Improved Process Control of Industrial Wood Waste Boilers

Award Number DE-FG36-01GO11011

Final Report
for period
6/15/2001 - 6/15/2003

Process Control Solutions, Inc.
P.O. Box 12544
Tallahassee, FL  32317-2544

R. H. (Rick) Meeker, Jr., P.E.
VP / Principal Controls Engineer
(850) 385-5100 ph.
(850) 385-5200 fax
rmeeker@procontrolinc.com
TABLE OF CONTENTS

PROJECT SUMMARY, GOALS AND OBJECTIVES .......................................................... 1

GOAL ......................................................................................................................... 1
BACKGROUND AND SUMMARY ................................................................................. 1
OBJECTIVES ................................................................................................................ 1

VARIANCE FROM PROJECT GOALS ........................................................................... 2

PROJECT RESULTS ................................................................................................... 3

CONTROL PROBLEM CHARACTERIZATION AND SELECTION OF DESIGN APPROACH ................................................................. 3
MODEL DEVELOPMENT AND VALIDATION ................................................................. 5
CONTROLLER DESIGN AND TESTING ........................................................................ 8
SUMMARY AND FOLLOW-UP .................................................................................... 10

COMPLETED MILESTONE TABLE ............................................................................... 12

FINAL GANTT CHART ............................................................................................... 14

ENERGY, WASTE, AND ECONOMIC SAVINGS ....................................................... 15

ENERGY ..................................................................................................................... 15
ENVIRONMENTAL ...................................................................................................... 16
ECONOMIC ................................................................................................................ 16

FUEL/ENERGY SOURCE BTU CONVERSION (TABLE) .............................................. 17

MARKET PENETRATION ESTIMATES / TECHNICAL TRANSFER ACTIVITIES .......... 18

COST SHARING .......................................................................................................... 18

INDUSTRY PARTICIPANTS ......................................................................................... 19

PARTNERS AND CONTRACTORS .............................................................................. 19
Project Summary, Goals and Objectives

**Goal**

This project's principal aim was the conceptual and feasibility stage development of improved process control methods for wood-waste-fired water-tube boilers operating in industrial manufacturing applications (primarily pulp and paper).

**Background and Summary**

Wood-waste boilers have unique process control challenges due to the highly variable nature of the fuel, the boiler design required to burn this type of fuel, and the frequent load swings required to meet changing process steam demands. Despite advances in controls technology and microprocessor-based control systems, these challenges are not being met in any uniformly effective manner in the pulp and paper industry as a whole. To stabilize operation and reduce vulnerability to wood-waste fuel variations, it is common practice to supplement fossil fuels (usually oil or natural gas) and to run excess air at unnecessarily high levels. Additionally, air distribution in the combustion zone, which affects combustion efficiency and, especially, emissions, is rarely optimal.

Improved control methods, algorithms, and models designed specifically for this type of application can potentially improve energy efficiency, fossil fuel conservation, and environmental impact (especially air emissions) across the pulp and paper industry and anywhere wood-waste boilers are in use. With hundreds of these boilers in operation at large pulp, paper, and paperboard mills in the U.S., potential net energy savings through efficiency improvement and reduced fuel consumption are substantial. Achieving a 1% average improvement in boiler thermal efficiency industry-wide, through improved process control, would result in approximately 6.5 – 7.0 trillion BTU’s in energy savings, and corresponding net reductions in emissions. In addition, NOx emissions are reduced by burning less fossil fuel, and by reducing excess air.

There has been very little prior work on advanced control methods for these types of boilers. The conceptual and feasibility stage research funded on this project involves development of a dynamic model of the boiler and use of that model to develop a robust optimal controller capable of handling uncertainty (a significant factor in control of this process due to the fuel and the design of the boiler).

Improved control of wood-waste fired boilers has potential far-reaching benefits due to the number of these types of boilers in service and the potential for reapplication. Across the industry, including process heating and on-site power generation applications, there is an opportunity to meet a greater percentage of the total energy demand with wood-waste, generally considered a renewable resource. Further, knowledge and methods developed for improved control of the wood-waste boiler are likely to have "cross-cutting" applicability to other bio-mass fueled boilers and certain other solid fossil-fuel fired boilers (in particular, coal).

**Objectives**

The specific objectives put forth in the original project proposal were as follows:

- fully characterize the wood-waste boiler control inter-relationships and constraints through data collection and analysis
- design an improved control architecture
- develop and test an appropriate control and optimization algorithm
- develop and test a procedure for reproducing the approach and deriving the benefits on similar pulp and paper wood-waste boilers

Detailed tasks were developed supporting these objectives (see Milestone Table for list of actual tasks).

Variance from Project Goals

The project achieved its principal goal, in developing a new control approach, a dynamic model and a robust optimal controller for the wood-waste boiler. Process Control Solutions now realizes that the complete scope of effort and tasks conveyed in the original proposal was somewhat overly ambitious to accomplish within the budgeted amount of effort (the maximum allowed for a Phase I grant at that time).

Areas where there is some variance from original goals and objectives include:

- Testing was performed only in the simulated environment. Work did not progress, within the allotted schedule and budget, to the point of testing on an actual boiler (more of a stretch goal than a firm commitment).

- No streamlined procedure was developed for re-application on boilers other than the boiler on which the design was based. Testing on an actual boiler would be desirable prior to attempting this task, in the likely event that real-world test reveals additional issues to address in re-application. Since testing on a actual boiler did not occur, this task also did not occur.

And two other ancillary commitments made in the original proposal where not achieved:

- Produce a best practice guideline for wood-waste fired boiler control strategies to aid the industry as a whole in applying a uniformly effective control approach to these types of boilers – the principal investigator has the documentation necessary to produce this and intends to produce it, but, as of this final report date, the document has not been prepared and, therefore, will not be completed with funds from this project.

- Investigation of inferential measurement techniques – while this would be an important area of research to aid in improved control of wood waste and other biomass and solid fuel boilers, it is truly an entirely separate R&D initiative in and of itself. That being said, portions of the development work that occurred under this project, particularly the dynamic model development, could be useful in inferential measurement R&D.
Project Results

The bulk of the project effort occurred in the following phases, in the order shown:

- Boiler control problem characterization and selection of the best control design approach.
- Development and validation of a dynamic boiler model suitable for control.
- Development of a controller based upon the dynamic model and the boiler design specifications.
- Testing of the controller.

Each of these phases is discussed in more detail:

**Control Problem Characterization and Selection of Design Approach**

Problem characterization and selection of control technology, design, and approach were based on the principal investigator's experience with control of these types of boilers, as well as interviews conducted with industry partners prior to grant award and during the course of the project (post-award).

The most important controlled variables for the large industrial wood-waste boiler, along with the most typical primary manipulated variable associated with each are shown in the table below:

<table>
<thead>
<tr>
<th>Controlled Variable</th>
<th>Primary Manipulated Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum Level</td>
<td>Feedwater Flow</td>
</tr>
<tr>
<td>Steam Pressure</td>
<td>Fuel Flow (firing rate)</td>
</tr>
<tr>
<td>Steaming Rate (sometimes controlled only indirectly)</td>
<td>Fuel Flow (firing rate)</td>
</tr>
<tr>
<td>Steam Temperature</td>
<td>Desuperheater/Attemperator Spray Flow</td>
</tr>
<tr>
<td>Furnace Pressure</td>
<td>ID Fan Speed or Damper</td>
</tr>
<tr>
<td>Flue Gas Carbon Monoxide (CO)</td>
<td>Combustion Air Flow (Air/Fuel Ratio)</td>
</tr>
<tr>
<td>Flue Gas Oxygen (O2)</td>
<td>Combustion Air Flow (Air/Fuel Ratio)</td>
</tr>
<tr>
<td>Flue Gas Particulate</td>
<td>Scrubber DP</td>
</tr>
</tbody>
</table>

*Table 1 - Important Boiler Control Variables*

Of the above controlled variables, it was decided that the water and steam side control would be the focus of the project, leaving the air, and therefore flue gas composition control, to continue to be controlled with conventional approaches. In the conventional approach, air flow is based on a firing-rate-dependent ratio to the fuel flow, trimmed within a set range (usually +/- 25%) by an O2 trim controller. The control effort for the project, then, would focus on the first four variables in the above table.

The general classes of control theory considered were:

- Model Predictive Control (or some hybrid form of it)
- Robust Optimal Control

The greatest challenges in control of the wood-waste boiler are the variability of the fuel (heating value, moisture, size, shape, and composition) and the design of the boiler combustion zone necessary to handle a solid wood-based fuel. Heating value and moisture data tested from bark fuel samples on one boiler during combustion tests at various times over the life of the boiler is as follows:
### Table 2 - Typical Fuel Heating Value and Moisture Statistical Data

<table>
<thead>
<tr>
<th></th>
<th>HHV as-fired [BTU/lb]</th>
<th>HHV dry basis [BTU/lb]</th>
<th>Moisture [%], mass basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4374.2</td>
<td>8593.4</td>
<td>49.0</td>
</tr>
<tr>
<td>Min.</td>
<td>3515.0</td>
<td>7657.0</td>
<td>41.3</td>
</tr>
<tr>
<td>Max.</td>
<td>5196.0</td>
<td>9328.0</td>
<td>60.4</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>372.4</td>
<td>431.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>

This data could be considered typical for bark. The plot below illustrates the variance, aggregating data for individual test dates together to arrive at the plotted data points:

![Bark Data](aggregate data points; individual samples fall over a wider range)

**Figure 1 - Bark Heating Value and Moisture Variability**

Neither heating value nor moisture is measured continuously. Therefore, model predictive control alone would not address the control challenge presented by fuel variability. For this reason, it was decided to investigate and develop a controller based on robust optimal control theory. Specifically, $H_\infty$ control theory was selected for the following reasons:

1. The ability to account for and handle uncertainty in disturbance variables is inherent in the design of the controller. This is important because of the fuel variability and the difficulty in modeling and prediction of behaviors in the combustion zone.

2. The controller is intrinsically multivariable. This is important, because, the manipulated variables, fuel feed rate and water feed rate, each affect all of the controlled variables - steam pressure and temperature, drum level, and steaming rate.

The process for designing an $H_\infty$ robust optimal controller requires first a suitable dynamic model of the process to be controlled.
Model Development and Validation

A dynamic model was developed for the wood-waste boiler, based on a 400,000 lb/hr bark and oil-fired traveling stoker-grate boiler located at one of the project participant's pulp manufacturing sites. The model was developed using first principles and physical boiler design data. Prior similar model development works were researched extensively and referenced where applicable (for example, work by Astrom and Bell proved useful).

In terms of process variables, the model structure was chosen as follows:

<table>
<thead>
<tr>
<th>State Variables</th>
<th>Input Variables</th>
<th>Disturbance Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Pressure (drum)</td>
<td>Feedwater Flow Rate</td>
<td>Steam Demand Flow Rate</td>
</tr>
<tr>
<td>Steam Temperature (drum)</td>
<td>Fuel (Bark) Feed Rate</td>
<td>Fuel Heating Value</td>
</tr>
<tr>
<td>Steam Pressure (superheated)</td>
<td></td>
<td>Fuel Combustion Efficiency</td>
</tr>
<tr>
<td>Steam Temperature (superheated)</td>
<td></td>
<td>Combustion and Heat Xfr Losses</td>
</tr>
<tr>
<td>Drum Level</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 - Model Variables

This is represented in the following diagram:

Development of the first principles model begins with writing the energy balance for the process:

\[
\frac{dQ_h}{dt} + h_{w(in)}(P_{w(in)}, T_{w(in)}) \frac{dm_{w(in)}}{dt} - h_{st(out)}(P_{st(out)}, T_{st(out)}) \frac{dm_{st(out)}}{dt} = \frac{d}{dt} \left( m_{w(h)}U_{w(h)} + m_{st(h)}U_{st(h)} + m_{sh}C_{sh}T_{sh} \right) \quad (\text{eq. 1})
\]

The remaining equations describing the model are as follows.
\[ P_{st(b)} = S(T_{st(b)}) \quad \text{(eq. 2)} \]

\[ \frac{dm_w(b)}{dt} + \frac{dm_{st(b)}}{dt} + \frac{dm_{st(sh)}}{dt} = \frac{dm_{w(in)}}{dt} - \frac{dm_{st(out)}}{dt} \quad \text{(eq. 3)} \]

\[ \Delta p = P_b - P_{st} = \frac{K}{\rho} \left( \frac{dm_{st(flow)}}{dt} \right)^2 \quad \text{(eq. 4)} \]

\[ \frac{dm_{st(flow)}}{dt} \approx \frac{dm_{st(out)}}{dt} \quad \text{(eq. 5)} \]

\[ P_{st} = \frac{RT_{st}\rho_{st}(P_{st}, T_{st})}{1 - b\rho_{st}(P_{st}, T_{st})} - \frac{a\rho_{st}^2(P_{st}, T_{st})}{T_{st}^{0.5} \left[ 1 + b\rho_{st}(P_{st}, T_{st}) \right]} \quad \text{(eq. 6)} \]

With nomenclature, as follows:

- \( m \): Mass
- \( h \): Enthalpy
- \( U \): Internal energy
- \( P \): Pressure
- \( T \): Temperature
- \( \rho \): Density
- \( l_d \): Drum level
- \( C_f \): Fuel calorific (heating) value
- \( C_{pm} \): Metal heat capacity
- \( t \): Time
- \( Q_l \): Heat losses
- \( \eta \): Combustion, or fuel conversion, efficiency

Subscripts:

- \( b \): Boiler
- \( d \): Drum
- \( f \): Fuel
- \( m \): Metal
- \( w(b) \): Boiler/Drum water
- \( w(in) \): Feedwater
- \( st(b) \): Boiler/Drum steam
- \( st(sh) \): Superheater steam
- \( st(out) \): Outflow steam

The model was programmed in MATLAB and Simulink. To solve for steam properties, as required in equations 2 and 6, the necessary portions of the 1997 formulation of the International Association for the Properties of Water and Steam (IAPWS) were programmed directly into MATLAB.
The preceding is merely a synopsis of the model. The detailed development and translation to MATLAB and Simulink is fairly laborious and involved. The investigators involved at Process Control Solutions can provide additional detail upon request (certain detail may be considered proprietary).

The model was tested and validated in MATLAB and Simulink against actual plant process data. Figures 3 and 4, below, illustrate predicted versus actual values for steam pressure and drum level, respectively.

Figure 3 - Boiler Drum Pressure, Model vs. Actual

Figure 4 - Boiler Drum Level, Model vs. Actual
It can be seen that, for the 33 minutes of simulation plotted in Figures 3 and 4, the model does not track perfectly, especially for steam pressure in the boiler drum. This is attributed largely to uncertainties in the unmeasured disturbance variables. These uncertainties are not modeled and are to be handled in the controller design.

The model development and validation effort constituted a considerable portion of the total project effort (more than originally planned). It is felt that this investment has produced a model that meets the needs of the remaining control development effort, as it proceeds towards a commercially viable result. Further, the model will likely be valuable for other purposes, such as gaining additional insight into the boiler dynamics and controllability, and for training and troubleshooting.

**Controller Design and Testing**

The $H_\infty$ control approach was selected due to plant uncertainties. Because the linearized model for this process turns out to be normally unstable, an $H_\infty$ loop shaping controller was designed. In broad terms, the procedure followed during this phase was as follows:

1. Linearization of the dynamic model
2. Development of the $H_\infty$ robust optimal controller from the linearized model
3. Loop shaping (visually and by trial and error) to obtain closed loop gain for the controller that satisfies the $H_\infty$ loop shaping specifications at low and high frequencies.
4. Testing the controller in the simulated environment against the plant data used in the model

Specialized robust optimal control toolbox features in MATLAB were used to aid in this process.

Figures 5 shows the results of the loop shaping - the distribution of singular values before and after applying the controller.

![Figure 5 - Singular Values for Controlled and Uncontrolled Reduced Plant](image-url)
Figures 6 and 7 show the performance of the controller in maintaining drum pressure and drum level in the presence of randomly varied disturbance variables (combustion efficiency, bark heating value, and heat losses). Due to the way in which the control problem was originally characterized and the model defined for purposes of developing an advanced multivariable controller, it turns out that only drum level and drum pressure are controlled (i.e. are independent); The remaining state variables, superheated steam pressure and temperature and drum temperature are directly dependent upon drum level and drum pressure. In the real boiler process, it is superheated steam pressure that is controlled, so the next revision of the controller would involve making it the independent controlled variable. Superheated steam temperature is normally a completely external control loop, controlled by flow of condensate spray in a desuperheater, so, this will not be an issue.

![Figure 6 - Control of Drum Pressure in Presence of Simulated Random Disturbances](image)
Summary and Follow-up

The "category 1", conceptual-stage research and development work performed with Department of Energy financial assistance during the course of this project has yielded the following substantial results:

- Development of a dynamic model in MATLAB/Simulink suitable for development of advanced controllers, as well as developing new insight into boiler process behavior and eventually as a training and troubleshooting tool.

- Programming selected parts of the IAPWS (properties of water and steam) formulation into MATLAB/Simulink.

- Development of an H\(_\infty\) loop shaping robust optimal controller for the steam and water side control of the boiler.

- Proof-of-concept and demonstration of technical feasibility by testing the controller in the simulation environment ("bench-scale model").

The results of this work were presented on June 19\(^{th}\) 2003 at the American Society of Mechanical Engineers (ASME) International Joint Power Generation Conference (IJPGC) held in Atlanta. A paper describing the results was published in the conference proceedings, a copy of which is being provided to the Department of Energy Golden Field Office along with this final report.
Technical follow-up work identified includes the following:

- More exhaustive bench testing and validation of the model
- Incorporate identifiable empirical relationships into the model, e.g. difference in combustion rate of change between increasing and decreasing fuel rates
- Incorporate fossil fuel co-firing into the model. (Wood-waste boilers are capable of co-firing one or more fossil fuels, typically oil, natural gas, and sometimes coal; The current model is based solely on wood-waste.)
- Port controller to code suitable for industrial control system platforms
- Add protective measures and interface functions that would be necessary to test on a production boiler, such as:
  - Input validation
  - Output clamping and rate-of-change limits
  - Error checking, etc.
- Test on operating industrial boilers
- Further refinement based on field testing and development of re-application methodology
- Explore reapplication to waste-incinerators, stoker-grate coal boilers and other difficult solid fuel boiler applications
### Completed Milestone Table

<table>
<thead>
<tr>
<th>Milestone / Task Title</th>
<th>Original Planned Completion</th>
<th>Revised Planned Completion</th>
<th>Actual Completion</th>
<th>Responsible Organization</th>
<th>Original Projected Cost (Fed/Non-Fed)</th>
<th>Revised Projected Cost (Fed/Non-Fed)</th>
<th>Actual Completed Cost (Fed/Non-Fed)</th>
<th>Milestone Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Data Analysis / Problem Characterization</td>
<td>9/15/01</td>
<td>12/13/01</td>
<td>12/13/01</td>
<td>PCSI</td>
<td>$4000 / $0</td>
<td>$4500 / $0</td>
<td>$4500 / $0</td>
<td>Complete</td>
</tr>
<tr>
<td>2 Design Control Architecture</td>
<td>12/15/01</td>
<td>7/12/02</td>
<td>7/12/02</td>
<td>PCSI</td>
<td>$4000 / $0</td>
<td>$3750 / $0</td>
<td>$3750 / $0</td>
<td>Complete</td>
</tr>
<tr>
<td>3 First Semi-Annual Report</td>
<td>1/30/02</td>
<td>10/31/01</td>
<td>10/31/01</td>
<td>PCSI</td>
<td></td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>4 Model Identification and Estimation</td>
<td>2/15/02</td>
<td>11/9/02</td>
<td>12/14/02</td>
<td>PCSI</td>
<td>$6000 / $0</td>
<td>$15000 / $0</td>
<td>$19255 / $0</td>
<td>Complete</td>
</tr>
<tr>
<td>5 Develop Algorithm</td>
<td>6/15/02</td>
<td>11/30/02</td>
<td>3/1/03</td>
<td>PCSI</td>
<td>$6000 / $0</td>
<td>$5000 / $0</td>
<td>$4154 / $0</td>
<td>Complete</td>
</tr>
<tr>
<td>6 Second Semi-Annual Report</td>
<td>7/30/02</td>
<td>4/30/02</td>
<td>4/30/02</td>
<td>PCSI</td>
<td></td>
<td></td>
<td></td>
<td>Complete</td>
</tr>
<tr>
<td>7 Code Prototype Software</td>
<td>8/15/02</td>
<td>12/20/02</td>
<td>3/1/03</td>
<td>PCSI</td>
<td>$5000 / $0</td>
<td>$3000 / $0</td>
<td>$1255 / $0</td>
<td>Complete (note 1)</td>
</tr>
<tr>
<td>8 Testing (&amp; refinement)</td>
<td>10/15/02</td>
<td>5/25/03</td>
<td>6/15/03</td>
<td>PCSI</td>
<td>$4000 / $0</td>
<td>$3000 / $0</td>
<td>$3454 / $0</td>
<td>Complete</td>
</tr>
<tr>
<td>9 Develop Implementation Methodology</td>
<td>12/15/02</td>
<td>2/14/03</td>
<td>--</td>
<td>PCSI</td>
<td>$3000 / $0</td>
<td>$950 / $0</td>
<td>$100 / $0</td>
<td>Phase II</td>
</tr>
<tr>
<td>10 Develop Best Practices</td>
<td>12/15/02</td>
<td>12/20/02</td>
<td>--</td>
<td>PCSI</td>
<td>$2000 / $0</td>
<td>$800 / $0</td>
<td>$100 / $0</td>
<td>In Progress (funded by PCSI)</td>
</tr>
</tbody>
</table>
### Table 4 - Milestone Table

<table>
<thead>
<tr>
<th>Milestone / Task Title</th>
<th>Original Planned Completion</th>
<th>Revised Planned Completion</th>
<th>Actual Completion</th>
<th>Responsible Organization</th>
<th>Original Projected Cost (Fed/Non-Fed)</th>
<th>Revised Projected Cost (Fed/Non-Fed)</th>
<th>Actual Completed Cost (Fed/Non-Fed)</th>
<th>Milestone Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 Attend Annual Project Review</td>
<td></td>
<td></td>
<td></td>
<td>PCSI</td>
<td>$1000 / $0</td>
<td>$0 / $0</td>
<td>$0 / $0</td>
<td>Cancelled</td>
</tr>
<tr>
<td>12 Project Management and Reporting</td>
<td>12/15/02</td>
<td>6/15/03</td>
<td>6/15/03</td>
<td>PCSI</td>
<td>$5000 / $0</td>
<td>$4000 / $0</td>
<td>$3425 / $0</td>
<td>Final Rpt. 11/24/03</td>
</tr>
</tbody>
</table>

**Notes:**

1. Regarding task 7, *Code Prototype Software*, coding was only in MATLAB and Simulink. Originally, this task was intended to also include translating the results to portable code such as C/C++, for industrial trials. The complexity of the model and controller require additional resources and development work to reach this point. Development of actual software suitable for prototyping in the industrial environment is truly category 2 work in its breadth and complexity.

2. In reality, there is some cost share by Process Control Solutions in the form of additional hours expended but not charged and some hours charged at less than the approved rate. Since no cost sharing was forecast in the original proposal, with the budgeted total project amount ($40,000) 100% Federal, the estimate of Process Control Solutions’ cost share is summarized only under the *Cost Share* section and not broken down any further for the table above.
Energy, Waste, and Economic Savings

**Energy**

Potential savings in energy were estimated in the original proposal at 6.5 – 7.0 trillion BTU’s per year, coming from an aggregate average improvement in efficiency and the reduction in wood-waste and fossil fuel that would result. The basis for this was as follows:

- From DOE OIT data, fuel combustion for the targeted pulp, paper and board mills is estimated at 450 trillion BTU’s annually.
- Assuming an average current thermal efficiency of 65% and a target industry average thermal efficiency of 66% (an absolute improvement of 1% on average, industry wide), savings, S, are computed:

\[
S = (1 - \frac{65}{66})(450) = 6.8 \text{ Trillion BTU's}
\]

Having not yet tried the technology being developed on an operating boiler, it is not possible to refine this estimate any further. Recalling that combustion air control has been left to conventional approaches, efficiency improvement from this technology would come indirectly from more stable operation of the boiler that should be possible with the robust optimal controller. More stable operation would result in better bed conditions on the stoker grate, which would reduce the amount of excess air needed. Combustion conditions are not included in the dynamic first-principles model developed, and, therefore testing of the controller in the simulated environment gives little indication. Because the controller designed is not directly optimizing combustion, it would probably be conservative to reduce the projected energy savings due to efficiency estimate somewhat. For example, assuming ½% efficiency improvement, revised (conservative) energy savings would be 3.4 trillion BTU’s.

The greater impact of this technology may be its potential to supplant more fossil fuel usage with biomass (wood-waste). The new control technology may aid this in the following ways:

- More stable operation of the boiler on wood-waste improves the turn-down of the boiler on wood-waste; Turn-down being the minimum firing rate that operators feel comfortable running before they feel it necessary to fire oil. Oil usage on a typical a 400,000 lb/hr steaming rate boiler is around 900,000 gallons/year (based on data from industry partner boiler). Other data suggest that up to 36% of the oil used is without clear cause – that is to stabilize operation or increase operator comfort. Being conservative and assuming a 15% reduction in oil usage is possible, that equates to 135,000 gallons/year, over 20 billion BTU’s/year, of oil on a 400,000 lb/hr boiler.
- Improved coordinated control of the boiler steaming rate, pressure, and drum level allows the boiler to be more responsive to changing process heating and power consumption requirements. Rate can then be adjusted more frequently to maximize usage of wood waste to meet plant energy needs.

Most wood-waste boilers co-fire oil. Shifting more of the total national energy production from oil to biomass reduces dependency upon foreign oil and is, thus, in the national interest.
**Environmental**

Supplanting more fossil-fuel usage with biomass results in a net reduction in green-house gases because of the CO2 consumed while the biomass was being grown. The Energy Information Administration (EIA) CO2 emission factor for heavy oil is 174 lb/million BTU, and, the CO2 emission factor for wood or wood-waste is 0. Supplanting 20 million BTU/year of oil usage with wood-waste, then, equates to a reduction of over 1750 tons/year in net CO2 emission on a single boiler.

Similar, though somewhat more involved, analysis can be applied to SO2 and NOx emissions, which will also be lower for wood and bark than for oil.

Other collateral environmental benefits from use of the new control technology may include:

- Reduced net emissions due to net reductions in fuel usage to achieve the same steam production (from efficiency improvement).
- Reduced NOx due to reduced excess air and better combustion zone conditions due to better overall control (i.e. less favorable conditions for NOx formation).
- Reduced particulate emissions due to better control in the combustion zone and more stable operation of the boiler.

**Economic**

Economic benefits may include:

- Improved industry competitiveness (especially on an international scale) by reducing cost of operations:
  - Steam and power cost reduction by improved efficiency and better control.
  - Operating cost reductions from supplying greater percentage of energy needs with lower cost biomass (wood-waste) fuel.
  - Operating cost reduction by reduced staffing in multiple unit operations control rooms (which are common).
## Fuel/Energy Source BTU Conversion (Table)

<table>
<thead>
<tr>
<th>Fuel Source</th>
<th>BTU/Barrel</th>
<th>BTU/Gallon</th>
<th>BTU/Pound</th>
<th>BTU/Cubic Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil</td>
<td>$6 \times 10^6$</td>
<td>$142 \times 10^3$</td>
<td>$18.6 \times 10^3$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Fuel Oil – 6</td>
<td>$6.2 \times 10^6$</td>
<td>$150 \times 10^3$</td>
<td>$17.8 \times 10^3$</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>Fuel Oil – 2</td>
<td>$6 \times 10^6$</td>
<td>$140 \times 10^3$</td>
<td>$18.6 \times 10^3$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Gasoline</td>
<td>$5.2 \times 10^6$</td>
<td>$126 \times 10^3$</td>
<td>$18.9 \times 10^3$</td>
<td>$940 \times 10^4$</td>
</tr>
<tr>
<td>Propane – L</td>
<td>$3.8 \times 10^6$</td>
<td>$92 \times 10^3$</td>
<td>$19.9 \times 10^3$</td>
<td>$690 \times 10^4$</td>
</tr>
<tr>
<td>Wood</td>
<td>----</td>
<td>----</td>
<td>$6.5 \times 10^3$</td>
<td>$148 \times 10^4$</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>$87 \times 10^6$</td>
<td>$2 \times 10^3$</td>
<td>$21 \times 10^3$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Methane</td>
<td>$87 \times 10^6$</td>
<td>$2 \times 10^3$</td>
<td>$21 \times 10^3$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Methanol</td>
<td>$2.9 \times 10^6$</td>
<td>$69 \times 10^3$</td>
<td>$9.6 \times 10^3$</td>
<td>$517 \times 10^3$</td>
</tr>
<tr>
<td>Ethanol</td>
<td>----</td>
<td>----</td>
<td>$20 \times 10^3$</td>
<td>$1.8 \times 10^3$</td>
</tr>
<tr>
<td>Ethane</td>
<td>----</td>
<td>----</td>
<td>$12 \times 10^3$</td>
<td>$652 \times 10^3$</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>----</td>
<td>----</td>
<td>$51 \times 10^3$</td>
<td>$270$</td>
</tr>
<tr>
<td>CO</td>
<td>----</td>
<td>----</td>
<td>$4.3 \times 10^3$</td>
<td>$316$</td>
</tr>
<tr>
<td>Coal - Bit.</td>
<td>----</td>
<td>----</td>
<td>$12.6 \times 10^3$</td>
<td>$800 \times 10^3$</td>
</tr>
<tr>
<td>Coal - Lig.</td>
<td>----</td>
<td>----</td>
<td>$8.6 \times 10^3$</td>
<td>$541 \times 10^3$</td>
</tr>
<tr>
<td>Coal - Ant.</td>
<td>----</td>
<td>----</td>
<td>$12.6 \times 10^3$</td>
<td>$800 \times 10^3$</td>
</tr>
<tr>
<td>Carbon</td>
<td>----</td>
<td>----</td>
<td>$14.6 \times 10^3$</td>
<td>$1.9 \times 10^6$</td>
</tr>
<tr>
<td>Ethylene</td>
<td>----</td>
<td>----</td>
<td>$20 \times 10^3$</td>
<td>$1,477$</td>
</tr>
</tbody>
</table>

Electrical Generation (32.4% efficient power plant) - 10,500 BTU/KWH

*Table 5 - BTU Conversion*
Market Penetration Estimates / Technical Transfer Activities

Work to date has been Category 1. There have been no marketing, technology transfer or commercialization activities to speak of.

Cost Sharing

No cost sharing was included in the original proposal or the approved financial assistance contract. However, Process Control Solutions, Inc. (PCSI) expended considerably more effort hours on this project than were funded. Additionally, recognizing early on that, even with the maximum Category 1 funding, effort hours were likely going to be insufficient, PCSI billed hours at lower than the approved indirect and fringe rates, to effectively budget more hours for the same cost. This is summarized and accounted for in Table 6 below:

<table>
<thead>
<tr>
<th>#</th>
<th>Company Name</th>
<th>Company Type</th>
<th>In-Kind Contribution</th>
<th>Cash Contribution</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Process Control Solutions, Inc.</td>
<td>Small Business</td>
<td>$10,925</td>
<td></td>
<td>$10,925</td>
</tr>
<tr>
<td></td>
<td>DOE</td>
<td></td>
<td></td>
<td>$39,993</td>
<td>$39,993</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>$10,925</td>
<td>$39,993</td>
<td>$50,918</td>
</tr>
</tbody>
</table>

*Table 6 - Cost Sharing*

Additional supporting detail for the PCSI cost-sharing figure is shown in Table 7:

<table>
<thead>
<tr>
<th>Meeker</th>
<th>Hours</th>
<th>Value</th>
<th>Billed</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-billed hours</td>
<td>50</td>
<td>$5,752.29</td>
<td>$0.00</td>
<td>$5,752.29</td>
</tr>
<tr>
<td>Under-billed hours</td>
<td>106.6</td>
<td>$12,263.89</td>
<td>$11,354.71</td>
<td>$909.18</td>
</tr>
<tr>
<td>Selekwa</td>
<td>Under-billed hours</td>
<td>508.5</td>
<td>$31,571.87</td>
<td>$27,307.98</td>
</tr>
<tr>
<td>Total cost absorbed by PCSI</td>
<td></td>
<td></td>
<td></td>
<td>$10,925.36</td>
</tr>
</tbody>
</table>

*Table 7 - Cost Sharing Backup*

There was no formal cost sharing from our industry participants in the form of financial assistance, however, we wish to acknowledge them for contribution of time and resources in problem definition and, importantly, for making available boiler operating and design data, which was used in model and control development:

- Weyerhaeuser Corp.
- Riverwood International
Industry Participants

As referenced above, industry participants played a vital role in this effort and will necessarily continue to play a vital role if this effort moves forward. Both participants have expressed written support encouraging Category 2 funding for Process Control Solutions' continued efforts with this initiative.

Partners and Contractors

There were no partners or contractors involved, only the industry participants, as mentioned above.