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Cost Estimates and Sensitivity Analyses for the Ammonia Fiber Explosion Process

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ABSTRACT

Process designs were conducted for each unit of the conceptual ammonia fiber explosion (AFEX) process, and fixed capital investment and operating costs were estimated. AFEX costs about $20–40/t of dry biomass treated. Several promising areas for reducing process costs exist. Return on investment (ROI) calculations were also done for AFEX-treated materials (as digestibility-enhanced animal feeds), in conjunction with sensitivity analyses on the overall processing costs. Estimated ROIs range from over 100%/y to negative, depending on the system variables. The most important variables are the cost of corn and corn fiber, ammonia loading, and whether or not drying is required.

Index Entries: Biomass pretreatment; cost estimation and economic analysis; process design; computer simulation; ammonia fiber explosion.

INTRODUCTION

The production of fuels and chemicals by fermentation of renewable resources has received increasing attention over the past several decades. Biomass is the only renewable resource that can be directly converted to liquid fuels. The dominant forms of biomass are grain starches and lignocellulosic crop and forest materials. The most viable carbohydrate substrates for fermentation to produce fuels and chemicals at very large scale will probably be derived from lignocellulosic crop and forest materials, rather than from grain or other food materials, because of economic considerations and the volume of raw material available. These lignocellulosic crop and forest materials have also been investigated for many years as potential animal feedstuffs.

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A key problem in utilization of these lignocellulosics for either feedstuffs or fuel/chemical production is the relatively unreactive nature of the cellulose, in particular the poor yields of glucose from cellulose by acids or enzymes. The AFEX pretreatment increases biomass digestibility significantly *(1)*; yields of fermentable sugars by enzymatic hydrolysis, following AFEX are typically 4–5X greater than those obtained on untreated materials. Ammonia, a volatile chemical, is easy to recover, compared with other chemical pretreatments. Few, if any, fermentation inhibitors or sugar degradation products are formed during the AFEX process *(2)*. In addition, the energy requirements and capital costs for AFEX are expected to be relatively modest *(3)*.

The purpose of this study was to develop a computer simulation program that could be used to carry out engineering and economic analyses of the current conceptual AFEX process, under different scenarios, using existing laboratory data.

METHODS

Process Design

Process Description

The current conceptual design for the AFEX process is simple and straightforward, but has two major variations: the so-called wet product option (Fig. 1) and the dry product option (Fig. 2). Under both options, a V-Ram pump feeder takes a slug of biomass from the hopper to the high pressure AFEX pretreatment reactor, in which the liquid ammonia is added. When the reaction is complete, a large valve at the bottom of the reactor opens, allowing the biomass to explode into a flash tank. The high pressure is suddenly released, and most of the ammonia flashes at that moment. The amount of ammonia flashed depends on reaction temperature, pressure, and, especially, the water and ammonia loading. The ammonia vapor from the flash tank is taken to a precondenser, which concentrates ammonia vapor to 99.8% (w/w), and then the ammonia vapor from the precondenser enters a total condenser, which condenses ammonia vapor to 99.8% (wt) liquid ammonia. The liquid ammonia from the total condenser is pumped and stored in an ammonia drum.

The liquid phase from the precondenser is taken to a distillation column. Ammonia vapor with a concentration of 99.8% (wt) is obtained from the top product of the distillation column, which enters a total condenser, and condenses to liquid ammonia. Through the liquid ammonia pump, pressurized liquid ammonia is transferred and stored in the ammonia drum. The recovered 99.8% (wt) liquid ammonia can be recycled to the AFEX pretreatment. The bottom product of the distillation column is water with 0.01% (wt) ammonia, which is stored in a water tank.

For the wet option, as shown in Fig. 1, the pretreated biomass from the flash tank is transferred to a unit that uses water to wash out enough

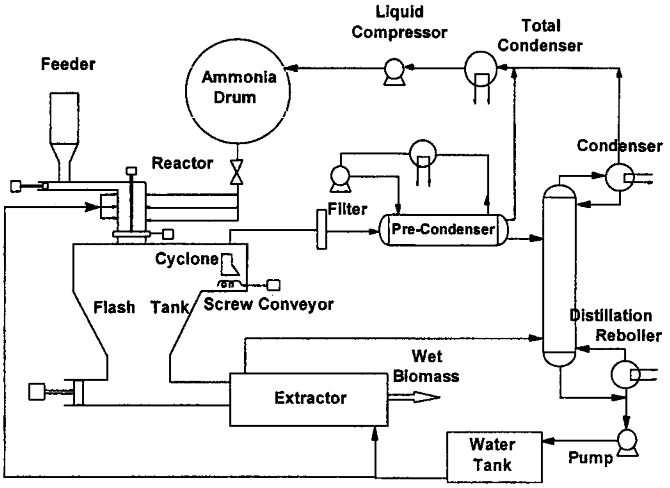

Fig. 1. The AFEX pretreatment process flow sheet diagram for the wet option.

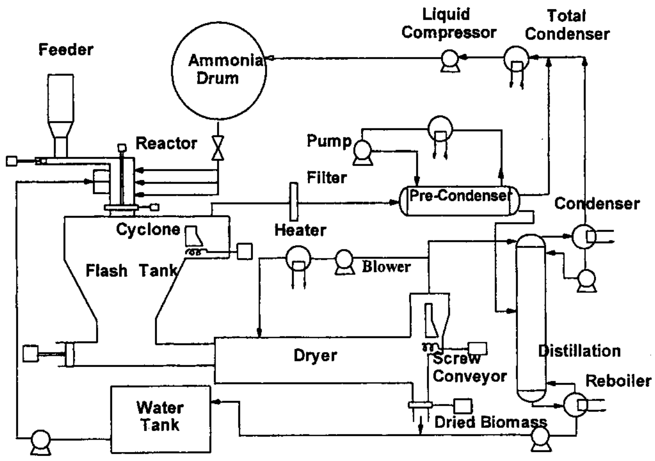

Fig. 2. The AFEX pretreatment process flow sheet diagram for the dry option.

of the remaining ammonia in the pretreated biomass to match the design requirement, which specifies how much ammonia can remain in the pretreated biomass as a nitrogen source for fermentation or for animal feeding. For the dry option, as shown in Fig. 2, the pretreated biomass from the flash tank is transferred to a dryer, which uses heated ammonia vapor to evaporate the extra ammonia remaining in the pretreated biomass, to meet the design requirement. This evaporated ammonia is absorbed in water and distilled as above. The pretreated biomass is now ready for hydrolysis, fermentation, or animal feeding. Dry AFEX-treated biomass can be easily stored and transported, but the wet, AFEX-treated biomass is presumed to be used within a few hours, and is not assumed to be transported significant distances.

Model Description

This computer simulation work was based on published AFEX experimental results *(1–4)*, as-yet unpublished results, personal communications *(5,6)* and the known vapor–liquid equilibrium of the ammonia–water system *(7,8)*. Since the strong polar character of aqueous ammonia solution causes severe nonideality problems, equilibrium models, which correlate other systems very well, often fail to correlate this strong polar and water-containing system. A set of equations developed by Schulz *(8)* was used to correlate vapor–liquid equilibria and other thermodynamic data for the ammonia–water system over relatively wide temperature and pressure ranges.

The most difficult work is in the modeling of the distillation columns and flash tank, because the strong polarity of the ammonia–water system causes difficulties with convergence of the model equations. Different numerical methods are used to solve the model equations *(9)*. Other areas of considerable uncertainty, and potential research subjects, are the drying curves for ammonia-laden biomass, and the equilibrium relationships between ammonia, biomass, and water in the biomass. Standard design equations are also used for equipment sizing *(10)*.

The calculation procedure was programmed in MS (i.e., Microsoft) Fortran, a Fortran programming language based on Fortran 77, which has some advanced features of Fortran 90. To enhance the portability of the program, an IBM-compatible PC was used in the programming. Microsoft Fortran 5.1 was used as the development tool, which does the compiling and linking of the program.

Summary Conditions: Base Case:

• Costs	1995 dollars
• Plant location	Unspecified
• On-stream time	8000 h/yr
• Feed	Corn fiber or rice straw
• Ammonia loading (lb ammonia/lb dry biomass)	1.0 (corn fiber), 1.5 (rice straw)
• Water loading (lb water/lb dry biomass)	1.5 (corn fiber), 1.5 (rice straw)
• Treatment pressure (kpa)	1135 (corn fiber), 2413 (rice straw)
• Treatment temperature (°C)	90 (corn fiber), 95 (rice straw)
• Treatment time (min)	30 (corn fiber), 20 (rice straw)
• Nominal capacity	10 t dry biomass/h
• Product	Pretreated biomass
• Utilities	Provided by existing facilities

Economics

The investment costs for different scenarios were developed by determining bare equipment costs for each piece of equipment. Costs of major pieces of equipment were obtained from recent vendor quotes *(11)*, as well as from other sources *(12)*. From the bare equipment costs, the fixed capital investment was estimated, using Lang multiplication factors *(12)* to calculate the capital necessary for the installed process equipment with all auxiliaries needed for complete process operation. Assuming the AFEX pretreatment plant is similar to an average chemical plant that processes both solids and liquids, the Lang multiplication factor used here is 4.1 *(12)*. The working capital for the AFEX process is estimated as 15% of the total capital investment *(12)*. The total capital investment is the sum of fixed capital investment and the working capital. All expenses directly connected with the manufacturing operation or the physical equipment of a process plant itself are included in the total manufacturing costs.

The assumed selling price for the AFEX-treated biomass was determined by measuring the digestibility of the treated material in rumen fluid, and assuming that the selling price was proportional to the digestibility, given the known digestibility of the corn fiber after treatment (90%), the digestibility and moisture content of grain (80 and 10%, respectively), and the average selling price of corn grain in the first three-quarters of 1995 *(13)*, or approx $3.80/bu. This approach tends to underestimate the value of the AFEX-treated corn fiber, since corn fiber also contains over 10% protein and some nonprotein nitrogen from the AFEX process, which will increase the feed value of the material. Since recent corn prices have been somewhat higher than historic levels ($2.50–$3.00/bu), a sensitivity analysis was done to determine the effect of corn prices at historical levels of about $2.50/bu on the calculated ROIs.

The return on investment is then calculated as the following:

$$\text{ROI} = (\text{Selling price} - \text{Feedstock price} - \text{Total manufacturing cost}) \cdot \text{ton of production/Total capital investment}$$

All cost estimates were performed in the spreadsheet program.

RESULTS AND ANALYSES

Capital Investment

Purchased-capital investment breakdowns for corn fiber are shown in Table 1 for the wet option, and in Table 2 for the dry-product option. The fixed capital investment for corn fiber in Table 1 is estimated at about $2.2 million for the wet option, and at about $14 million for the dry option (Table 2), reflecting the much higher costs for the dryers needed in the second option. Since there is little or no information on the rate of ammonia evaporation from biomass, a very conservative approach to cost estimation was taken, and this probably contributed to the high estimated drying costs.

Table 1
Purchased Equipment Cost for Corn Fiber Base Case: Wet Option

Purpose	Equipment	Unit price ($)	Total cost ($)
Feeding and flashing	V-Ram pump feeder	17,300	69,200
	Reactor agitator	11,900	47,600
	Reactor	46,610	186,440
	Flash tanks	50,430	50,430
	Flash tank cyclone	3020	3020
	Flash tank screw Conveyor	4420	4420
	Sub total		361,100
Ammonia recovery from treated corn fiber and flash vapor	Washer	100,000	100,000
	Distillation column	36,730	36,730
	Distillation condenser	8320	8320
	Reboiler	4620	4620
	Reflux pump	2080	2080
	Reboiler pump	4890	4890
	First condenser	1670	1670
	Total condenser	2600	2600
	Liquid compressor	3200	3200
	Accumulator	4620	4620
	Sub total		169,400
	Total		530,500
	Total updated to 1995		910,000
	Fixed capital investment		3,730,000

Note: Costs of major pieces of equipment were obtained from recent vendor quotes *(11)*, as well as from other sources *(12)*. From the bare equipment costs, the fixed capital investment was estimated using Lang factor *(12)*, which represents the capital necessary for the installed process equipment with all auxiliaries needed for complete process operation. Assuming the AFEX pretreatment plant is similar to an average chemical plant that processes both solids and liquids, the Lang multiplication factor used here is 4.1 *(12)*. Marshall and Swift equipment cost indexes were used to update cost data to 1995. The Marsh and Swift all-industry equipment index for 1995 is 1042.9.

Production Costs

Summaries of the costs of production of AFEX-treated corn fiber base case for both options are shown in Tables 3 and 4. The feedstock cost at \$50/t *(13)* is the largest component of the cost for both options, representing 53% of the total costs for the wet option and 32% of the costs for the dry option. Utility costs are high for both options, and fixed charges are nearly as significant as utility costs for the dry option.

SENSITIVITY ANALYSES

Using available experimental data *(1,2,6)*, a variety of simulations were obtained from the computer simulation program and spreadsheet

Table 2
Purchased-Equipment Cost for Corn Fiber Base Case: Dry Option

Purpose	Equipment	Unit price ($)	Total cost ($)
Feeding and flashing	Feeder	17,300	69,200
	Reactor agitator	11,900	47,600
	Reactor	46,610	186,440
	Flash tanks	50,430	50,430
	Flash tank cyclone	3020	3020
	Flash tank screw Conveyor	4420	4420
	Sub total		361,100
Flash vapor recovery	First condenser	1670	1670
	Distillation column	33,830	33,830
	Distillation condenser	11,890	11,890
	Reflux pump	2070	2070
	Distillation reboiler	2920	2920
	Reboiler pump	3520	3520
	Total condenser	2600	2600
	Liquid compressor	3200	3200
	Accumulator	4620	4620
	Sub total		66,320
Ammonia recovery from treated corn fiber	Dryer screw conveyor	4420	75,140
	Dryer	49,550	842,350
	Cyclone	11,400	193,800
	Blower	88,170	1,499,000
	Heat exchanger	6030	102,510
	Sub total		2,712,790
	Total		3,140,000
	Total updated to 1995		5,340,000
	Fixed capital investment		21,900,000

Note: See corresponding note for Table 1.

program. Selected results from these simulations are presented in Fig. 3A–D to 5A–C.

Effect of Ammonia Loading and Reaction Pressure

Figure 3A–C shows that when the ammonia loading is increased (which also increases the reaction pressure), the total capital investment (TCI) increases, because larger equipment is required to recover the extra ammonia. The value of TCI increases very quickly for the dry option, because the number of dryers that is required for recovering extra ammonia increases dramatically, and these dryers are a dominant part of the TCI for this option. As the ammonia loading increases, the reaction pressure also increases. This also raises the TCI, because the higher reaction pressure requires more robust equipment.

Table 3
Preliminary Cost Estimate for Corn Fiber Base Case: Wet Option

Selling price ($/t)	$202	
Feedstock price ($/t)	$50	
H/yr	8000	
Tonnes/hr feedstock	10	
Number of operators per hr	2	
Direct costs:		
Equipment costs:	$910,000	
Lang factor (solid/fluids processing plant)	4.1	
Fixed capital investment (FCI)	$3,731,000	
Working capital (15% of FCI)	$560,000	
Total capital investment (TCI)	$4,291,000	
Manufacturing costs:	**$/t**	**$/yr**
Raw materials ($0.10/lb of ammonia)	0.66	53,000
Operating labor ($16/h)	3.20	256,000
Direct supervisory and clerical labor (18% of operating labor)	0.58	46,000
Maintenance and repairs (6% of FCI)	2.80	224,000
Operating supplies (15% of maintenance)	0.42	33,600
Lab charges (15% of operating labor)	0.48	38,400
Utilities:	**$/t**	**$/yr**
Coal ($3/million BTU)	10.09	810,000
Cooling cost ($2.00/t–d (288,000 BTU removed)	20.46	1,640,000
Fixed charges:	**$/t**	**$/yr**
Depreciation (10-yr life, straight line, no salvage value)	4.62	370,000
Local taxes (2.5% of FCI)	1.16	93,000
Insurance (0.7% of FCI)	0.32	26,000
Total manufacturing cost:	44.80	3,590,000

The ammonia loading also affects operating costs, especially for dryer operation. When the ammonia loading is increased from 0.10 to 2.0 (kg ammonia/kg biomass), the TCI increased by almost $3 million for the wet option, and by $13 million for the dry option. The utility cost increased almost $16/t biomass in the wet option, and $30/t biomass in the dry option.

However, the ammonia loading effect on ROI does not parallel the effect on TCI and utilities, because improvements in expected rumen digestibility increase the value of the treated material, and digestibility does not change in the same way with the changing ammonia loading *(6)*. Better data on the effect of ammonia loading on digestibility are needed, especially at low ammonia loadings, but it is obvious that the less ammonia, the better the ROI, at least down to the point at which the effectiveness of the treatment is significantly reduced. Even at 0.1 kg ammonia/kg dry

Table 4
Preliminary Cost Estimate for Corn Fiber Base Case: Dry Option

Selling price ($/t)	$202	
Feedstock price ($/t)	$50	
H/yr	8000	
Tonnes/hr feedstock	10	
Number of operators per h	3	
Direct costs		
Equipment costs	$5,340,000	
Lang factor (new technology and solid/fluids)	4.1	
Fixed capital investment (FCI)	$21,900,000	
Working capital (15% of FCI)	$3,870,000	
Total capital investment (TCI)	$25,770,000	
Manufacturing costs	**$/t**	**$/yr**
Raw materials ($0.10/lb of ammonia)	1.10	88,000
Operating labor ($16/h)	4.80	384,000
Direct supervisory and clerical labor (18% of operating labor)	0.86	69,120
Maintenance and repairs (6% of FCI)	16.43	1,314,000
Operating supplies (15% of maintenance)	2.46	197,100
Lab charges (15% of operating labor)	0.72	57,600
Utilities	**$/t**	**$/yr**
Coal ($3/million BTU)	15.15	1,212,000
Cooling cost ($2.00/t/d (288,000 BTU removed)	29.06	2,324,800
Fixed charges	**$/t**	**$/yr**
Depreciation (10-yr life, straight line, no salvage value)	27.38	2,190,000
Local taxes (2.5% of FCI)	6.84	547,500
Insurance (0.7% of FCI)	1.92	153,300
Total manufacturing cost	107.00	8,540,000

corn fiber, very substantial improvements in digestibility were obtained. Significant, although not nearly as large, improvements in rice straw digestibility were also obtained at low ammonia loadings.

The results for the different simulation cases are summarized in Fig. 3C. Although the calculated ROI values for the dry option are still economically attractive, they are much less attractive than those for the wet option. Although it is perhaps somewhat obvious, it is still worth knowing explicitly that one should not attempt to evaporate ammonia twice, once in the dryer and a second time in the distillation column, otherwise, process economics suffer.

Effect of Treatment Temperature

These simulations were done using experimental results obtained on rice straw, since there is not a complete corresponding data set for corn

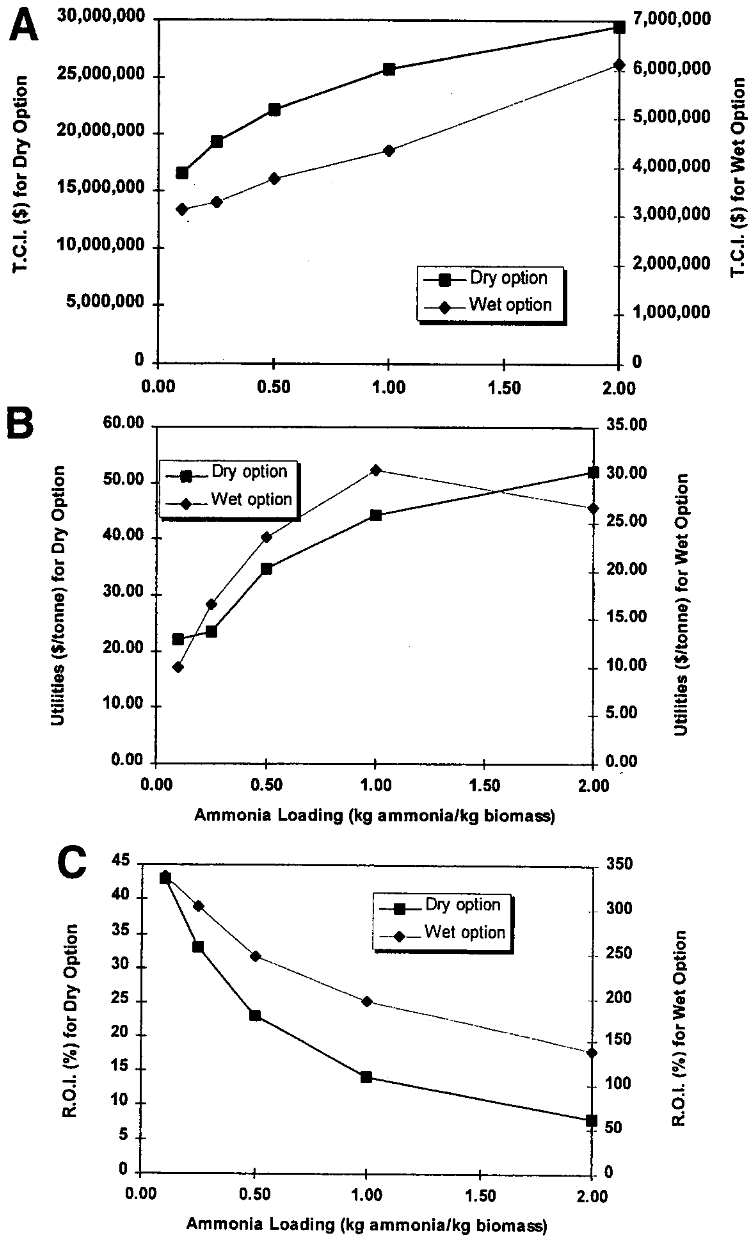

Fig. 3. **(A)** Ammonia loading effect on TCI for corn fiber. **(B)** Ammonia loading effect on utilities for corn fiber. **(C)** Ammonia loading effect on ROI for corn fiber.

fiber. From Fig. 4A–C, the treatment temperature strongly affects the values of TCI and utilities in the dry option. When the treatment temperature increased from 80 to 95°C, the value of TCI for the dry option increased about $20 million, and utilities increased by about $24/t of biomass. The dryers made a significant contribution to the TCI and utilities increases

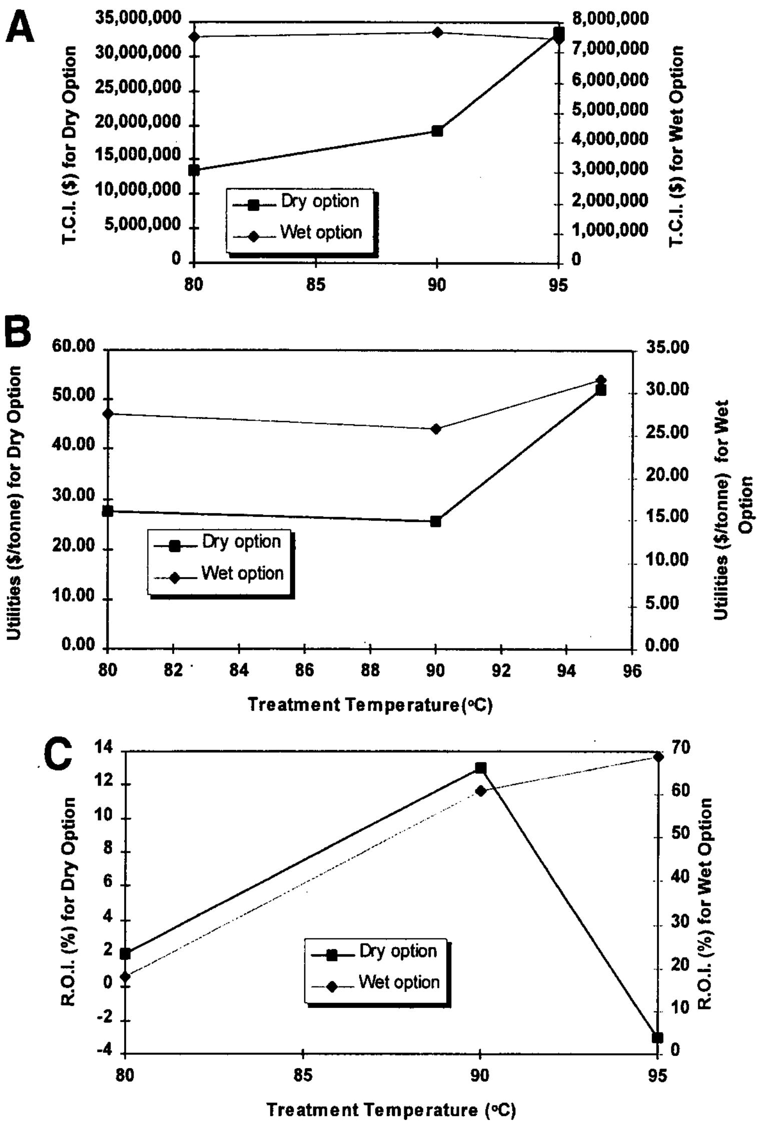

Fig. 4. **(A)** Treatment temperature effect on TCI for rice straw. **(B)** Treatment temperature effect on utilities for rice straw. **(C)** Treatment temperature effect on ROI for rice straw.

because the number of dryers increased very fast when the treatment temperature increased.

In the wet option, the treatment temperature did not affect TCI significantly, because the reaction pressure was not as strong a function of temperature, because of the presence of water. In the wet option, utilities were not significantly affected by the temperature because the wet option requires much less energy than the dry option. Because the digestibility was significantly improved when the treatment temperature increased, the value of ROI also improved significantly for the wet option. However, the dry option costs much more in TCI and utilities, and as a result the digestibility improvement did not much affect the ROI. However, as mentioned, drying costs are probably substantially overestimated because of lack of information on the rate of ammonia evaporation from biomass, and the temperatures required.

In general, the wet option seems to be preferred to the dry option for the AFEX pretreatment process, because it does not cost nearly as much in both TCI and utilities, and both TCI and utility costs are not strongly affected when the ammonia loading and treatment temperature are increased in order to increase the effectiveness of the treatment. However, there may be cases in which a wet AFEX-treated material is not practical for subsequent use, and, at least under some conditions, the dry option still provides attractive economics (e.g., Fig. 3C). Note also that calculations of ROI depend on product values determined from estimates of ruminant digestibility, and that these estimates are still quite preliminary and incomplete. Notwithstanding the uncertainties surrounding ROI calculations, the relative merits of the wet and dry options, and the relative impacts of various system parameters on the system economics, are quite clear. Clarifying the relative importance of these factors was the major purpose of this study.

Effect of Reaction Time

From Fig. 5A–C, one sees that, when the reaction time increases from 4 to 20 min, the TCI increases by about 50% in the wet option. Reaction time does not affect the TCI significantly for the dry product option because the TCI for this option is dominated by the dryer costs. The TCI for the dry option depends on the ammonia loading, water loading, and reaction pressure. Reaction time does not affect the utility cost in either option, because the utility costs are most strongly determined by the ammonia loading and the water loading. Reaction time does affect the ROI, because the digestibilities of treated biomass are significantly different at different reaction times.

Effect of Feedstock Price, Cost of Cooling, Cost of Energy, and Cost of Corn

As the results in Fig. 6, indicate the feedstock price has a large impact on ROI When the feedstock prices for corn fiber are 30, 40, 50, and $60/dry t, the values of ROI are 234, 216, 197, and 179%, respectively—a decline of 56% for a doubling in the feedstock price. In Fig. 7, one sees that, when the cost of cooling varies from $1.00–2.50/t/d for the corn-fiber base case, the ROI declines from 216 to 188%, a decline of 19%, for a doubling in cooling cost. In Fig. 8, when the cost of energy doubles from $2 to $4/million BTU for corn fiber base case, the ROI decreases from 203 to 191%,

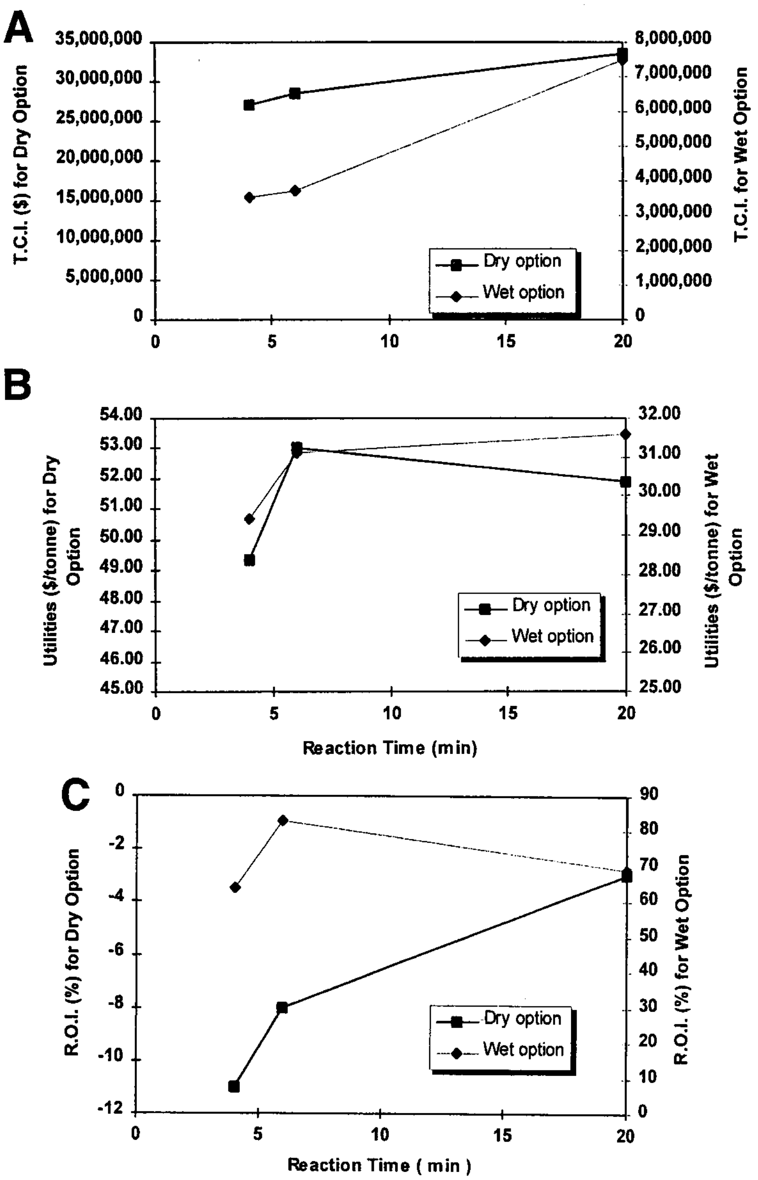

Fig. 5. **(A)** Reaction time effect on TCI for rice straw. **(B)** Reaction time effect on utilities for rice straw. **(C)** Reaction time effect on ROI for rice straw.

a decline of 12%. Therefore, the costs of cooling and energy do significantly affect the ROI value, but they are not nearly as important as the feedstock cost in their impact on ROI, as expected.

However, by far the most significant effect of all is the effect of corn price on the ROI. Figure 9 shows that, under the corn fiber base case conditions for the wet product option, a 50% increase in corn selling price (from about $2.50/bu to about $3.80/bu) increases the ROI from 74 to 197%, or

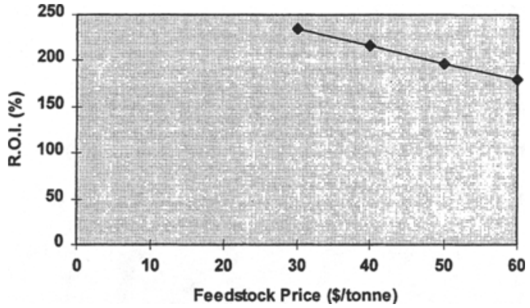

Fig. 6. Feedstock price effect on ROI for corn-fiber base case.

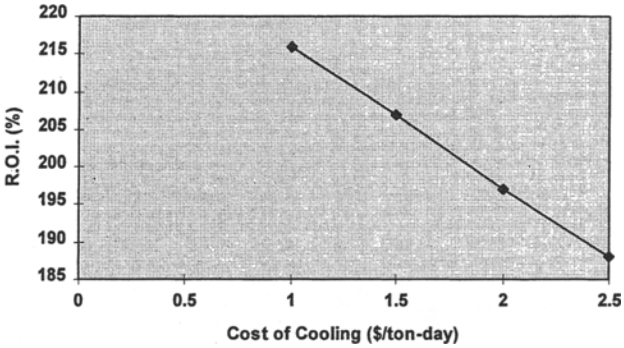

Fig. 7. Cooling cost effect on ROI for corn-fiber base case.

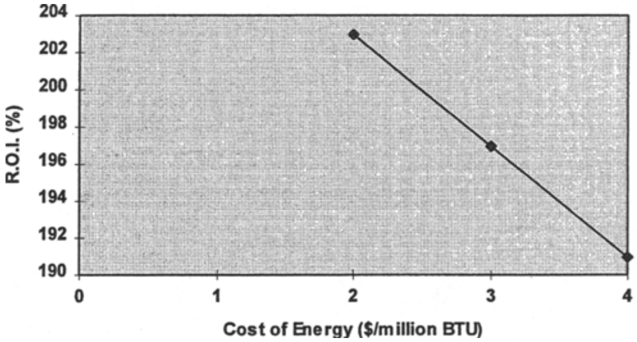

Fig. 8. Energy cost effect on ROI for corn-fiber base case.

an increase in ROI of 266%. Similar percentage changes are observed for the dry-product option. Obviously, profitability depends very strongly on the spread between the feedstock price and the price of the competing digestible material, which is corn in this case. In countries with ample grass and other cellulosic feedstocks, such as tropical areas, but where grain is costly, the AFEX process might have an exceptional impact.

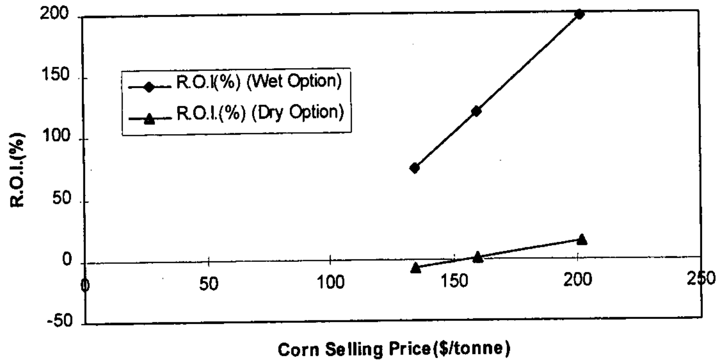

Fig. 9. Effect of corn selling price on ROI for corn-fiber base case.

CONCLUSIONS

A computer simulation program has been developed for the AFEX pretreatment process. This program can be used to assist design of the process, and to predict the economics for the AFEX pretreatment under different scenarios, thereby helping guide further research to reduce costs and increase profitability. Although some of the data on which the program relies are incomplete (e.g., the evaporation rate of ammonia from biomass), a number of important conclusions have resulted from this first generation model and simulation study, namely:

1. The cost of AFEX treatment is about \$20–\$40/t of dry biomass treated for the wet option, and significant opportunities exist for further reducing process costs.
2. Very attractive ROIs result for AFEX-treated biomass as an animal feed in these studies, and treated corn fiber has significantly better ROIs than rice straw, because of its very high digestibilities.
3. The wet option is to be preferred to the dry option under most conceivable circumstances, because it has much lower TCI and utility costs.
4. The cost of corn is the dominant factor in ROI, when AFEX-treated biomass is considered as a replacement for corn grain in ruminant animal diets. Cost of the biomass itself is the next most important effect on ROI.
5. Higher reaction pressures (and temperatures) will increase both TCI and utility costs, but much less for the wet option, compared to the dry option.
6. Ammonia loading does not affect TCI greatly, but low ammonia loadings do improve the ROI through lower utility costs.
7. Increased water-loading significantly increases TCI and utility costs, and decreases the ROI, especially for the dry option.

8. Increased reaction time increases TCI significantly for the wet product option. It also increases the ROI somewhat because of the increased digestibility.
9. Finally, the AFEX process conditions must be tuned, both technically and economically, for a given feedstock and a given intended final use of the sugars made available by the pretreatment. Optimal conditions are not obvious beforehand.

Parallel cost–benefit studies on preparing AFEX-treated material for enzymatic hydrolysis to fermentable sugars are strongly suggested by these results, in order to optimize the treatment for such applications, and to suggest future research priorities.

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