Executive Summary
of
NREL/Amoco CRADA Phase 3 Final Report

The National Renewable Energy Laboratory (NREL) and SWAN Biomass Company, a partnership between Amoco Ethanol Development Corporation and Stone and Webster Engineering Industrial Technology Corporation, have completed Phase 3 of the Amoco /NREL Cooperative Research and Development Agreement (CRADA) 91-0003. The objective of Phase 3 was to develop sufficient information at pilot plant scale to justify construction of a demonstration facility for converting biomass to ethanol. Phase 3 included a laboratory program to evaluate the yeast strains developed at Purdue University and support pilot scale testing, a series runs in the NREL process development unit (PDU) using corn fiber as the feedstock, and process design and economic modeling.

Enormous progress was made in the definition and verification of the biomass to ethanol process during Phase 3. SWAN's pretreatment process produced substrate that was highly reactive with cellulase enzymes, with virtually all of the hemicellulose converted to mononumeric sugars, and without high concentrations of reversion inhibitors such as furfural. The Purdue yeast was able to ferment glucose and xylose simultaneously. Two PDU runs of about 1000 hours each were completed, and over ten tons of solid residue was produced to be tested as an animal feed. Laboratory fermentations were found to closely mimic the results in the PDU, confirming that the work completed at smaller scale will translate easily to the larger unit. The data were successfully modeled, and the model was used to derive a commercial design and cost estimate. The estimated cost for ethanol produced from corn fiber in a commercial facility is about $0.86 per gallon, including a 15% internal rate of return on the capital.

Before Phase 4 is initiated, a number of technical problems need to be solved, and a fully integrated run demonstrating the proposed commercial process configuration in the PDU must be made. Most of the technical problems can be addressed in tests using any of a number of feedstocks. The most significant unresolved generic problem is how to eliminate or control the negative impact of fermentation inhibitors on the rate of fermentation. Programs have been established outside of the CRADA to address this issue, and preliminary results indicate that a commercially acceptable solution to the problem has been found. For corn fiber feedstock, it is also critical to learn how to collect and dry the solid coproduct more efficiently.

Summary Results

Laboratory Program

The key objective of the laboratory program was to develop bench scale data on the performance of fermenting organisms before they were used in the PDU. Work was limited to the evaluation of three yeasts acquired from Purdue University, *Saccharomyces* Strain 1400 and two recombinant derivatives: 1400 (pLNH33), a yeast with xylose-fermenting genes in an inserted plasmid, and 1400 (LNHST2), with xylose-processing genes integrated into the yeast chromosome. Experimentation included growth studies, yeast addition rates, and the impact of inhibitors, nutrients, and solids levels.

Continuous and batch studies demonstrated that 1400 (LNHST2) can metabolize xylose more effectively than 1400 (pLNH33), particularly in the presence of glucose. Furthermore, the latter was completely stable in all tests run, even when xylose was not present to maintain pressure on the organism to retain the xylose-conversion genes.

SSCF Kinetic Model

Reaction kinetics modeling was used in parallel with all bench scale and PDU experiments as a guide to subsequent work. The CRADA model accurately predicts batch fermentation behavior in both shake flasks and larger fermenters, and predicted concentrations within 6% of those measured during PDU runs. However, the model parameters were determined by fitting the equations to data where individual effects were not isolated. Ideally one would like to design and conduct experiments that isolated variables to determine model parameters and then test the model on data from more complex experiments. Because of the way the CRADA model was developed, it fits the existing data, but there is some uncertainty that it can be used to extrapolate to other conditions or feedstocks.

PDU Operations

The PDU includes equipment for feedstock handling, size reduction, pretreatment, fermentation (3 stages), distillation and solid-liquid separation. It is supported by utilities for steam, cooling water, chilled water, hot water, deionized water, plant and instrument air, and nitrogen. The nominal maximum feed rate is 1 ton per day of dry biomass.

Seven runs were made in the PDU. The first four used Strain 1400 and SSF, the last three used the recombinant yeast, LNHST2, and SSCF. The runs with 1400 were the first ones to be attempted following mechanical completion of the PDU, and were useful to demonstrate PDU operability over the range of parameters of interest for the CRADA program. However, these runs were not intended to provide design quality information on fermentation performance.

Amoco Pretreatment Reactor (APR) Results

The development of the APR has been one of the key accomplishments in Phase 3. Amoco had conceived and tested the APR at low throughput in their joint development program within Canada during 1994. The Phase 3 program confirmed that this device was capable of supplying high-quality pretreated feed for SSCF, and showed that it was possible to increase the flowrate through the APR by at least 8 times. However, the program failed to determine optimum operating conditions for corn fiber at high throughput, because corn fiber runs in the PDU were completed before the improvements in the APR operation was made.

The APR performed through four continuous runs of 224, 695, 1100 and 977 hours in Phase 3. As mechanical problems were resolved, downtime decreased to about 5%; downtime should virtually disappear in the future because of operational improvements demonstrated at the very end of Phase 3. Significant improvements were also made in the selection of materials of construction for the APR .

Fermentation Results

Batch fermentations performed using LNHST2 at the bench scale and in the PDU showed no performance differences with increased reactor size. Bench-scale continuous fermentations also had similar performance to PDU runs. Thus, bench scale runs are a good indication of large scale performance.

The last two PDU runs, each about 1000 hours long, provided continuous performance information on SSCF using LNHST2. During these fermentations, all of the monomeric and most the oligomeric glucose in the pretreated material was converted to ethanol and other products. However, while xylose conversion was about 75% at 15% solids in the feed to the first fermenter, when the solids content was raised to 25%, xylose conversion fell to 25%. Poor xylose conversion was caused by the presence of inhibitors which are created during pretreatment.

The ethanol process yields (defined as ethanol produced divided by potential ethanol from starch, cellulose, galactan, and xylan) for PDU runs ranged from 40% to 55%. These low yields are due to inadequate pretreatment and the presence of fermentation inhibitors, problems that have been addressed outside of Phase 3 of the CRADA.

Contamination was a recurring problem during PDU runs. *Lactobacillus* bacteria were routinely found in the fermenters, and isolated in CSL and in pretreated feed when there were problems with pretreatment equipment operation.

Solid Residue Recovery and Testing Results

Ten tons (dry basis) of solid coproduct was produced during the last two PDU runs on corn fiber for testing as an animal feed supplement. The processing requirements for separating the solids from the liquids in the bottoms product from the distillation column and making a marketable product were also examined. The techniques tested for solid-liquid separation were not attractive for commercial use.

Centrifuge tests, conducted at NREL and by two different vendors, indicated that there is a significant tradeoff between high percent solids in the wet cake and solids recovery levels, and that decanter centrifuges may not be an appropriate choice for commercial facilities. Vendor tests also suggested that rotary vacuum filtration is not practical for this application. Coproduct drying tests were carried out in a rotary steam tube dryer in a vendor's facility. Results indicate that although this type of equipment can be used, the cake is so wet that very large solids recycle is needed, and repeated heating downgrades the product by darkening it and possibly reducing its nutritional value. Drying the material in this manner results in a fine powder which must be subsequently pelletized before it can be used in the animal feed market.

Animal feeding tests were carried out on poultry, swine and cattle. Final test results are not available yet.

Process Design

A conceptual process design and technoeconomic evaluation was carried out in order to evaluate the commercial application of the SWAN biomass-to-ethanol technology to a feedstock blend of corn fiber and corn screenings. It was assumed that the feedstock would be provided by a corn wet mill in Illinois (approximate capacity of 150,000 bushels of corn per day) with the biomass-to-ethanol unit installed in an integrated fashion with the mill and assumed to operate 350 days per year, 24 hours per day.

A platform case was defined and used as the basis for complete process flow diagrams and a detailed costed equipment list. The plant design includes feedstock transfer from the wet mill, pretreatment, neutralization, fermentation, ethanol recovery and dehydration, ethanol blending and storage, animal feed coproduct processing and storage, chemical storage, and a chilled water system. Other utility and support systems required for the plant's operation is assumed to be provided by the wet mill plant. They are accounted for through operating costs and other assessments.

The platform case facility is fed 750 dry tons per day of corn fiber and corn screenings per day, and produces 21.4 million gallons per year of ethanol.

Technoeconomic Evaluation

The economic evaluation uses a discounted cash flow analysis, and fourth quarter 1996 dollars. The result of the analysis is given as the cost to produce a gallon of ethanol, including a 15% internal rate of return on invested capital. There is no inflation, and 100% equity financing is assumed.

A spreadsheet model was developed and used to estimate ethanol cost. After setting input parameters, the model is run in an iterative fashion varying enzyme dose, SSCF residence time, internal recycle rates and other parameters, until the lowest cost for ethanol product is found. Yields and conversions used in the optimization are determined separately in the SSCF kinetic model.

The capital cost was estimated to be $41.0 million, +/- 25%. The major capital equipment costs were based on vendor quotes or internal information provided by Stone & Webster Engineering Company, and the installed cost were factored from this information. The total capital cost includes 4% construction management, 8% for engineering design, 2% for procurement, 3% freight on equipment, 3% sales tax on equipment and 20% contingency.

The cost of ethanol from this facility was estimated to be $0.86/gal. Ethanol costs are made up of three major pieces, variable operating costs, fixed operating costs, and byproducts credits. Variable operating costs are those for feedstock ($0.38/gal), utilities ($0.16/gal), chemicals ($0.14/gal) and enzymes ($0.18/gal). Fixed operating costs consist of the labor ($0.06/gal), MTIO ($0.03/gal) and capital costs ($0.34/gal). Byproduct credits are taken for methane ($0.05/gal) and animal feed coproduct ($0.38/gal). The animal feed value is the same as the feed cost because both are based on an invariant value for protein, and almost all protein is recovered in the solid product.

Sensitivity Studies

During Phase 3 several design and operating parameters were identified as having potentially significant effects on the capital and operating costs for the conceptual design. A total of thirty seven economic sensitivity studies were carried out using the spreadsheet model to identify any work needed to justify the CRADA proceeding to Phase 4. Both kinetics and operating variables were modified to examine their incremental effect on the cost of ethanol from the platform case design. All parameters except those under consideration were held constant. Each run was optimized for residence time and cellulase dosage.

The study of sensitivities was lopsided in that many more of the effects examined had a negative impact on costs than a positive one. This is not uncommon when new processes are evaluated because emphasis is usually put on examining risk. Most improvements are already included in the platform case.

The sensitivity studies showed that the following must be demonstrated before it is prudent to proceed to Phase 4 under the CRADA using corn fiber as a feedstock:

a. Cost-effective removal of inhibitors using any of a number of biomass feedstocks in the PDU. If inhibitors can be recovered and sold, the byproduct credits could be very important to project justification.
b. Optimum pretreatment of corn fiber/corn screenings.
c. Properly dry and successfully test coproduct solids as an animal food. The value of the coproduct is critical to the overall economics for this process when corn fiber is the chosen feedstock.

Other improvements could reduce the cost of ethanol, but are not critical:

a. Improve the fermentive organism to react xylose to ethanol more quickly.
b. Improve the reliability of starch conversion to ethanol. Conversion was incomplete in some PDU runs.
c. Demonstrate the use of ammonia in the PDU as a source of nitrogen for the fermentive organism. This technique will both reduce the cost of the nutrient and help keep lactic acid out of the SSCF vessels. It is expected that if ammonia works for any feedstock, it should work for corn fiber; the reverse may not be true, since corn fiber contains all necessary nutrients other than nitrogen.

Recommendations

The Phase 3 data and results of the process design/economic analysis lead to the conclusion that the process for manufacturing ethanol from corn fiber developed under the CRADA is not ready yet for scale up to a demonstration plant. The key work needed to prepare the technology for commercial demonstration includes: (1) development of technology to control the effects of fermentation inhibitors; (2) determination of optimum pretreatment parameters for corn fiber; (3) testing and selection of equipment to separate product solids from waste liquids suitable for commercial use, and (4) integrated operation of the PDU using the configuration expected for the demonstration facility.