The DOE Bioethanol Pilot Plant

A Tool for Commercialization

Inside one of four 9000-liter fermentation tanks at the National Renewable Energy Laboratory's Bioethanol Pilot Plant. The facility enables NREL and its industry partners to move advances in producing ethanol and other fuels and chemicals from biomass into the development phase.

Would you like the opportunity to test biomass-processing technology in a world-class pilot plant without building a facility of your own? And in a pilot plant capable of handling recombinant organisms and one where national laboratory expertise is also available? A U.S. Department of Energy (DOE) user facility operated by the National Renewable Energy Laboratory (NREL) in Golden, Colorado, may provide that opportunity for you.

With funding from the DOE National Biofuels Program, NREL constructed a fermentation pilot plant facility to test bioprocessing technologies for production of ethanol or other fuels or chemicals from cellulosic biomass. The Process Development Unit (PDU) of the Bioethanol Pilot Plant can test biomass fuel or chemical production processes from start to finish at a scale of about 900 kilograms (1 dry ton) per day of dry feedstock. An associated Mini-Pilot Plant is ideal for preliminary testing at small scale. As part of NREL's Alternative Fuels User Facility (AFUF)—and in keeping with NREL's role as a U.S. Department of Energy national laboratory—the PDU, Mini-Pilot Plant, and associated Bioethanol Pilot Plant facilities are available to support industrial and academic research and development. Projects can be arranged under cooperative research and development agreements, work-for-others contracts, or other flexible business agreements. If you are developing a technology that uses biological organisms for large-scale conversion of biological materials, the facilities and expertise of NREL that are available at the Bioethanol Pilot Plant may be exactly what is needed to commercialize that technology.

The Process Development Unit

The Bioethanol Pilot Plant's one-ton-per-day Process Development Unit is a complete system for producing ethanol or other fuels or chemicals from cellulosic biomass sources. PDU operational components include:

- Feedstock washing and milling
- Thermochemical pretreatment
- Enzymatic hydrolysis
- Fermentation
- Microorganism seed growth and holding tanks
- Ion exchange and chromatographic separations
- Distillation
- Solid-liquid separations.

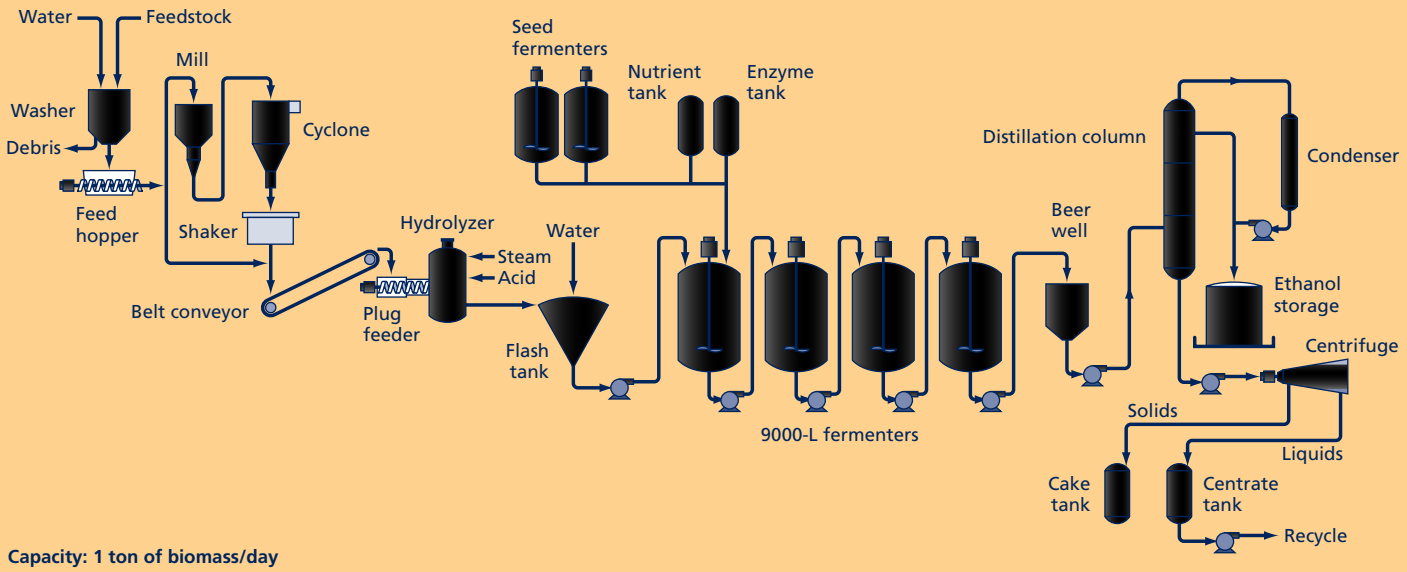
The enzymatic hydrolysis and fermentation equipment includes four 9000-liter, two 1450-liter, and two 160-liter fermenters. All can be used for aerobic or anaerobic fermentation, with separate or combined hydrolysis. The distillation equipment includes a 10-meter stripping column. The PDU is one of relatively few facilities specifically designed to safely handle metabolically engineered as well as native microorganisms. It can also process high solids material (greater than 20% total solids), which is crucial for developing cost-effective biomass-based processes.

The PDU has a very sophisticated control and data acquisition system for all facets of plant operations in its control room. Spectroscopic monitoring of fermentation-off-gas composition makes it possible to calculate oxygen transfer rates. The data acquisition system provides information to conduct material and energy balances.

The Mini-Pilot Plant

In addition to the PDU, the AFUF has a Mini-Pilot Plant for preliminary process testing at a more cost-effective small scale. The Mini-Pilot Plant offers batch and continuous fermentation processing. A flexible system of several vessels ranging from 10 liters to 100 liters allows configuration appropriate to a wide range of processes. The Mini-Pilot Plant can validate batch, fed-batch, or continuous bioprocessing technologies. As with the PDU, it can accommodate high solids concentrations and recombinant organisms and can be used to determine carbon mass balance closure.

Process Flow Diagram of the Process Development Unit



Capacity: 1 ton of biomass/day

Pretreatment Options

Of the various steps for processing biomass, pretreatment is most feedstock sensitive and the one for which testing at pilot plant scale is critical. NREL offers three different thermochemical technologies for solubilizing hemicellulosic sugars and making cellulosic sugars more accessible to hydrolysis enzymes and fermentation organisms. The PDU has a continuous dilute-acid pretreatment system from Sunds Defibrator (now Valmet). This commercially available equipment can be readily included in setting up your own biomass processing system.

Steam Gun Thermochemical Pretreatment

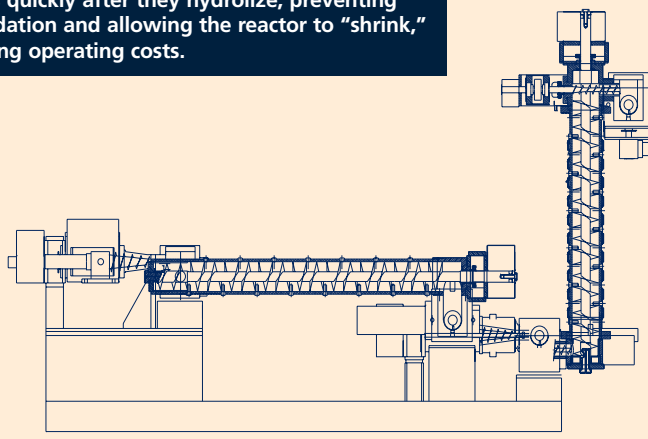
As an alternative to the Sunds pretreatment system, the Bioethanol Pilot Plant offers a batch-process steam gun system that uses high pressure and high temperature to enhance dilute-acid pretreatment. This system is also good for test runs when the amount of feedstock is limited. Feedstock can be impregnated with the acid either at atmospheric pressure or in a 14-liter pressurized vessel. After "cooking" the feedstock with steam for a few minutes, the steam gun expels it into a flash tank. The explosive pressure drop rapidly cools the material to precisely stop the reaction. The steam gun system makes it easy to experiment with a wide range of temperature, pressure, acid concentration, and other conditions. Although not commercially available, the steam gun equipment set up can be easily built to include in your biomass processing system.

Countercurrent Pretreatment

NREL's third pretreatment option is a novel countercurrent reactor system. This patented technology also uses dilute acid, high temperature, and pressure, but in a way that releases and preserves more of the sugars. Conventional dilute acid pretreatment hydrolyzes the hemicellulose (breaks it down to xylose and other five-carbon sugars), which also physically exposes the cellulose to hydrolysis (typically enzymatic). At a higher temperature, dilute-acid pretreatment will also hydrolyze cellulose (breaking it down to glucose). Temperatures high enough for cellulose hydrolysis, however, are also high enough to degrade the xylose and other hemicellulose sugars.

NREL's countercurrent pretreatment technology incorporates several innovations to make pretreatment more effective. Countercurrent flow in the second stage removes hydrolyzed sugars from the system more quickly upon their release, limiting exposure of the sugars to the hot acid, which is fed in the opposite end. Staged temperature increase takes advantage of the fact that a portion of the hemicellulose hydrolyzes more easily—removing this portion in the first stage before the temperature is raised to hydrolyze the rest of the hemicellulose in the second stage. Both of these innovations increase yield by reducing degradation of the xylose. They also allow a third innovation—"shrinking" the required reactor volume in the second stage via its vertical orientation as first the remaining hemicellulose and then cellulose is hydrolyzed. The vertical orientation allows the remaining solids to remain compact as the solids

The countercurrent pretreatment system removes sugars quickly after they hydrolize, preventing degradation and allowing the reactor to "shrink," reducing operating costs.



are lifted upward. This not only reduces the amount of hot dilute acid solution needed—a critical consideration in achieving acceptable process economics—but maintains more effective contact between the solid particles and the flowing dilute acid. This is believed to reduce mass transfer reaction resistances, allowing for lower temperatures and lower acid concentrations to achieve the same degree of hydrolysis as in more traditional reactor designs.

The countercurrent exchange pretreatment system is hooked up to a data control and acquisition system allowing precise control and sophisticated data analysis. Although the equipment is not yet commercially available, with appropriate agreements for use of the technology, it could be incorporated in setting up your biomass processing system.

Continuous Ion Exchange and Chromatography Separation System

Hardwood feedstocks present an extra challenge—acetic acid, an inhibitor of the yeast fermentation process. The liquid solution of sugars that comes from the pretreatment of hardwoods contains significant amounts of acetic acid. The PDU includes a continuous ion exchange system to remove the inhibitory acetic acid prior to fermentation. The system uses commercially available standard ion exchange resins, to which the acid adsorbs, removing the inhibitor from the hydrolyzate. The system—which is sized to be compatible with the PDU 1-ton/day feed rate—can be readily connected to the PDU for process testing or to your biomass processing system. The system can also be hooked up to the PDU systems upstream or downstream of fermentation for ion-exchange or chromatographic purification or separation of products from chemical production processes.

Expertise/People

The Bioethanol Pilot Plant is far more than just a collection of state-of-the-art equipment. NREL has more than 50 scientists, engineers, and technicians from a wide range of disciplines with expertise in biomass conversion and bioprocess development. They can help you use the facility to move your technology from a scientific concept to a technically and economically proven process ready for commercial production—before you commit to staff and capital investment. NREL has been developing biomass-to-ethanol and other biofuels technologies since 1977 and has an outstanding biofuels staff. They have the scientific and technical expertise to work with metabolically engineered microorganisms and enzymatic processes. They also have the operation skills necessary to keep a plant operating smoothly and the engineering skills to scale up processes. In addition, the NREL biofuels staff is experienced in working with outside partners, providing needed help, and protecting proprietary information and processes.

Experience/Success

Since opening in 1994, the Bioethanol Pilot Plant has already been used for numerous cooperative projects to help develop bioprocessing technologies—several of which are now moving into commercial production (see below).

Collaborations Using the PDU

Industrial Partner	Feedstock	Product	Key Processes	Organism	Scale	Business Mechanism
Amoco	corn fiber	ethanol, animal feed	pretreatment systems (2), glucose/xylose cofermentation	yeast (including recombinant)	PDU (9000 liter)	CRADA
BC International	bagasse, rice straw, wood	ethanol	pretreatment, fermentation	recombinant *E. coli* bacteria	20-L, 160-L	CRADA
Arkenol	rice straw	ethanol	glucose/xylose cofermentation	recombinant *Zymomonas* bacteria**	160-L	CRADA
Sustainable Technology Energy Partnership*	mix of a variety of solid wastes	ethanol	dilute acid and enzymatic hydrolysis with enzyme recycle	yeast	4-L steam gun, 30-L fermenter	collaboration
Sealaska Corp.	softwood	ethanol	hydrolysis, fermentation	Nx7 yeast**	4-L steam gun, bench scale	memorandum of understanding
Quincy Library Group	softwood forest thinnings	ethanol	hydrolysis, fermentation	Nx7 yeast**	4-L steam gun, bench scale	collaboration
Collins Pine, California Energy Commission	softwood	ethanol	hydrolysis	none	4-L steam gun	collaboration and subcontract
Swan Biomass	rice straw	ethanol	pretreatment, glucose/xylose fermentation	recombinant *Saccharomyces* yeast	PDU pretreatment, bench-scale fermentation	collaboration

*DOE, NREL, California Energy Commission, California Institute of Food and Agricultural Research at UC Davis, Waste Energy Integrated Systems
**Proprietary NREL organisms available for license

DOE has made the investment in a world-class NREL facility for pilot testing biomass-processing technologies, so you do not have to.

From Bioethanol Pilot Plant to Biorefinery of the Future

A little less than 100 years ago, the first oil refineries started cracking crude oil to separate it into gasoline and a handful of other useful products. Today, the petroleum industry converts billions of barrels of oil per year (approximately 14 million barrels per day in the United States alone) into a dozen fuels and hundreds of plastics. Our economy is built on these products, but oil and other fossil fuels are expensive, pose environmental risks to extract and transport, and their supplies are ultimately limited. Their combustion generates much of our air pollution and most of the greenhouse gases that threaten to change the Earth's climate.

Instead of importing oil, we can home-grow biomass to provide the feedstock for many of our fuels and chemicals. Hydrolysis of cellulosic material to sugars and then fermentation or other bioprocessing of those sugars can supply many of the fuels and chemicals (or equally good alternatives) for which we now depend on petrochemicals. The more we turn to such a "sugar platform" instead of petrochemicals, the better off our domestic economy and environment will be. Producing ethanol from non-food plant materials for use as an automotive fuel is just one of a myriad of possible sugar-based bioprocesses. Our user facility is titled the Bioethanol Pilot Plant, but it is equally available to your process that produces other fuels or chemicals. Together we can make the Pilot Plant the forerunner of the biorefinery of the future.

Availability

NREL's Bioethanol Pilot Plant was explicitly designed to assist industry and outside researchers develop commercial bioprocessing technology. The PDU and other Pilot Plant facilities—and associated NREL staff expertise—are available for major trials of an entire process, for research and development of individual bioprocessing steps, or for cooperative basic research of your or NREL's bioprocessing technologies. NREL can work with private industry or other research institutions under a variety of flexible business-venture arrangements. Most typically, cooperative research and development agreements (CRADAs) are used for joint projects to advance renewable energy or energy-efficiency technologies . Work-for-others agreements (WFOs) are used to apply NREL's unique facilities and expertise to develop proprietary industrial processes. NREL welcomes inquiries from companies and research institutions interested in using Bioethanol Pilot Plant facilities to develop and commercialize technology for making valuable fuels and chemicals from biomass. Whether with a CRADA, a WFO, or some other business device, chances are good we can work together.

For more detailed information on the Bioethanol Pilot Plant contact Biofuels Technology Manager Robert Wooley: 303-384-6825; robert_wooley@nrel.gov. To inquire about setting up a cooperative project using the plant's facilities, contact Mark Yancey: 303-384-6858; mark_yancey@nrel.gov

You may also visit our web site at www.ott.doe.gov/biofuels.

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