Georgia Tech is taking a comprehensive and interdisciplinary approach toward developing the technologies needed to economically produce bioethanol from forest products. In addition to addressing all five steps in the biofuel production process, researchers are also looking broadly at the entire production system.

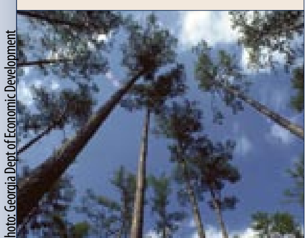

Photo: Georgia Dept of Economic Development

Changing Energy

Georgia Tech takes interdisciplinary approach to developing biofuels from forestry products.

By Abby Vogel

We feel it at the pump. Fuel prices are at record highs and so is the demand for alternative fuels. But major scientific and technological advances are still required before economically viable alternative fuels become a significant part of the U.S. energy supply.

Researchers across the Georgia Institute of Technology campus are focusing their attention on biofuels. And while most experts agree that biofuels are not the silver bullet to solve the world's long-term fuel needs, they see biofuels as a necessary complement to conventional oil and gas.

Each year, the state of Georgia alone produces more than five million tons of trees beyond what its pulp and sawmill operations need. A research group (right) headed by Christopher Jones is pre-treating pine with catalysts used in the petroleum industry.

Photos: Gary Meek

Biofuel research at Georgia Tech intensified in 2004 with the launch of the Strategic Energy Institute (SEI), created to enable, facilitate and coordinate programs related to energy research and education.

"Many energy issues are truly multidisciplinary and can't be addressed by one faculty member," says Roger Webb, interim director of the SEI. "The Strategic Energy Institute has been broadly engaging companies to define projects that many faculty members at Georgia Tech can pursue in a collaborative effort."

This interdisciplinary approach was a major reason why Chevron Corporation chose Georgia Tech as its first strategic research alliance partner, according to Rick Zalesky, vice president of the biofuels and hydrogen unit of Chevron Technology Ventures.

"Georgia Tech has the infrastructure so that researchers from various departments work together in the same building to solve complex problems, and we think that's terrific," says Zalesky.

With funding from Chevron, Atlanta startup C2 Biofuels, the Georgia Research Alliance and one of the U.S. Department of Energy's new BioEnergy Research Centers, Georgia Tech researchers are exploring advanced technologies aimed at making transportation fuels from forestry products.

Georgia Tech researchers are examining and optimizing the five major steps required to produce bioethanol, or ethanol obtained from the carbohydrates in many agricultural crops. These steps include selecting the best plant material, preparing the plants for conversion, breaking down the carbohydrates into simple sugars, fermenting the sugars into alcohol and separating the ethanol from water.

Choosing a Plant Source and Preparing It for Conversion

Bioethanol produced from corn is being manufactured at a rate of more than five billion gallons per year in the United States, but concerns exist about the future price and availability of corn as a food crop if it's being used to help meet energy needs.

Because forest products are a more efficient source of ethanol and more than five million tons of trees are available for harvest each year in Georgia beyond what is needed for pulp mill and sawmill production, Georgia Tech researchers are turning to Southern pine trees.

Switchgrass, a fast-growing tallgrass, is another attractive source of plant material because of its ability to grow in poor soil and adverse climate conditions, its rapid growth and its low fertilization and herbicide requirements.

Art Ragauskas, a professor in the School of Chemistry and Biochemistry, studies the chemistry and structure of the starting plant material, known as biomass, to determine which varieties and characteristics of switchgrass and pine trees improve conversion to ethanol.

He also examines how different acids react with the wood chips to make accessible the complex interior mixture of carbohydrate polymers, including cellulose, hemicellulose and lignin.

"Pre-treatment is performed under severe chemical conditions and very high temperatures. Understanding the chemistry should allow us to make pre-treatments more efficient, less costly and more effective," says Ragauskas.

After the acid pre-treatment, the wood is placed in a reactor and exposed to high-pressure steam.

John Muzzy, a professor in the School of Chemical and Biomolecular Engineering, and Kristina Knutson, a postdoctoral fellow in the School of Chemistry and Biochemistry, are working with Ragauskas to develop a continuous reactor that will employ mechanical energy and/or boiling water instead of acid and high temperatures to break up the wood. That would greatly reduce processing and chemical costs while increasing the life expectancy of the reactors, Ragauskas notes.

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CONTACTS

Pradeep Agrawal
404. 894. 2826
pradeep.agrawal@chbe.gatech.edu

Andy Bommarius
404. 385. 1334
andreas.bommarius@chbe.gatech.edu

Bill Bulpitt
404. 385. 6939
bill.bulpitt@energy.gatech.edu

Rachel Ruizhen Chen
404. 894. 1255
rachel.chen@chbe.gatech.edu

Charles Eckert
404. 894. 7070
charles.eckert@chbe.gatech.edu

W.J. (Jim) Frederick, Jr.
404. 894. 2082
jim.frederick@chbe.gatech.edu

Kristiina Iisa
404. 894. 5757
kristiina.iisa@chbe.gatech.edu

Christopher Jones
404. 385. 1683
christopher.jones@chbe.gatech.edu

William Koros
404. 385. 2845
bill.koros@chbe.gatech.edu

John Muzzy
404. 894. 2882
john.muzzy@chbe.gatech.edu

Sankar Nair
404. 894. 4826
sankar.nair@chbe.gatech.edu

Art Ragauskas
404. 894. 9701
arthur.ragauskas@chemistry.gatech.edu

Matthew Realff
404. 894. 1834
matthew.realff@chbe.gatech.edu

Sam Shelton
404. 385. 6330
sam.shelton@me.gatech.edu

Roger Webb
404. 385. 4954
roger.webb@ece.gatech.edu

Roger Reisert is CEO of C2 Biofuels, a startup ethanol company that has supported research at Georgia Tech.

Photo: Rob Felt

Photo: Gary Meek

Professor William Koros and postdoctoral fellow Wulin Qiu (above) are developing a hollow fiber membrane used to separate water from ethanol.

Professor Art Ragauskas (below) is part of the team that formed the AtlantIC Alliance for BioPower, BioFuels and Biomaterials in 2003.

IN BRIEF

ROADMAP FOR BIOFUELS AND BIOMATERIALS

Researchers at Georgia Tech, Imperial College London and the Oak Ridge National Laboratory formed the AtlantIC Alliance for BioPower, BioFuels and Biomaterials in 2003. Researchers including Georgia Tech's Art Ragauskas developed a roadmap that contained a series of comprehensive research and policy plans to increase the practicality of using biofuels and biomaterials as a supplement to petroleum. A condensed version of the roadmap was summarized as a review article, called "The Path Forward for Biofuels and Biomaterials," which appeared in the January 27, 2006 issue of *Science*. For a summary, see gtresearchnews.gatech.edu/reshor/rh-ss06/ragauskas.html.

Photos: Gary Meek

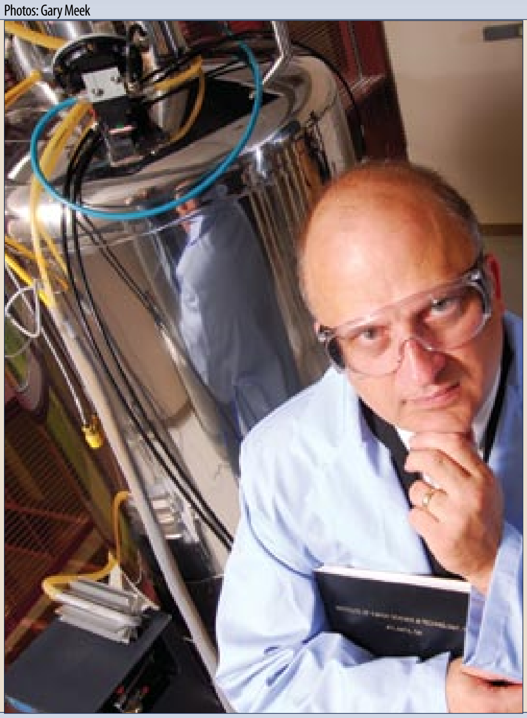

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Photo: Gary Meek

Professor Art Ragauskas prepares samples containing cellulose, lignin and hemicellulose for analysis using advanced nuclear magnetic resonance (NMR) techniques.

Breaking Down the Sugars and Converting Them to Ethanol

After the pre-treatment, the cellulose and hemicellulose are further broken down to free the sugar for fermentation to alcohol. Commercially available enzymes can do this, but they are too expensive to use in biofuel production, according to Andreas (Andy) Bommarius, a professor in the School of Chemical and Biomolecular Engineering and the School of Chemistry and Biochemistry. As an alternative, he is identifying novel enzymes and engineering them to be longer-lasting and more effective at breaking down cellulose polymers to sugars than those commercially available.

"We want to produce enzymes more efficiently and make them more active and stable, at the same time improving bioethanol production at a lower cost," explains Bommarius.

In conventional ethanol production, the sugars obtained are then fermented with yeast to produce alcohol. Rachel Ruizhen Chen, an associate professor in the School of Chemical and Biomolecular Engineering, is working to increase the ethanol production rate by using the bacteria *Zymomonas mobilis* instead of yeast in the fermentation process because it has a three- to five-fold higher productivity than yeast when making bioethanol. Chen plans to manipulate the enzymatic, transport and regulatory functions of the bacterial cell to improve the bioethanol fermentation process.

The lignin portion of the biomass must be extracted from the mixture prior to fermentation. Unfortunately, current pre-treatments break down some of the lignin, which enables it to be carried over to the fermentation process where it acts as a fermentation inhibitor.

RISING DEMAND FOR IMPORTED OIL

Annual U.S. oil imports increased from approximately two billion barrels in 1981 to more than five billion barrels in 2005. With domestic oil production declining, the U.S. is becoming more dependent on other countries for its energy supplies. In 2005, the top five countries from which the U.S. imported oil were Canada, Mexico, Saudi Arabia, Venezuela and Nigeria. At $70 per barrel, these expanding oil imports are adding significantly to the nation's balance of payments deficit. "A near term solution to our growing transportation oil demand is urgently needed," says Roger Webb, interim director of Georgia Tech's Strategic Energy Institute. Webb testified before the U.S. Senate Committee on Agriculture, Nutrition and Forestry in January 2007.

William Koros, the Roberto C. Goizueta Chair in the School of Chemical and Biomolecular Engineering, is investigating efficient ways to separate the lignin from the cellulose and hemicellulose portions of the biomass. Koros, a Georgia Research Alliance (GRA) eminent scholar in membranes, plans to extract the lignin byproducts by pulling the hydrolyzed biomass mixture through a selective membrane with a vacuum using a process called pervaporation.

Lignin is an important by-product of the enzymatic process and has many potential uses. Ragauskas is examining the possibility of converting lignin to a biofuel precursor or using lignin as a building block chemical to make new polymers or chemicals. Professors Christopher Jones and Pradeep Agrawal, both of the School of Chemical and Biomolecular Engineering, are exploring ways to chemically fractionate pine and convert suitable portions to true gasoline fuels.

To produce a biofuel with a similar energy density to gasoline from renewable feedstocks, they plan to convert pre-treated pine to fuel using chemical catalysts traditionally used by the petroleum industry, rather than enzymes. These biofuels could yield higher miles-per-gallon than traditional ethanol-rich fuels such as E-85, according to Jones.

Separating Ethanol from Water

For bioethanol, once the sugars are fermented into alcohol, a significant amount of water must be separated out. This separation primarily occurs in a distillation column, which involves heating the mixture and separating the components by the differences in their boiling points.

"Distillation is very energy intensive and expensive, and it might defeat the purpose when you're trying to produce biofuel economically," says Sankar Nair, an assistant professor in the School of Chemical and Biomolecular Engineering, who is collaborating with Koros on two separation projects aimed at improving the energy efficiency of the biofuel process.

A membrane-based approach would avoid the need to supply heat energy, and instead rely on differences in the transport rates of the components through a membrane to achieve separation. The challenge is in producing selective membrane systems that can produce pure ethanol. Polymer materials have been widely investigated and have the advantage of high throughput, but such membranes can't yet produce pure ethanol from a dilute ethanol-water mixture, notes Nair.

Instead, Koros and Nair are exploring membranes that contain nanoparticles of porous inorganic materials called zeolites that are so small they can be dispersed efficiently into a polymer matrix. The very specific porosity of the zeolite should allow separation of ethanol from water. By using two membranes in series – the first hydrophobic to remove ethanol from a large mass of water and the second hydrophilic to remove any trace water in the ethanol product from the first membrane – it may be possible to design an economical membrane process for biofuel separation from water.

Taking a Systems Approach

Producing ethanol from biomass involves more than these process steps. Researchers must also decide how to ship the biomass to the processing plant, how large the processing plant should be, where it should be located, and how to ship the ethanol to fueling stations.

Bill Bulpitt, an SEI senior research engineer who returned to Georgia Tech in 2004 after working 17 years for Southern Company, is working with students who are running computer simulation models that represent what a full-scale production plant

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IN BRIEF

WORKING WITH GEORGIA TECH

"Georgia Tech excels at collaboration with industrial partners. A very important attribute is Georgia Tech's ability to maintain balance between an industrial partner business objective and the independence of the faculty. Georgia Tech has a good appreciation for how to develop and share in the development of intellectual property with industrial partners. Couple these points with our successful ongoing relationship in other areas of technology research, and we have a win-win for this new area of distributed manufacturing to support the growing biofuels technology field."

Rick Zalesky, vice president of the biofuels and hydrogen unit of Chevron Technology Ventures.

Photos: Gary Meek

Associate professor Rachel Chen prepares ethanol samples (above) for high performance liquid chromatography (HPLC) analysis.

Wood chips (below) provide the starting material for many conversion processes that lead to biofuel production.

THERMOCHEMICAL TECHNOLOGIES

Professor John Muzzy in the School of Chemical and Biomolecular Engineering (CHBE) is evaluating a process called pyrolysis. Biomass is heated with catalysts to form a synthetic natural gas and create volatile compounds that can be condensed for blending with oil. Since current pyrolysis techniques require very high temperatures, Muzzy aims to perform catalytic pyrolysis at lower temperatures and create a stable bio-oil with reduced oxygen content.

Professor W. J. (Jim) Frederick, Jr. and principal research engineer Kristiina Iisa, also of CHBE, study a similar process called gasification. They add oxygen or steam to the biomass mixture to create a gaseous mixture of carbon monoxide and hydrogen. Their research focuses on both gasification and removing contaminants from the product gas so that it can be converted into ethanol, synthetic diesel and other fuels through catalytic processes. Using a large-scale reactor on the Georgia Tech campus, they can study the high pressure, high temperature conditions the gas encounters in the catalytic reactors.

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might look like. The models analyze the costs for the various components of the system, which helps to determine the optimal biorefinery size.

"When building a biorefinery, there is a certain size that's economically viable. That's what we are trying to determine," Bulpitt explains.

To evaluate a biofuel system, the project team must consider the energy balance – that is, how much energy goes in versus how much comes out. A biofuel system must take into account positive or negative energy balances, positive or negative net greenhouse gas emissions, and positive or negative environmental and ecosystem impacts.

Ethanol biorefineries could get a significant economic boost from the sale of high-value chemicals that could be generated from the same feedstock. Charles Eckert, a professor in the School of Chemical and Biomolecular Engineering and collaborators Charles Liotta and Art Ragauskas are exploring the use of environmentally friendly solvent and separation systems to produce specialty chemicals, pharmaceutical precursors and flavorings from a small portion of the ethanol feedstock.

Matthew Realff, an associate professor in the School of Chemical and Biomolecular Engineering, is developing optimization models to determine the best structure for a biofuel processing system. Realff's model integrates information from crop production through processing to fuel distribution. It includes information on the location and number of crop acres available, the current economic value of the crop, distances and ability to ship the crop, the economic scaling of the cost of the processing equipment with size and the location of the distribution terminals.

These optimization models are valuable to companies like C2 Biofuels that plan to build biorefineries. And they complete the comprehensive research approach Georgia Tech has taken toward optimizing bioethanol production process.

"Researchers at Georgia Tech have different strengths and take different approaches toward solving the problem of developing biofuels," says Christopher Jones. "If you assemble all of the pieces together, you will come up with the best solution." rh

Photo: Gary Meek

Georgia Tech researchers are studying alternative separation techniques that could make bioethanol production more efficient.

IN BRIEF

BIOENERGY RESEARCH CENTER

Georgia Tech is one member of a new $125 million U. S. Department of Energy (DOE) Bioenergy Research Center, intended to accelerate basic research in the development of cellulosic ethanol and other biofuels. The Center aims to advance President Bush's Twenty in Ten Initiative, which seeks to reduce U.S. gasoline consumption by 20 percent within ten years through increased efficiency and diversification of clean energy sources. Georgia Tech's primary role in the center will focus on biomass characterization and the fundamental chemistry of plant cell walls. The goal will be to study the chemical bonds of poplar and switchgrass to help create more efficient methods of breaking the plants down into the sugar needed to make ethanol.

Photo: Gary Meek

COMPANIES AND GEORGIA RESEARCH ALLIANCE SUPPORT BIOFUEL RESEARCH AT GEORGIA TECH

Vacuum dewar flasks with liquid nitrogen coolant keep water/ethanol samples cool for later analysis in the lab of William Koros.

With support from a broad range of organizations, Georgia Tech researchers are exploring advanced technologies aimed at making transportation fuels from forestry products.

Chevron Corporation

In June 2006, Chevron Corporation and Georgia Tech formed a five-year, $12 million strategic research alliance to pursue advanced technology aimed at making cellulosic biofuels and hydrogen viable transportation fuels.

The alliance focuses its research on four areas:

- Producing cellulosic biofuels
- Understanding the characteristics of biofuel feedstocks
- Developing regenerative sorbents (porous materials used to remove gases such as carbon monoxide, carbon dioxide and nitrogen)
- Improving sorbents used to produce high-purity hydrogen

A portion of the money will be used to set up a bioethanol laboratory on the Georgia Tech campus to support ongoing and future biofuel research. The laboratory will contain new equipment, including analytical equipment to study how much ethanol is being produced, how long it takes to ferment and the quality of the ethanol being produced.

C2 Biofuels

C2 Biofuels is a Georgia Tech VentureLab startup that seeks to develop fuel-ethanol production from biomass material available in large quantities in the Southeast, including Southern yellow pine. Led by Roger Reisert, a Georgia Tech alumnus, C2 Biofuels obtained two $100,000 grants from The Agriculture Innovation Center in Tifton to match the initial investment from Georgia Tech alumnus Glen Robinson Jr.

Reisert has provided grants to Georgia Tech and University of Georgia researchers to evaluate and develop processes and technologies. Since the target ethanol yield has been met by the researchers, Reisert's efforts are now focused on building a pilot bioethanol plant in Georgia.

Georgia Research Alliance (GRA)

Founded in 1990, the Georgia Research Alliance (GRA) helps build Georgia's technology-rich economy by bringing business and state government together to invest in the innovative research at six affiliated Georgia research universities, including Georgia Tech.

With the support of Governor Sonny Perdue and the Georgia Legislature, the GRA added an energy initiative last year, the Energy Research Seed Grant Program (ERSGP), to spark university-based research into the development of new approaches to producing and conserving energy resources.

With Georgia's abundant resources and potential of cellulosic biomass, this program sought contributions to the growth and efficient harvest of improved cellulosic crops (including forest resources) and the conversion of cellulosic crops to higher value energy and/or chemical co-products. Four Georgia Tech researchers were awarded seed grants under the ERSGP for funding from July 1, 2006 to June 30, 2007. rh

– Abby Vogel