

## **DRAFT WHITE PAPER**

### **CONVERSION OF OREGON BIOMASS TO LIQUID TRANSPORTATION FUELS**

#### **BIOMASS CONVERSION TECHNOLOGIES WORKING GROUP**

**Revision Date June 26, 2007**

#### **PURPOSE**

The purpose of this White Paper is to identify key research and development needs for the conversion of *Oregon biomass* into liquid transportation fuels. This White Paper is a product of the Biomass Conversion Technologies Working Group (BCTWG). The BCTWG consists of ten faculty from Oregon State University (OSU) with scientific and engineering expertise on processes that convert lignocellulosic biomass into fuels and chemicals.

#### **SCOPE**

This White Paper focuses on a description of process technologies appropriate for the conversion of Oregon lignocellulosic biomass to liquid transportation fuels, primarily ethanol and Fischer-Tropsch diesel. Although Biodiesel is a liquid transportation fuel, it is not made from lignocellulosic biomass, and so was not within the scope of this White Paper.

This White Paper does not provide a detailed description of the types, amounts, and distribution of lignocellulosic biomass found within Oregon. Furthermore, a technical and economic discussion of the collection and transportation issues associated with Oregon biomass is beyond the scope of this White Paper.

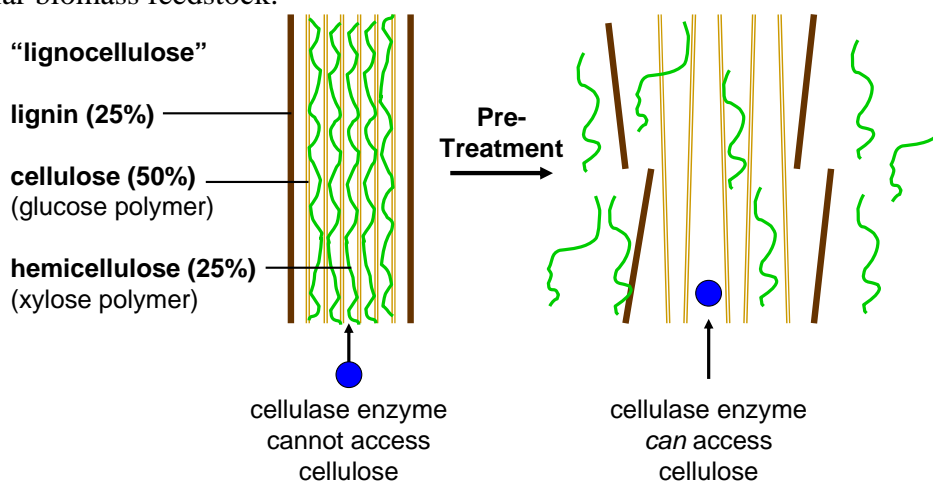
With this scope in mind, the BCTWG framed the key research needs for conversion of Oregon biomass to liquid transportation fuels. The BCTWG developed these research needs under four guiding principles. First, the BCTWG decided that only biomass feedstocks currently produced in Oregon in nominal volumes exceeding one million tons per year, such as grass straw, wheat straw, and softwood forestry residues, would be considered for analysis. These materials would be collectively called *Oregon Biomass*. Second, the BCTWG decided that an integrated Sugar Platform and Thermochemical Platform would be appropriate for conversion of Oregon biomass to liquid transportation fuels at large scales, whereas a stand-alone Thermochemical Platform might be appropriate for small or “farm scale” fuel production processes. Third, the BCTWG wanted to leverage exciting new research coming out of OSU laboratories that could have a significant impact on improving the technical and economic feasibility of processes for conversion of *Oregon Biomass* to liquid transportation fuels. Consequently, this White Paper strongly reflects the expertise and the R&D capabilities of the BCTWG team members. Finally, the BCTWG emphasized an interdisciplinary approach in identifying the research needs. The BCTWG team members, who are profiled at the end of this document, included chemical engineers, biological engineers, microbiologists, and chemists from a diversity of departments at OSU, particularly Chemical Engineering, Biological & Ecological Engineering, Wood Science & Engineering, and Food Science & Technology. The

BCTWG also included research faculty at the USDA Agricultural Research Service in Corvallis, and the OSU/DOE-PNNL Microproducts Breakthrough Institute in Corvallis.

## OREGON BIOMASS

Lignocellulosic biomass consists of three major constituent biopolymers: cellulose (~50 wt%), hemicellulose (~25 wt%), and lignin (~25 wt%). Cellulose is a linear biopolymer of the hexose sugar glucose. The cellulose polymer forms crystalline microfibrils through hydrogen bonding and is therefore difficult to hydrolyze to glucose. Hemicellulose is an amorphous branched biopolymer composed mainly of the pentose sugar xylose, and several other minor hexose sugars. Hemicellulose is easily hydrolyzed to its constituent sugars. The glucose and xylose released by hydrolysis of the cellulose and hemicellulose fractions are fermentable to ethanol. Lignin is a complex, amorphous biopolymer based on phenylpropane monomers connected by ether linkages. Lignin is extremely difficult to break down into its constituent monomers.

Cellulose, hemicellulose, and lignin are organized into complex hierarchical structures within lignocellulose biomass. These structures are collectively called the lignocellulosic matrix. In the simplest terms, paracrystalline cellulose microfibrils bound into fibers serve as the rigid structure. Hemicellulose and lignin interpenetrate the cellulose fibrils to provide the matrix material (*Figure 1*). Consequently, in order for hydrolytic enzymes to access cellulose, a pretreatment step is required to solublize the hemicellulose away from the lignocellulosic matrix and disrupt the lignin structure within the biomass. Pretreatment also produces fermentation inhibitors, including furfurals and uronic acids, from hemicellulose fractionation and hydrolysis. The structure, content, and chemical composition, of hemicellulose and lignin can vary widely for different types of lignocellulosic biomass. Therefore, the pretreatment step must be tailored to a particular biomass feedstock.



*Figure 1.* The lignocellulosic matrix.

Oregon has three relatively abundant forms lignocellulose biomass that are each available in quantities near or exceeding one million tons per year. They are grass straw, wheat straw, and softwood forestry residues. A formal statement and analysis of the total liquid transportation

fuel production capacity from Oregon biomass is beyond the scope of this White Paper, as a formal accounting of Oregon biomass availability is not yet available. But collectively, these materials could produce 100-200 million gallons per year of ethanol [need to refine number]. Oregon straws have a relatively low lignin content (~15 wt%) that is easily solubilized by chemical pretreatment of the biomass. However, straws also have a relatively high silica content, which complicates biomass processing. Oregon softwoods have a relatively high lignin content (~30 wt%) that is not removed by pretreatment. Furthermore, softwood forestry residues contain compounds such as oxalic acid from bark that inhibit fermentation. Consequently, detoxification of inhibitors will be an important step in biomass conversion processes for softwoods.

Since the composition and properties of Oregon biomass are unique, new approaches will be needed to convert this resource into liquid transportation fuels. Below, approaches for conversion of Oregon biomass to ethanol and diesel using integrated Sugar and Thermochemical Platforms are described, and specific Research Needs to further the development of a cellulosic biofuels industry in the state of Oregon are identified.

## **BIOMASS CONVERSION TECHNOLOGY OVERVIEW**

All biomass conversion processes require the collection and transfer of lignocellulosic biomass to a central location. The biomass is dried and then mechanically treated to reduce the particle size and increase the surface area per mass.

The conversion of biomass into liquid transportation fuels occurs by primarily two platforms, the *Sugar Platform* and the *Thermochemical Platform*. Specifically, the Sugar Platform converts the hemicellulose and cellulose fractions of biomass to ethanol. The Thermochemical Platform converts the lignin fraction of biomass to gaseous fuels needed to provide energy for the Sugar Platform, or converts biomass constituents directly to liquid fuel products similar to Fischer-Tropsch diesel. An integrated Sugar and Thermochemical Platform process for conversion of Oregon straw to liquid fuels is presented in *Figure 2*, whereas an integrated Sugar and Thermochemical Platform process for conversion of Oregon softwood forestry residues to liquid fuels is presented in *Figure 3*. *Figures 2* and *3* indicate that after biomass is fractionated, the lignin component is converted by the thermochemical processes into liquid fuels, but if desired, all biomass can be processed by the thermochemical platform alone.

### **The Sugar Platform**

The Sugar Platform uses biochemical processes to convert the hemicellulose and cellulose fractions of lignocellulosic biomass to ethanol.

The first step common to all Sugar Platform processes is *Pretreatment*, where biomass is fractionated into its major constituents: cellulose, hemicellulose, and lignin. Hemicellulose and lignin can be separated from the biomass through a variety of processes that generally involve heating the biomass with water. Acids, bases, other chemicals and enzymes are also used in this

step. The hemicellulose and some lignin is solubilized and separated from the solid cellulose and lignin..

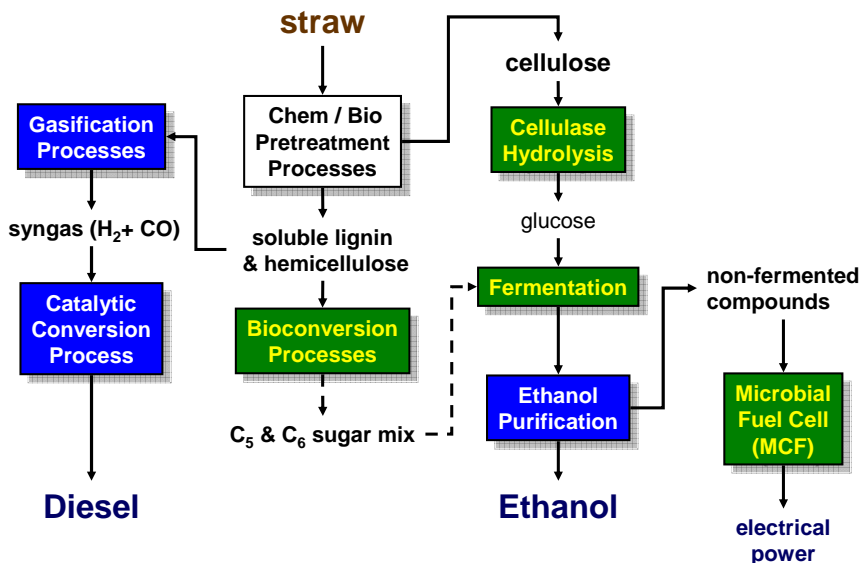


Figure 2. Integrated Sugar and Thermochemical Platform for conversion of straw to liquid transportation fuels.

*Hydrolysis* is the conversion of the cellulose and hemicellulose into glucose and xylose respectively. This process is accomplished through either chemical and/or enzymatic treatment. The most common chemical hydrolysis process is dilute acid hydrolysis. The enzymatic hydrolysis of cellulose is catalyzed by cellulases and hemicellulose hydrolysis is catalyzed by xylanases.

During pretreatment and hydrolysis, organic compounds are produced that are inhibitory to yeast fermentation. These inhibitors include soluble lignin fragments and sugar degradation compounds such as furfurals. Many methods have been studied to remove or degrade these compounds. *Detoxification* processes include removal of inhibitory compounds by activated carbon adsorption or ion exchange, enzymatic degradation of inhibitory compounds, or chemical degradation of furfurals by over-liming at high pH. Although hydrolysis of the cellulose and hemicellulose into sugar monomers and detoxification of the hydrolysate normally follows pretreatment, these steps can also occur simultaneously.

Following detoxification, microorganisms ferment the sugar stream and ethanol is produced. Both glucose and xylose can be fermented to ethanol, but xylose fermenting organisms are less tolerant to high concentrations of ethanol in the broth. Ethanol is purified from the fermentation broth by distillation. The distillation process is energy intensive and adds to the process operating cost. Typically, the lignin fraction is burned to produce steam to drive the distillation process.

## The Thermochemical Platform

Lignocellulosic biomass or its constituents (cellulose, hemicellulose, lignin) can be converted into liquid fuels or fuel intermediates by thermochemical processes such as

gasification or pyrolysis. Gasification involves heating biomass in air under oxygen-limited conditions to produce syngas, a gaseous mixture consisting of CO, CO<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub>, and other light gases. Utilizing appropriate catalytic processes, syngas can be converted into methanol, mixed alcohol fuels, or other fuel intermediates. Pyrolysis involves heating biomass under carefully controlled conditions in the absence of air to produce char and bio-oil. Bio-oil, like crude oil, can be refined to produce liquid transportation fuels. Both processes hold promise as scalable technologies for converting Oregon biomass into fuel or fuel intermediates.

Syngas can be converted to liquid fuels through a number of routes, but the main commonality is the selective hydrogenation and coupling of a CO/H<sub>2</sub> gas mixture to hydrocarbons and alcohols. These processes include methanol production, mixed alcohols production, and Fischer-Tropsch (FT) synthesis.

The simplest and most widely used of these processes is methanol production. Currently, methanol is manufactured worldwide from syngas produced by natural gas reforming, making it a top ten chemical. A whole suite of subsequent processes could then be used to convert methanol to other liquid hydrocarbons, such as DME, ethylene, propylene, acetic acid, and ethanol. The vast majority of methanol consumed today goes into acetic acid, MTBE, and formaldehyde.

Mixed alcohol production (a mix of C<sub>1</sub>-C<sub>5</sub> alcohols) involves a complex set of reactions with multiple product pathways impacted by kinetic and thermodynamic constraints. Consequently, mixed alcohol production from syngas has proven difficult to optimize. A number of processes have been studied, but none of them are yet practiced commercially. FT synthesis is further developed, and state-of-the-art processes use clean syngas to produce liquid hydrocarbon fuels through different process routes leading to either diesel or gasoline products.

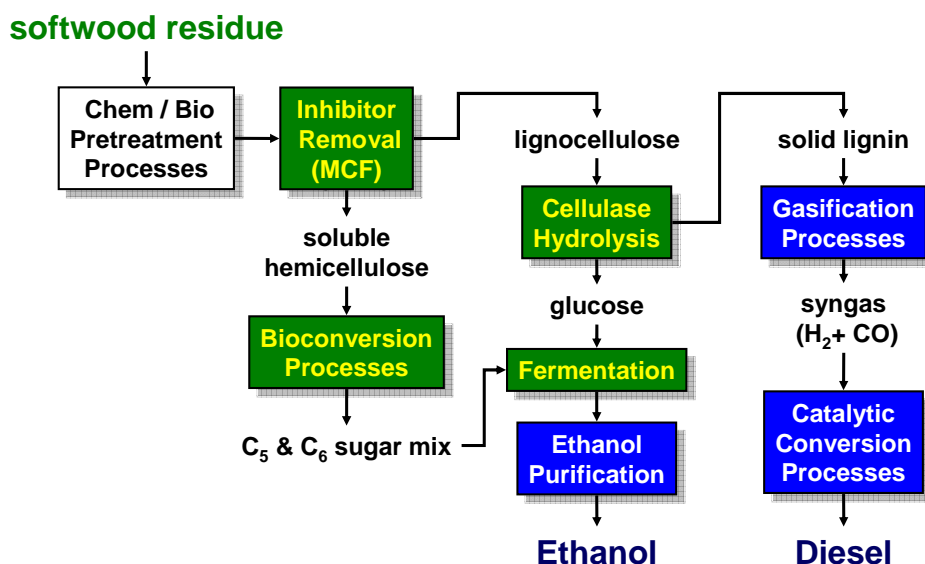


Figure 3. Integrated Sugar and Thermochemical Platform for conversion of straw to liquid transportation fuels.

## RESEARCH NEEDS

The Biomass Conversion Technologies Working Group has identified seven key research areas needed to facilitate the development of a cellulosic biofuels industry in Oregon. These research needs were developed under the guiding principles described in the Scope section of this White Paper. The seven research areas are:

- Area 1. Pretreatment & Bioconversion Technologies for Oregon Biomass
- Area 2. Robust Organisms for Fermentation of Oregon Softwood Hydrolysates
- Area 3. Electrical Power Generation from Ethanol Production Waste Streams
- Area 4. Small Scale Processes for Ethanol Recovery
- Area 5. Thermochemical Gasification of Pretreatment Streams and Residual Lignin Using Microchannel Reactor Technology
- Area 6. Thermochemical Conversion of Synthesis Gas to Liquid Fuels & Chemicals Using Microchannel Reactor Technology
- Area 7. Distributed (Farm Scale) Gasification Processes

### **Area 1: Pretreatment & Bioconversion Technologies for *Oregon Biomass*** (Christine Kelly, Chemical Engineering, OSU; Mike Penner, Food Science & Technology, OSU; Murti Ganti, Biological & Ecological Engineering, OSU)

The Pacific Northwest region of the United States has diverse agricultural and climatic regions that limit large scale farming of a single feedstock. Dispersed sources of limited feedstock necessitate development of novel technologies that can efficiently process mixed feedstock. Determination of effect of feedstock variability on ethanol production process is a critical need, particularly in the pretreatment and the enzymatic hydrolysis steps.

Pretreatment is the most significant processing cost in the production of ethanol from lignocellulosic biomass. Optimization of the chemical and enzymatic treatments needed to obtain high sugar yields at low cost from the types of lignocellulosic biomass abundant in Oregon will dramatically improve the technical and economic feasibility of cellulosic ethanol from *Oregon biomass*.

Optimization of cellulosic and hemicellulosic enzymatic hydrolysis step is also essential in the development of technologies and machinery for use with diverse biomass feed stocks found in Oregon. For such process optimization, greater understanding of the hydrolysis dynamics as achieved by modeling and simulation is essential. Development of control system technologies incorporating these optimal strategies will further contribute to reduced operational costs and increased overall profitability of cellulosic ethanol production.

### **Area 2: Robust Organisms for Fermentation of Oregon Softwood Hydrolysates** (Alan Bakalinsky, Food Science & Engineering, OSU; Ganti Murthy, Biological & Ecological Engineering, OSU)

Fermentation processes are at the heart of most technologies for conversion of Oregon biomass to liquid transportation fuels. With advances in genetics, microbiology, and process

control, a greater understanding of the complex processes associated with fermentation has been achieved. However, there are still key areas for greater research focus, particularly with respect to the fermentation of sugars derived from Oregon biomass.

Pretreatment of lignocellulosic Oregon biomass is necessary for making the polymeric substrates accessible to hydrolytic enzymes. However, pretreatment processes generate inhibitory compounds against the microorganisms needed to convert sugars to ethanol. Because these inhibitors can significantly reduce the efficiency of the fermentation process, it is important to identify and remove them, or alternatively, develop microbial strains of fermenting organisms that are resistant to these inhibitors. Research is needed to systematically identify the quantitative effects of known and presently unknown inhibitors generated during pre-treatments on the ethanol productivity of the yeast *Saccharomyces cerevisiae*. Research is also needed to identify yeast genes responsible for the inhibition, and genes derived from yeast or other organisms whose overexpression can overcome the inhibition. Long-term goals are to identify the mechanisms of inhibition and to construct recombinant microorganisms optimized for production of ethanol. In addition to being the premier industrial workhorse for the production of fuel and beverage alcohol, the yeast *Saccharomyces cerevisiae* is also currently one of the best characterized and experimentally tractable model microorganisms. This knowledge base provides significant experimental advantages and increases the likelihood of identifying the biological basis for the inhibitors and for developing resistant yeast strains.

*Saccharomyces cerevisiae* (yeast) can naturally ferment many hexose sugars such as glucose. In addition, Oregon biomass has significant amounts of pentose-rich hemicelluloses and lignin rich in polyphenolic compounds. Fermentation of pentose sugars is an important area of research for increasing ethanol yields from Oregon biomass. Fermentation of additional sugars can be achieved in two ways: 1) genetic modification of hexose fermenting organisms to have added pentose fermentation capabilities; 2) co-fermentation using multiple microorganisms having hexose or pentose fermentation capabilities. Due to diverse growing conditions of microorganisms, one of the key challenges in the co fermentation is in determining and optimizing fermentation conditions to achieve optimal fermentation performance.

Understanding fermentation is an important step for optimization of the processes to improve efficiency and efficacy of the conversion technologies. Description of fermentation processes by modeling and simulation will provide a deeper understanding of the underlying dynamics of fermentation processes. With a greater understanding of the fermentation processes, it would be possible to develop optimal control systems for fermentation processes. Development of such optimal control systems is essential, as most of the industrial fermentations are complex and require expert monitoring. Development of optimal control systems, incorporating expert knowledge, has the potential to reduce operational costs.

### **Area 3: Electrical Power Generation from Ethanol Production Waste Streams (Hong Liu, Department of Biological and Ecological Engineering, OSU)**

Cellulosic ethanol production from Oregon biomass will produce non-fermentable, water soluble materials. Generating energy from the “free” organic material in waste streams and

accomplish the waste treatment at the same time can make immediate contributions to the total energy production by reducing the expenditures in waste and wastewater treatment.

A novel microbial fuel cell (MFC) technology, which uses naturally occurring microorganisms as catalyst to directly generate electricity from organic materials, provides a completely new approach for energy generation from biomass. When wastewater is used as the fuel source, not only electricity can be generated, but wastewater treatment can be accomplished at the same time. Various organic materials, including fatty acids, acetate (an inhibitor for ethanol production), all kinds of sugars, and proteins in wastewater can be used to directly generate electricity in MFCs.

Using MFCs as a companion technology, working in sequence and/or in parallel to pretreatment and fermentation and ethanol recovery processes would greatly increase the economical feasibility of a biorefinery because of its following three characteristics. First, a mixture of sugars, extractives, and acid-degradation byproducts from the pretreatment and fermentation processes can be directly used in a MFC. Separation of individual components is not necessary. Second, microorganisms used in MFCs are directly enriched from a dirty wastewater stream, being able to use a wide variety of organic substances including some acid-degradation byproducts that are inhibitory to the fermentation of glucose to ethanol. Third, the final products of MFCs are electricity and clean water. No extra separation step is needed.

A single chamber air cathode MFC system developed in Dr. Liu's lab recently demonstrated a power density of  $2 \text{ kW/m}^3$ , the highest reported power density generated by MFC so far. Such a power density is 100-300% higher than the  $0.5\text{-}1 \text{ kW/m}^3$  generated by anaerobic digester, a process that was traditionally used to produce biogas (mainly methane) from waste streams and burned to turn a turbine generator. A power density of up to  $10 \text{ kW/m}^3$  is expected with further modification on the MFC system.

#### **Area 4: Small Scale Processes for Ethanol Recovery (John Simonsen, Wood Products & Engineering, OSU; Alex Yokochi, Chemical Engineering, OSU)**

Ethanol recovery from the fermentation broth by distillation is a significant operating cost of the sugar platform process. Promising advances in ethanol selective membranes have yet to be realized. Progress in this area would dramatically impact the feasibility and ability to operate sugar platform processes, particularly at smaller production rates.

The development of advanced membrane-based separations processes to separate ethanol directly from the fermentation broth in fuel ethanol production systems would greatly enhance the feasibility of effective implementation of the production of cellulosic ethanol. Currently, separating the ethanol from the production fluid consumes a large amount of energy. Membranes are already utilized in some facilities in the final step of ethanol production, namely, breaking the ethanol/water azeotrope. However, large improvements in efficiency and cost could be realized if a membrane and process were available to separate ethanol directly from the fermentation broth, avoiding the azeotrope and distillation steps entirely. Membrane technology might simplify the ethanol recovery scheme so that that distributed, i.e. local, production of fuel ethanol becomes economically feasible.

## **Area 5: Thermochemical Gasification of Pretreatment Streams and Residual Lignin Using Microchannel Reactor Technology (Greg Rorrer, Department of Chemical Engineering)**

Alkaline pretreatment of straw is commonly used to separate cellulose from the hemicellulose and lignin fractions (see *Figure 2*). For example, alkaline pretreatment with 1.0 wt% sodium hydroxide typically solubilizes a significant fraction of both the lignin and hemicellulose fractions. Often, it is not cost effective to neutralize this alkaline pretreatment stream, hydrolyze the soluble hemicellulose to fermentable sugars, and then precipitate out and recover the soluble lignin. A novel alternative is to process the alkaline pretreatment stream directly into syngas. In this process, the aqueous stream is raised to a temperature and pressure sufficient to generate supercritical water. The supercritical water then gasifies both the hemicellulose and recalcitrant lignin to a mixture of gases including CO, CO<sub>2</sub>, H<sub>2</sub>, and CH<sub>4</sub>. The presence of alkali salts serves as a catalyst for this process. Water and alkaline salts are condensed and recycled back the pretreatment step, reducing both water and chemical consumption. The key to making the gasification process energy efficient is microchannel reactor technology, which would greatly accelerate that rate of heat transfer to the reaction step and facilitate energy recovery during the heating and cooling steps. These gases could then be cleanly burned in a boiler to produce steam for distillation or be catalytically upgraded to liquid fuels using catalytic microchannel reactor technologies described under Area 6.

Other biomass constituents can be gasified by supercritical water in a microchannel reactor. The Rorrer laboratory has already demonstrated that glucose can be completely converted to a mixture of CO<sub>2</sub> and H<sub>2</sub> within a two second residence time using a supercritical water microchannel reactor. It is also possible to gasify residual lignin from the softwood sugar platform using supercritical water in a microchannel reactor.

## **Area 6: Thermochemical Conversion of Synthesis Gas to Liquid Fuels & Chemicals Using Microchannel Reactor Technology (Dan Palo, OSU/PNNL Microproducts Breakthrough Institute; Greg Rorrer, Chemical Engineering, OSU)**

Syngas conversion is an ongoing research emphasis at the DOE Pacific Northwest National Laboratory. Both reactor-based and catalyst-based improvements have been studied in the use of syngas to produce many of the relevant liquid fuels being considered for a biomass-derived process. This includes methanol, DME, mixed alcohols, and FT liquids. Each process requires different reaction conditions, catalysts, and syngas composition. The ratio of H<sub>2</sub> to CO in the syngas is a key consideration in producing the desired product. Research is ongoing that would allow products to be made from non-optimal syngas compositions. Syngas tailoring can also be conducted through processes such as the water-gas shift reaction, which is used to shift the H<sub>2</sub>/CO ratio of the raw syngas before conducting the synthesis.

With current technology, the catalytic conversion of synthesis gas to ethanol provides relatively low yields of ethanol from the biomass feedstock. This reflects the suboptimal selectivity to ethanol during synthesis. Furthermore, low conversion rates result in the need to recycle a large portion of the feed gas, requiring a synthesis reactor that is relatively large and

adding to capital costs. Improvements in ethanol yield and selectivity would be welcomed in this area.

The reaction that produces Fischer-Tropsch (FT) hydrocarbon fuels from syngas is highly exothermic and very sensitive to reactor temperature. For this reason, PNNL has shown significant progress in applying intensive heat exchange using microchannel reactors to control this process. Optimal thermal control of the reactor bed reduces the amount of methane produced as a byproduct in FT synthesis. Additional work at PNNL has been focused on developing catalyst formulations that provide better product yield and distribution, both of which are important in making FT fuels attractive economically.

**Area 7: Distributed (Farm-Scale) Gasification Processes (Gary Banowetz, USDA-ARS, Corvallis; Greg Rorrer, Chemical Engineering, OSU; Dan Palo, OSU/PNNL Microproducts Breakthrough Institute)**

The distributed nature of Oregon biomass may result in high transportation costs that significantly impact the economic feasibility of biomass conversion processes. A number of previous studies have demonstrated that delivery of straw to a centralized conversion facility has transportation, handling and storage costs in the range of \$45 - \$55 per ton. The processes of baling, loading, transporting, storing, “un-baling”, and grinding represent significant energy inputs and costs that have plagued the economic feasibility and energy balance of earlier efforts to develop a bioenergy industry in the northwest. One approach to make Oregon bioenergy production more feasible is to develop farm- or local-scale technologies that enable on-farm conversion of straw to energy with the subsequent transport of energy-dense products from the farmstead. Scalable technologies and integrated processes that can operate without the economy of scale are needed to implement this approach.

Factors that limit the development of thermochemical approaches to convert Oregon biomass into liquid fuels or intermediates include lack of scalable technologies that enable economic distributed production consistent with the distributed nature of the biomass feedstocks in the state, mineral composition of straw that reduces the useful life of current technologies, economic gas conditioning technologies, robust catalytic technologies suitable for distributed production schemes, and lack of local refinery capacities to convert bio-oil into marketable fuels. There also is need for approaches to convert ash residues generated during thermal chemical conversion into marketable co-products.

**NEXT STEPS?**

The state of Oregon has abundant and unique forms of cellulosic biomass such as grass straw, wheat straw, and softwood forestry residues that can be converted to liquid transportation fuels such ethanol and Fischer-Tropsch diesel. Since straw and softwood residues are the dominant feedstocks currently available in Oregon, development and deployment of process technology tailored to these feedstocks is of regional interest and so must be initially supported at the state level by the state of Oregon.

The Governor's budget for the 2008 biennium includes support for Oregon Bio-Economy and Sustainable Technologies Signature Research Center, known as BEST. Cellulosic biofuels is a core initiative of the proposed BEST Signature Research Center, as it seeks to "jump start" the development of an emergent biofuels industry within Oregon that will make Oregon more energy self sufficient while creating jobs for Oregonians.

Implementation of a focused research agenda in cellulosic biofuels will produce two main outcomes needed to support an emergent cellulosic biofuels industry here in Oregon. First, although cellulosic biofuels is a "hot ticket" nationally, Oregon-based feedstocks are not a federal priority. However, new technologies coming out of OSU research laboratories will work to demonstrate that conversion of Oregon-grown biomass to transportation fuels is both feasible and economical, providing an incentive for biofuel companies to locate here in Oregon. Second, state support of a focused research agenda will provide the "critical mass" of expertise needed to win large federal grants in the rapidly-expanding arena of cellulosic biofuels. These two outcomes will also work to position the state of Oregon as regional leader in cellulosic biofuels.

#### **MEMBERS OF THE BIOMASS CONVERSION TECHNOLOGIES WORKING GROUP (BTCWG)**

**Greg Rorrer (co-leader)** is a Professor of Chemical Engineering at Oregon State University. Dr. Rorrer has an established research program in biochemical engineering and biomass conversion. His expertise in biomass conversion processes includes acid-catalyzed hydrolysis of lignocellulose to fermentable sugars, catalytic conversion of carbohydrates to valued-added organic acids, and conversion of biomass carbohydrates to fuel-cell hydrogen using supercritical water in microchannel reactor systems.

**Christine Kelly (co-leader)** is an Associate Professor of Chemical Engineering at Oregon State University. Dr. Kelly has an established research program in biochemical engineering and bioproducts. Her expertise in biomass conversion processes includes production of novel delignification enzymes by genetically engineered yeast, fermentation of carbon monoxide to ethanol, and bioconversion of pentose sugars to xylitol.

**Alan Bakalinsky** is an Associate Professor of Food Science & Technology at Oregon State University. Dr. Bakalinsky has an established research program that focuses on the microbiology and molecular biology of alcohol-producing yeasts. His expertise in biomass conversion processes focuses on the identification of alcohol-producing yeast strains that are tolerant to inhibitory compounds found in biomass hydrolysates.

**Gary Banowetz** is Supervisory Plant Physiologist at USDA Agricultural Research Service in Corvallis, Oregon, where he leads various projects associated with improved wheat and grass straw utilization. His expertise in biomass conversion processes focuses on development of farm-scale gasification systems for conversion of waste straw to electrical power.

**Hong Liu** is an Assistant Professor of Biological and Ecological Engineering at Oregon State University. Dr. Liu is developing a research program in microbial fuel cells. Her expertise in biomass conversion focuses on conversion of non-fermentable carbohydrates to electrical power

using microbial fuel cells, and is also interested in the potential of microbial fuel cells to remove compounds in biomass hydrolysates that inhibit ethanol fermentation processes.

**Ganti Murthy** is an Assistant Professor of Biological and Ecological Engineering at Oregon State University. Dr. Murthy is developing research program in biofuels. His expertise in biomass conversion processes includes process control of ethanol fermentation systems and pentose sugar fermentation processes.

**Dan Palo** is a Senior Research Engineer of the Microproducts Breakthrough Institute at the U.S. Department of Energy's Pacific Northwest Laboratory Oregon on the Hewlett-Packard campus. Dr. Palo has an established research program in the development of microtechnology-based reactor systems for fuel-cell hydrogen production. His research expertise relevant to biomass conversion includes development of microtechnology-based reactor systems for catalytic conversion of biomass-derived syngas to methanol or hydrocarbons similar to gasoline or diesel using the Fischer-Tropsch process.

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