. Transmission Information:

STI PRODUCT IS BEING TRANSMITTED:

- ☒ 1. Electronic via Elink
- ☐ 2. Via mail or shipment to address indicated
in award document (*Paper products,
CD-ROM, diskettes, videocassettes, et.*)

☐ 2a. Information product file name
(*of transmitted electronic format*)
050930 Energy Saving Grain Drying Report

PART III: STI PRODUCT REVIEW/RELEASE INFORMATION

(To be completed by DOE)

A. STI Product Reporting Requirement Review:

- ☐ 1. THIS DELIVERABLE COMPLETES ALL
REQUIRED DELIVERABLES FOR THIS AWARD
- ☐ 2. THIS DELIVERABLE FULFILLS A
TECHNICAL REPORTING REQUIREMENT,
BUT SHOULD NOT BE DISSEMINATED
BEYOND DOE.

B. DOE Releasing Official

- ☐ 1. I VERIFY THAT ALL NECESSARY
REVIEWS HAVE BEEN COMPLETED AS
DESCRIBED IN DOE G 241.1-1A, PART II,
SECTION 3.0 AND THAT THE STI
PRODUCT SHOULD BE RELEASED IN
ACCORDANCE WITH THE INTELLECTUAL
PROPERTY/DISTRIBUTION LIMITATION
ABOVE.

Released by (*name*) _____

Date _____
(mm/dd/yyyy)

E-mail _____

Phone _____

DEVELOPMENT OF AN ENERGY-SAVING GRAIN DRYING INVENTION

DE-FG36-01GO11037

Final Report
October 4, 2005

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1. Executive Summary

A grain drying process that recovers a portion of both sensible heat and the latent heat of vaporization from the exhaust air has been developed. The dryer configuration uses parallel flow of air and grain which assures uniform treatment of all of the grain and precise control of maximum kernel temperatures. Compared to conventional dryers, this dryer will provide vastly superior energy efficiencies and grain quality, and superior moisture control capabilities. A conceptual computer model of the process has been developed; a prototype system has been designed, fabricated, and installed but not tested. Project funds have been exhausted and a one-year extension has expired. Shivvers is continuing to develop the process and intends to bring the system to market, provided adequate funding becomes available. Additional funds are being sought.

2. Background information/Problem Identification

The vast majority of the U.S. corn and rice crops are dried with heated air to prevent spoilage.

The most common dryer configuration found on farms and at commercial elevators is the "crossflow" or some variation thereof. In crossflow dryers heated air passes horizontally through a vertical column of grain. The crossflow configuration always results in significant temperature and moisture gradients across the column of grain. Grain at the air inlet is over-dried and excessively heated while grain on the air discharge side of the column retains an elevated moisture content and lower temperature. A cooling section, in which unheated air rapidly lowers the grain's temperature prior to its discharge from the dryer, often follows the heated air section of crossflow dryers. High-temperature drying, followed by rapid cooling, is known to cause stress cracking of kernels, leading to kernel breakage and quality loss. This quality degradation results in economic loss, as well as loss of international market share.

Another popular dryer configuration is an "in-bin counter flow". In these dryers the grain moves downward as the heated air moves upward through the grain bed. Cooling is typically done in long-term storage after the grain exits the dryer.

Drying is energy intensive, using over 1/3 of the energy required for corn production¹. The energy used to dry the grain far exceeds theoretical requirements to evaporate the water (i.e. 2400 - 2800 Btu/lb. for typical crossflow dryers vs. 1160 Btu/lb. theoretical.)

Drying of the 9.3 billion bushel U.S. corn crop typically consumes 882.4 million gallons of propane and over 3,230 million kilowatt hours of electricity resulting in the release of over 1.98 million tons of CO₂ annually. Drying of the 180 million cwt. rice crop consumes an additional amount.

¹ Hansen, R.C., M.A. Berry, H.M. Keener, R.J. Gustofson. 1996. "Current grain drying practices in Ohio." App. Eng. In Agric., 12(1):65-69.

In contrast to crossflow drying, this new, innovative grain dryer provides vastly superior energy efficiencies and grain quality, and superior moisture control capabilities. The new drying system has the potential to reduce energy use by more than 60% to less than 1160 Btu/lb by utilizing the recapture of latent heat from the exhaust air stream. In addition, the configuration uses parallel flow of air and solid streams to provide gentle and uniform treatment of the grain. Each kernel receives identical treatment through the process with carefully controlled maximum temperatures and final moisture content.

Advantages over in bin counter flow dryers are superior energy efficiencies and higher capacity models.

3. Goals and Objectives

Goal: To develop the world's best grain dryer, where best is defined in terms of energy efficiency, grain quality protection, and minimal environmental impact.

In order to achieve maximum efficiency in the use of heat supplied to the innovative dryer, several goals needed to be achieved:

- Most of the heat should be utilized as latent heat to evaporate moisture.
- Drying should occur on the steeper portion of the drying rate curve.
- The air should be nearly saturated with water as it is discharged from the drying system.
- As much latent heat as practical should be recaptured by some means.

The objective of this project is to design, build, and test an innovative grain dryer which uses far less energy than conventional grain dryers because it reclaims sensible heat and latent heat. In addition, the innovative dryer will provide gentle and uniform treatment of grain so as to maintain grain quality. The innovative dryer will possess these attributes and yet will be moderately priced, compared to conventional dryers.

4. Comparison of Accomplishments with Original Goals and Objectives

The drying system process has been simulated, the mechanical design for a prototype was completed, and the prototype has been fabricated. Delays occurred and the project schedule was extended. Mechanical problems plagued startup and the system has yet to be fully run in order to validate the process design in spite of the project time extension. Although the simulation has not been validated with the physical demonstration and the control system has not been optimized, we continue to believe that the project is sound and the goal can be accomplished with additional engineering effort and funding.

The process is designed to achieve the goals of assuring that most of the heat input to the system is utilized as latent heat for evaporation. Heat which leaves the drying chamber as sensible heat of the moist air is reclaimed. Then, additional heat is reclaimed via condensation of water vapor from the exhaust air stream (recapture of latent heat). The conceptual process model shows that an optimized control system can maintain the desired degree of saturation of the exhaust air. Only the initial drying will occur on the steep portion of the drying rate curve as there are no steeping

sections in the prototype design. The process model shows net energy use well below 1160 Btu/lb. of water removed.

The process and mechanical design achieves the objective of gentle and uniform treatment of the grain during the drying process. This assures preservation of grain quality through the drying process.

The ownership cost of the commercial product will be competitive with systems of similar capacity.

5. Summarize Project Activities

Note: All Task Numbers in this section refer to the original List of Tasks in the original grant application. Numbers of some tasks have been reassigned in later editions of progress reports.

Task 1 was to optimize design of the process via computer simulations. This work led into the final multi-stage process design that includes a proprietary component that circulates through all five stages. Due to the circulation of this material, it became essential that the non-steady-state models of each successive stage be married into one overall system simulation. This simulation task took much longer than originally planned.

The models, as discussed in section 7 below, apply numerical solution techniques to systems of simultaneous non-linear partial differential equations that describe the theory of heat and mass (moisture) transfer among process streams. Several of the process stages are counterflow configurations resulting in two-point boundary value problems. Successful numerical solution of such systems of equations is highly sensitive to the selection of time and distance (volume) step-sizes. Marriage of successive stage processes and the transient nature of the problem lead to the necessity of using the smallest time step-size, or a multiple thereof, throughout all stages. Moreover, conservation of mass requires careful selection of distance (volume) step-sizes relative to material velocity so that inflows and outflows are exact matches from stage to stage.

The models indicate a very high moisture transfer rate in the stage where heat is reclaimed. This requires very small step-sizes in this stage and consequently extremely computationally intense programs.

It was impossible to proceed with mechanical design (Task 2) until firm process parameters were established either by simulation or a complex series of bench scale experiments. As this project requires freshly harvested high-moisture grain, and such grain is only locally available during a relatively short time period during harvest season in early fall, any delayed milestone can force the project into the next crop production cycle.

Delays in system process design optimization resulted in the need to reconfigure both the project budget and timeline. Intensive mechanical design and fabrication did not begin until spring of 2003. At this same time, it was determined that a combination of our existing Command Center computerized control system could be modified to assist manual control of the prototype dryer system (Tasks 3 & 4). Nevertheless,

Prototype Mechanical Design (Task 2); and Fabrication of Prototype (Task 5); were not accomplished in time for the 2003 harvest season. A one year extension was requested and granted.

Fabrication of Prototype (Task 5), and Prototype Testing (Task 6) continued throughout 2004 and the system was ready for testing near the end of harvest in November, 2004. Unfortunately, mechanical functioning problems prevented full system startup. As these problems were being addressed, winter weather set in making site work impossible. Work resumed in testing the mechanical operation of various components (Prototype Testing, Task 6), in Design Improvement (Task 8), and in Prototype Modification (Task 9) in 2005 when temperatures warmed above 32°F. Figures 1 and 2 depict views of the installed prototype drying system.

Significant design problems were encountered in the filling process and sealing system for the heat reclamation section. Unanticipated mechanical failures occurred in portions of the material handling apparatus. Unresolved problems were encountered in the material separation apparatus. Most but not all of these problems have been solved and we are confident that all can be solved given the time and funds to do so.

Shivvers has continued development work and as of September 1, 2005 has expended \$280,000 in excess of its originally budgeted portion of \$40,000 on this project. Work has now ceased until additional funding becomes available.

With the expiration of the project time extension and expenditure of all funds, Shivvers has been asked to submit this Final Report. Shivvers is committed to finding such additional funding as may be necessary to carry the project forward and to ultimately commence commercial production.

Figure 1. Experimental dryer, looking west.

Figure 2. Experimental dryer, looking east.

6. Identify Products Developed and Technology Transfer Activities:

- a. Publications, conference papers, or other public releases....;**
8-01-05 Confidential Report titled: "Development of an Energy-Saving Grain Drying Invention" for the Center for Advanced Technology Development, Iowa State University (report written to IPRT, an arm of ISU), who partially funded the project
- b. Web site or other Internet sites that reflect the results of this project;**
N.A.
- c. Networks or collaborations fostered;**
N.A.
- d. Technologies/Techniques**
A confidential technique was developed to very efficiently dry particulate material such as grain.
- e. Inventions/Patent Applications**
Patent application(s) are in process.
- f. Other products, such as....software, models,or equipment.**
Prototype equipment was designed and fabricated to accomplish the confidential technique. The prototype system is instrumented for purposes of collection of performance data. Computer programs were developed to simulate the system.

7. Computer model

- a. Model description, key assumptions, version, source and intended use;**
The overall model for the grain drying system is a combination of models for individual stages.

The models for heat and moisture transfer are similar to the MSU Grain Dryer Models published by F.W. Bakker et al. (1974)² as amended for PC execution and adapted to FORTRAN 90 coding conventions. These models are based upon the assumptions:

1. The volume shrinkage of kernels is negligible during the drying process.
2. Thermal radiation is negligible.
3. Temperatures are always greater than the freezing point of pure water.
4. Temperature gradients within individual kernels are negligible.
5. The kernel-to-kernel conduction is negligible.

² Bakker-Arkema, F. W., L. E. Lerew, S. F. DeBoer and M. G. Roth (1974) Grain dryer simulation. Research Report 224. Agricultural Experiment Station, Michigan State University: East Lansing, MI.

6. The airflow and grain flow are plug type and constant.
7. The partial derivatives of air temperature and humidity with respect to time are negligible compared with the partial derivatives with respect to depth.
8. The bin walls are adiabatic, with negligible heat capacity.
9. The heat capacities of moist air and grain are constant during short time periods.
10. The diffusion equation coupled with empirical equations for moisture equilibrium accurately expresses the drying rate.
11. The moisture evaporation takes place at the drying air temperature.

Revision of the equations was required to add the proprietary component.

b. Performance criteria for the model related to the intended use;

The model must converge to steady-state with constant inputs and adequately model non-steady-state behavior when input conditions vary. In addition, the model should indicate the sensitivity of the overall process to the properties of the various components, flow rates, and physical dimensions of the stages. Such information is required for design of optimal mechanical and control systems.

If the model does not predict the actual exact magnitude of each measurable property, the results must accurately illustrate the relative trends of temperatures and moistures with time, depth, and variable inputs.

c. Test results to demonstrate the model performance criteria were met

The model output shows convergence to steady state conditions after about six hours of operation.

Figure 3 shows the cumulative and instantaneous thermal efficiency, expressed as Btu per pound of water removed, during startup of the system. This does not include non-thermal system inputs such as electrical energy to run motors for conveying mechanisms. This graph shows cumulative efficiency better than 700 Btu per pound of water as the system achieves steady-state operation. Instantaneous efficiency is better than 600 Btu per pound of water removed after the grain that first enters the dryer stage at startup reaches the discharge. (Cumulative efficiency will asymptotically approach the instantaneous over time.)

Behavior with transient inputs has not been studied. Only limited sensitivity runs relating to assumed parameter values (such as specific surface areas) were made due to the length of time consumed by model development and the lack of additional project funding for modeling.

The full model and several component models have not been validated by large scale tests. The equipment designed and fabricated under this project has not operated without mechanical breakdown as of the termination date. The project is incomplete.

Results from similar models of grain dryers compared to data from prototype to full-sized facilities have a history of acceptability.

d. Theory behind the model, expressed in non-mathematical terms;

The model works with very small slices of the stage volume perpendicular to the flow direction during a small increment of time. The equations are derived by writing conservation of enthalpy and mass terms plus transfer rate expressions. Conservation requires that transfer of heat and moisture from one combined constituent equals the heat and moisture received by the other combined constituents. Moreover, since the materials are in motion, during any time increment, heat or mass entering the thin slice must equal the heat or mass leaving the slice or the enthalpy or mass within the slice must increase or decrease by the difference.

When properly formulated, one temperature equation and one water content equation for each combined constituent results. Terms within these equations represent the transfer rate expressions for thermal conduction or convection and evaporation or condensation of water. The equations form a system of simultaneous non-linear partial differential equations that must be solved to give temperature and moisture/humidity values at each slice during each time increment.

The equations for water content in the dryer include one that expresses the rate of diffusion of water from within the grain kernels to the surface where the rate of evaporation is a function of the difference between the surface node moisture and the equilibrium moisture content affiliated with the air humidity and temperature.

After one or more time increments, the slice at the air inlet is removed and a new slice is added at the grain inlet. The slice thickness and time increment sizes are adjusted so that the material flow rate can be expressed as a whole number of slices per time increments or one slice per some whole number of time increments. The magnitude of these step-sizes is determined by the relative magnitude of coefficient terms within the equations. If step-size is improperly set, the solution will diverge or oscillate about the true solution—a condition known as mathematical instability.

Figure 3. Thermal Efficiency During Startup

8. Additional research and development required

Additional work is required to overcome mechanical hurdles and achieve data collection from the prototype dryer system in operation. This data will serve to validate the computer model or lead to modifications of the model so that it generates acceptable results.

The computer model, in conjunction with additional data from operation of the prototype, will lead to final specifications for the first commercial demonstration unit.

Mechanical design and fabrication of a commercial demonstration unit will follow.

Sales orders will be accepted following successful operation of the commercial demonstration unit.