SERI/TP-231-3996
UC Category: 241
DE91002125

Ethanol Annual Report
FY 1990

Edited by
R.H. Texeira and
B.J. Goodman

January 1991

Prepared under task no. BF921010

Solar Energy Research Institute
A division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Preliminary Estimate of the Cost of Ethanol Production for SSF Technology

N. D. Hinman, D. J. Schell, C. J. Riley,
P. W. Bergeron, and P. J. Walter
Biotechnology Research Branch
Fuels and Chemicals
Research and Engineering Division
Solar Energy Research Institute
Golden, Colorado 80401

Abstract

SERI recently completed a detailed engineering and economic analysis of the simultaneous saccharification and fermentation (SSF)-based wood-to-ethanol process. The base case design was based on a plant capacity of 1,920 dry tons/day and a wood cost of $42/dry ton. For this case, the preliminary estimate of the production cost of the ethanol product is about $1.27/gal. The combined effects of optimization, increasing plant capacity to 10,000 dry tons/day, and reducing wood cost to $34/dry ton are to reduce the preliminary estimate of the production cost to about $0.83/gal. Other technology improvements further reduce the production cost to about $0.60/gal or less. Certain technical assumptions, inherent in the analysis, are being investigated further.

Introduction

Ethanol has received considerable attention over the years as an octane booster, fuel extender, or neat liquid fuel. Today, there is heightened interest in ethanol as a transportation fuel. This stems from the facts that half of all Americans live in areas that fail to meet federal clean air standards and that the combustion of conventional hydrocarbon transportation fuels contributes more to our nation's ground level air pollution than any other human activity. In addition, essentially all conventional transportation fuels are derived from petroleum, a finite resource in the United States. We currently import about 50% of the petroleum we consume as a nation. Moreover, approximately 40% of the U.S. balance-of-payments deficit results from dollars paid for imported oil. Finally, combustion of conventional transportation fuels contributes about 27% of the CO_2 released to the atmosphere in the United States each year; many believe that the accumulation of CO_2 will lead to the warming of the earth and severe climatic, environmental, and socioeconomic consequences. Ethanol produced from lignocellulosic biomass can make a significant contribution to solving these problems.

Several carbohydrate-containing feedstocks, including sugar crops, starch crops, and lignocellulosic materials, can be used as substrates for biological production of ethanol. In the United States, about 6.9 million tons of sugar are produced annually, but with prices controlled at about $360 per ton, sugar is too expensive to use for ethanol production. Almost all of the 800 to 850 million gallons of fuel ethanol currently produced in the United States is derived from corn kernels, a starch crop. Because corn typically sells for about $90 per dry ton (about $2.10/bushel), the price of the ethanol produced from this substrate is currently higher than the price of gasoline. Moreover, the potential annual ethanol production from corn kernels is estimated to be 4 billion gal/yr, which is only about 4% of the current automobile fuels market.

Lignocellulosic materials have promise as a substrate for ethanol production in the United States because of their low cost and their huge potential availability. This potential has been estimated at 2.7 billion tons per year or the equivalent of about 300 billion gallons of ethanol, which is significantly more fuel than the current U.S. automobile fleet consumes annually.

Lignocellulosic materials are composed of carbohydrate polymers known as cellulose and hemicellulose plus lignin and smaller amounts of other materials. Agricultural residues, municipal solid waste, underutilized standing forests and residues from logging operations, energy crops such as short-rotation woody crops and herbaceous crops, and waste streams from industrial operations are examples of this largely untapped source of renewable material.

The use of domestic lignocellulosic substrates for fuel ethanol production would increase fuel flexibility and reduce the related strategic vulnerability of our petroleum-based transportation fuel system. Also, because the carbon dioxide released during production and use of ethanol is recycled during the growth of biomass, there would be much less net accumulation of CO_2 to the atmosphere. In fact, if ethanol is used to run lignocellulose production operations, the net contribution of CO_2 to the atmosphere would be essentially zero. Thus, ethanol from lignocellulosic materials holds great promise as a new industry in the United States and has the potential for making a significant contribution to the solution of major problems facing our country.

The purpose of this study was to carry out an engineering and economic analysis of the current wood-to-ethanol process. A detailed analysis was performed on a base case process having a plant capacity of 1,920 dry tons/day and a hardwood feedstock cost of $42/dry ton. Using the design and economic information from the base case, a spreadsheet model of the wood-to-ethanol process was developed. This model was used to optimize the base case process and to examine the effect on ethanol production cost of (1) increased plant capacity, (2) decreased wood cost, and (3) technological improvements.

Methodology

Process Design

Introduction

The current process of wood to ethanol is a simplified, straightforward process that contains significant improvements over processes developed in the early 1980s. As shown in Figure 1, the basic units of this process consist of feed handling, pretreatment, cellulase production, xylose and cellulose fermentations, and ethanol purification. In this study, several alternative technologies were considered for pretreatment, cellulase production, and xylose and cellulose fermentations. The technologies selected for each of these basic units were as follows:

Unit	Technology
Pretreatment	Dilute sulfuric acid
Cellulase production	Batch culture with *Trichoderma reesei*
Xylose fermentation	Genetically engineered *E. coli*
Cellulose fermentation	SSF

The performance data on which the base case design was based come from SERI and other laboratories. The reported yields are not the best ever achieved, but rather conservative and reproducible values that form a reasonable basis for a design, reflecting the current state of process development. For dilute sulfuric acid pretreatment, yields and process conditions were taken from the work of K. Grohmann et al. (1985); performance data obtained by D. Spindler (1989) for a genetically engineered *E. coli* developed by L. Ingram of the University of Florida was used for xylose fermentation; cellulase production was carried out using data from several laboratories including Tangnu et al. (1981) and Hendy et al. (1982); and data for SSF were obtained from Spindler et al. (1988; 1989a; 1989b).

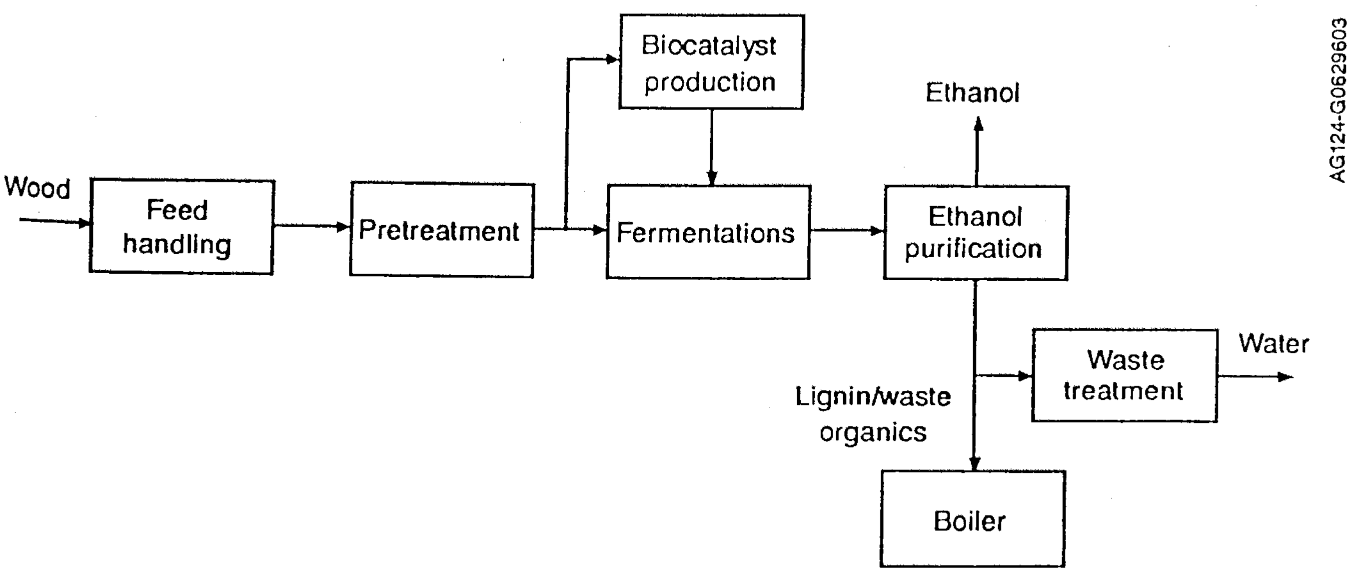

Figure 1. Biomass-to-ethanol process

Design Basis

The design basis of the base case process follows.

• Plant type	Grass roots, N^{th} plant
• Plant location	Unspecified
• On-stream time	8,000 h/yr
• Feed	1.0-in. wood chips
• Nominal capacity	160,000 lb dry wood/h (1,920 dry tons/day)
• Feed composition (dry basis)	46.2 wt% cellulose 24.0 wt% xylan 24.0 wt% lignin 5.6 wt% solubles 0.2 wt% ash
- Moisture content	50.0 wt%
• Lignin utilization	Boiler fuel
• Environmental	Cooling tower blowdown sent to evaporation pond Gypsum and boiler ash sent to off-site disposal Fermentative CO_2 vented to atmosphere Flume pond drained to evaporation pond
• Utilities	
- Steam	On-site generation from lignin and other waste organics
- Electricity	On-site generation from excess steam Excess sold over the fence

Design Procedure

For the base case, 19 detailed process flowsheets were prepared for the entire plant, including inside battery limits as well as off-sites. Detailed material balances were calculated for all areas of the plant and a complete utility summary was prepared. A complete list was compiled with sizes and specifications for more than 230 pieces of equipment, including spares.

Economics

Introduction

SERI developed investment and cost of production estimates for a base case plant producing 57.9 million gal/yr of denatured ethanol product based on a wood feedstock. The plant is based on the process design described above.

Capital Investment

The investment cost for the base case was developed by determining bare equipment costs for each piece of equipment. Costs on major pieces of equipment were obtained from recent vendor quotes (Chem Systems, Inc. 1990) as well as from other data sources, which include the ICARUS (1987) cost estimating system and engineering studies carried out under subcontract to SERI (Badger Engineers 1984; A.D. Little, Inc. 1984; Chem Systems, Inc. 1985, 1990; Stone and Webster 1985a, 1985b). From the bare equipment costs, the fixed capital investment was estimated using installation factors. These factors are based on vendor information, data for fermentation-type plants, and information from ICARUS (1987). Fixed capital investment includes direct field costs (labor and materials for purchased equipment, equipment setting, piping, civil, steel, instrumentation, electrical, insulation, painting, and buildings) and indirect costs (engineering, construction overhead, contractor's fee, contingency, and special charges).

The total capital investment includes fixed capital investment, miscellaneous fees, start-up costs, and working capital. Start-up costs are 5% of fixed capital cost and working capital is based on a formula that takes into account warehouse/spare inventory, accounts receivable/payable, and cash on hand.

Annual Cash Costs

Cash costs include expenditures for wood, raw materials, utilities, labor, maintenance, plant overhead, property taxes, and insurance. For the base case, the cost of wood was assumed to be $42/dry ton, and materials costs were at the current market value. Labor rates were assumed to be $29,400/yr to $40,000/yr, and direct overhead was at 45% of labor. Maintenance costs were at 3% of fixed capital investment and plant overhead was at 65% of labor plus maintenance. Taxes and insurance were 1.5% of fixed capital investment.

Annual Capital Charge

The annual capital charge was at 20% of the total capital investment. This includes depreciation, income taxes at 37%, 10% rate of return after tax, 15-year plant life, and 3-year construction period.

Results of Base Case Analysis

Capital Investment

A breakdown of the total capital investment for the base case is shown in Table 1. The fixed capital investment is estimated at $120 million and the total capital investment is estimated at $147.2 million. Utilities account for 40.3% of the fixed capital. In fact, the boiler and turbo generator alone account for 29% of the fixed capital. The prehydrolysis area accounts for 17.7% of the fixed capital and the SSF area

Table 1. Estimated Base Case Capital Investment

Plant Area	MM$
100 Wood Handling	2.28
200 Prehydrolysis	7.42
300 Xylose Fermentation	1.98
400 Cellulase Production	0.86
500 SSF	7.10
600 Ethanol Recovery	1.24
700 Off-site Tankage	1.00
800 Environmental Systems	1.31
900 Utilities (except boiler)	10.60
Miscellaneous	2.03
Total Equipment Cost (except boiler)	35.82
Times 2.85 Installation Factor	102.06
Boiler Package	18.02
Fixed Capital Investment	120.07
Miscellaneous	12.00
Start-up Costs	6.00
Working Capital	9.10
Total Capital Investment	**147.20**

accounts for 16.8%. The remaining 25.2% is divided fairly evenly between the other six plant areas and miscellaneous items.

Steam Consumption/Production

All steam requirements for the plant are provided by the combustion of lignin and waste organics. Total steam produced for the base case is 444 thousand lb/h of 1,100 psia steam. From this, 41.4 thousand lb/h of 150 psig and 222.9 thousand lb/h of 50 psig steam are extracted in a turbo generator and electricity is generated. The steam requirements of the plant are shown in Table 2. Steam is used primarily by the ethanol recovery and pretreatment units. The total steam energy consumed per gallon of ethanol product is 33,000 Btu/gal.

Electricity Production/Consumption

All power requirements for the plant are provided by cogenerated power from lignin and other waste organics. Total electricity produced for the base case is 36.1 MW, whereas 22.7 MW is consumed by the plant. The remaining 13.4 MW is sold at $0.03/kWh. A breakdown of electricity usage is shown in

Table 2. Plant Steam Requirements

	Thousand lb/h 50 psig	150 psig
100 Wood Handling	-	-
200 Pretreatment	30.6	41.4
300 Xylose Fermentation	-	-
400 Cellulase Production	0.12	-
500 SSF	-	-
600 Ethanol Purification	171.1	-
700 Off-site Tanks	-	-
800 Waste Treatment	-	-
900 Utilities	1.1	-
Miscellaneous	20.0	-
Total	**222.92**	**41.4**

Table 3. Here it is seen that the utilities area consumes 44.5% of the electricity, mainly by the chilled water system and air compressors. The next largest users are the mills in the wood handling area. This area consumes 33.8% of the electricity. Total electricity consumed per gallon of ethanol product is 3.14 kWh/gal.

Production Costs

A summary of the costs of production for the base case plant is shown in Table 4. For this case, the preliminary estimate of the cost of ethanol production is about $1.27/gal, which includes a $0.06/gal credit for electricity sales. The annual capital charge is the largest component of this cost, representing 38.3% of the cost. The wood cost at $42/dry ton is the second largest cost at 35% of the total cost. Materials are 10.1% of the cost and the remaining 16.6% is divided between maintenance, labor/direct overhead, general overhead, taxes/insurance, and miscellaneous. The estimated production cost minus the wood is $0.81/gal.

Potential Improvements to Base Case Economics

Optimization of the Base Case

A spreadsheet model of the SSF-based biomass-to-ethanol plant was developed from the design and equipment cost information from the base case. This model was used to optimize certain base case operations.

One operation examined was the use of recycled water to meet process water requirements. For the base case, process water requirements are met partially by recycled water and partially by fresh well water. However, analysis shows that maximum use of recycled water is preferable, lowering the cost of ethanol production by $0.04/gal. This results from a smaller waste treatment plant and improved overall yield of ethanol from recycled xylose.

Table 3. Plant Electricity Requirements

Area No.	Section	Electricity Consumed (kW)
100	Wood Handling	7,690
200	Pretreatment	410
300	Xylose Fermentation	597
400	Cellulase Production	746
500	SSF	2,237
600	Ethanol Purification	485
700	Off-site Tanks	89
800	Waste Treatment	373
900	Utilities	10,126
Total electricity consumed		22,753
Electricity produced, kW		36,100
Surplus power produced		13,347

Table 4. Estimated Base Case Cost of Production

Capacity: 1,920 dry tons/day
Throughput: 57.91 million gal/yr
Total Capital Investment: $147.2 million

	MM$/Yr	¢/gal
Wood	26.88	46.4
Materials	7.74	13.4
Gypsum Disposal	0.40	0.7
Electricity	(3.22)	(5.6)
Water	0.12	0.2
Labor/Supervision	1.57	2.7
Maintenance	4.14	7.2
Direct Overhead	0.71	1.2
General Overhead	3.71	6.4
Insurance, Property Tax	2.07	3.6
Total Cash Cost	**44.11**	**76.2**
Annual Capital Charge	29.44	50.8
Total Cost of Production	**73.55**	**127.0**

The optimum amount of cellulase to employ with SSF was also examined. In the base case, 7 international units (IU) of cellulase per gram of cellulose was used in SSF, whereas a more optimal use is about 13 IUs. At this level, the base case production cost drops by about $0.07/gal. Although the cost associated with the cellulase production unit increases, the SSF yield improves.

The combined effect of the two optimizations described above is to lower the base case production cost by $0.11/gal.

Effect of Increased Plant Capacity

The effect of increased plant capacity on production cost is shown in Table 5. Here it can be seen that increasing plant capacity from 1,920 dry tons/day to 10,000 dry tons/day decreases the production cost by $0.25/gal. Assuming a biomass yield of 10 tons/acre, the radius of feedstock collection for this larger plant is only a little over 10 miles.

Effect of Wood Cost

The effect of wood cost on the production cost relative to the base case is shown in Table 6. This table shows that at $34/dry ton (the goal of the Biomass Production Program), the production cost is lowered $0.09/gal, whereas at zero feedstock cost, the production cost is lowered $0.46/gal.

Combined Effect of Optimization, Increased Plant Capacity, and Lower Feedstock Cost

The combined effects of optimization and increasing plant capacity to 10,000 dry tons/day as a function of feedstock cost are shown in Figure 2. Here it is seen that for an optimized plant at 10,000 dry tons per day capacity and a feedstock cost of $34/dry ton, the production cost of ethanol is lowered $0.44/gal.

Table 5. Effect of Plant Capacity on Estimated Production Cost

Plant Capacity (dry tons/day)	Production Cost ($/gal)
1,920 (base case)	1.27
5,000	1.11
10,000	1.02
20,000	0.94

Table 6. Effect of Wood Cost on Estimated Production Cost

Wood Cost ($/dry ton)	Production Cost ($/gal)
42	1.27
40	1.25
35	1.19
34	1.18
30	1.13
25	1.08
20	1.02
15	0.97
10	0.91
0	0.81

Improvements to Technology

Improvements to the base case biomass-to-ethanol technology can reduce the cost of production by (1) increasing the yield of available carbohydrate to ethanol, (2) increasing the revenue from electricity, (3) decreasing capital-related costs, or (4) decreasing noncapital-related cash costs. The effect of improving yield and decreasing capital- and noncapital-related cash costs is shown in Figure 3. Clearly, improving yield over the 68% yield for the base case has the biggest impact on production cost. Decreasing capital-related costs is next in importance, with decreasing noncapital-related cash cost of least importance.

Using the spreadsheet model, the effects of several specific performance improvements in the base case were investigated, as shown in Table 7. As expected, improvements of yields, particularly SSF yields, have significant impact on the production cost. Reduction of SSF fermentation time also has a significant effect. The combined effect of the individual improvements is shown in Table 8 for the case with wood at $42/dry ton and plant capacity of 1,920 dry tons/day as well as for wood at $34/dry ton and a plant capacity of 10,000 dry tons/day. For the latter case, the production cost is $0.61/gal.

Other technology improvements besides those shown in Table 7 are possible. They include (1) use of feedstocks with higher carbohydrate content, (2) further reduction of power for milling, (3) reduced power and capital for air compression, (4) increased efficiency of the boiler/turbo generator, (5) improved heat integration, (6) reduced nutrient costs, and (7) advanced bioreactor designs.

Conclusions

Progress in the development of an SSF-based biomass-to-ethanol process has been steady and significant since 1980. In 1980, the production cost of ethanol was estimated at $3.60/gal; today the preliminary estimate of the cost for a base case design is $1.27/gal. This current base case cost assumes a feedstock cost of $42/dry ton and a plant capacity of 1,920 dry tons/day. Moreover, this cost is for an unoptimized

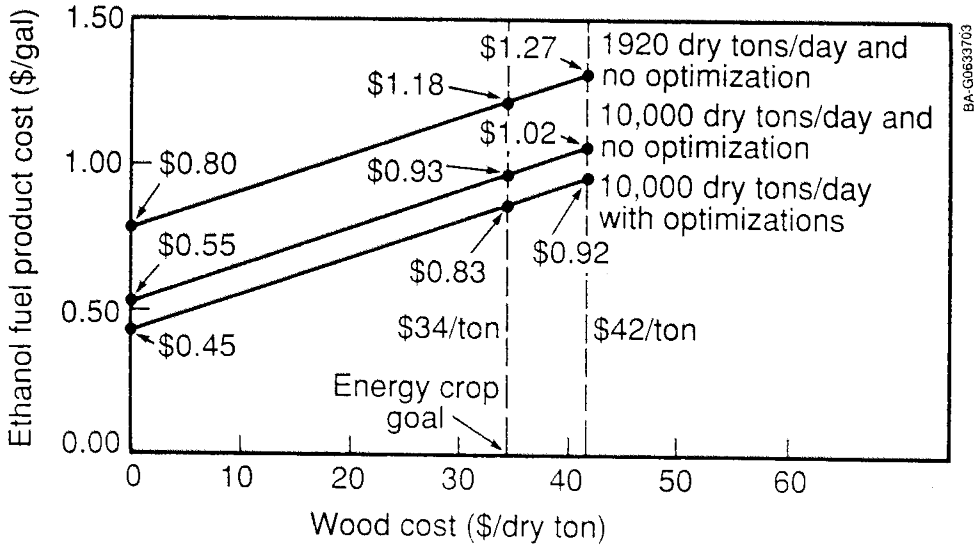

Figure 2. Combined effects of plant size and optimization versus wood cost

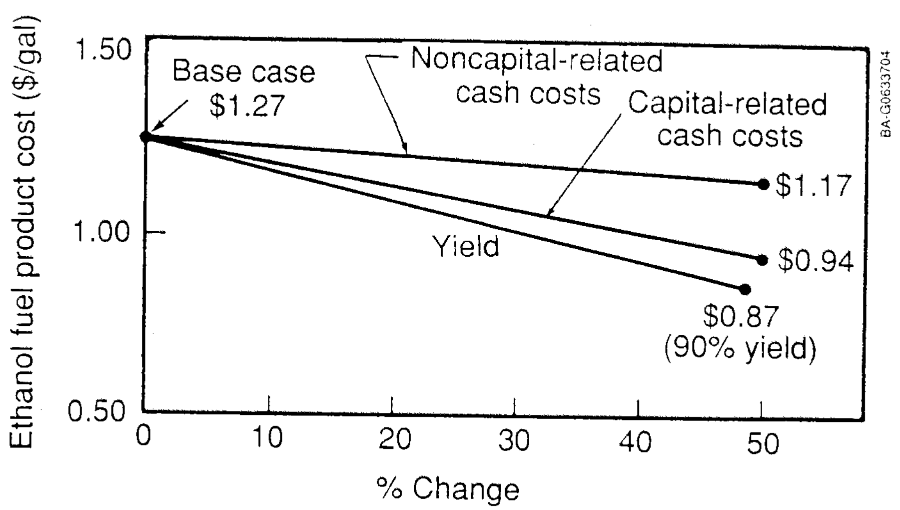

Figure 3. Effect of increased yield, decreased capital cost, and decreased cash costs

SERI

Table 7. Effect of Specific Improvements on Estimated Production Cost of Fuel Ethanol

Improvement	Decrease From Base Case of $1.27/gal (¢/gal)
Yield-Related	
• Improve SSF yield to 90%	15
• Improve xylose to ethanol yield to 90%	7
• Minimize need to regrow *T. reesei* to produce each batch of cellulase	6
• Improve xylan to xylose yield to 90%	2
Capital-Related	
• Decrease SSF fermentation time to 2 days	8
• Decrease xylose fermentation time to 1 day	3
• Decrease cellulose fermentation time to 4 days	2
Noncapital-Related	
• Decrease milling HP by 35%	2

Table 8. Combined Effect of Individual Technical Improvements on Estimated Production Cost of Ethanol

Case	Production Cost ($/gal)
Base case of wood at $42/dry ton and capacity at 1,920 dry tons/day	1.27
Technical improvements shown in Table 7, wood at $42/dry ton and capacity at 1,920 dry tons/day	0.83
Technical improvements shown in Table 7, wood at $34/dry ton and capacity at 10,000 dry tons/day	0.61

plant. However, certain technical assumptions inherent in the analysis must be investigated before the analysis can be finalized.

For an optimized plant using wood at $34/dry ton and having a capacity of 10,000 dry tons/day, the production cost of fuel is estimated to be 34% below the base case cost. The base case yield of ethanol from available carbohydrate is 68%, and improvements in yield will have a significant impact on the production cost. Substantial improvements in yield are possible and are being achieved in the laboratory. Technology improvements that result in lower capital-related costs will also have a significant impact on production cost, but not to the same extent as yield improvements. Lowering noncapital-related cash costs will have less impact on production costs.

Use of a spreadsheet model of the SSF-based biomass-to-ethanol process indicates that, with certain specific improvements in yields and reaction rates together with $34/dry ton feedstock and a capacity of 10,000 dry tons/day, the cost of ethanol production can be reduced to $0.61/gal. Other improvements, which could reduce the cost even further, are also possible.

Acknowledgment

This work was supported by the Ethanol from Biomass Program of the U.S. Department of Energy's Biofuels Systems Division.

References

Arthur D. Little, Inc. 1984. SERI Subcontract No. 625-RIER-BEA-84.

Badgers Engineers, Inc. 1984. SERI Subcontract No. ZX-3-030-96-2.

Chem Systems, Inc. 1985. SERI Subcontract No. XX-3-03097-2.

Chem Systems, Inc. 1990. Subcontract No. HD-0-10116-1.

Grohmann, K., Torget, R., and Himmel, M. 1985. *Biotechnol. Bioeng. Symp.* 15:59-80.

Hendy, N., Wilke, C., and Blanch, H. 1982. *Biotechnol. Lett.* 4(12):785-788.

ICARUS Corporation. 1987. *Cost Systems User's Manual.*

Spindler, D.C., Wyman, C. E., Mohagheghi, A., and Grohmann, K. 1988. *Appl. Biochem. Biotechnol.* 17:279-283.

Spindler, D.D., Wyman, C. E., and Grohmann, K. 1989a. *Biotechnol. Bioeng.* 34:189-195.

Spindler, D.D., Wyman, C. E., Grohmann, K., and Mohagheghi, A. 1989b. *Appl. Biochem. Biotechnol.* 20/21:529-540.

Spindler, D. D. 1989. Personal communication, Solar Energy Research Institute.

Stone and Webster Engineering Corp. 1985a. SERI Subcontract No. ZX-3-03097-1.

Stone and Webster Engineering Corp. 1985b. SERI Subcontract No. ZX-3-03096-1.

Tangnu, S.K., Blanch, H. W., and Wilke, C. R. 1981. *Biotechnol. Bioeng.* 23:1837-1849.