0273-2289/95/5152—0593$06.40

Economic Assessment of Ethanol Production Comparing Traditional and Fluidized-Bed Bioreactors†

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ABSTRACT

This study analyzes the economic impact that a fluidized-bed reactor (FBR) using immobilized *Zymomonas mobilis* would have on a plant converting cornstarch into ethanol. The study addresses substituting this new technology into an existing plant or using it for a new plant. We have compared the processing steps required by the FBR with conventional technology, and developed process flow schematics, priced required equipment, and generated plant capital and operating cost estimates. This allowed a cost evaluation between the FBR and traditional technologies, such as well-mixed fed-batch fermentation. The study results indicate that the FBR technology can provide a significant reduction in the production costs of ethanol—a savings of >$0.02/gal if inserted into an existing plant, and a savings of >$0.06/gal if used at a new plant.

Index Entries: Ethanol fermentation; fluidized-bed reactor (FBR); *Zymomonas mobilis*; operating costs.

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INTRODUCTION

The purpose of this study was to prepare an economic assessment to determine the impact that a new technology, demonstrated at small scale, would have on the capital and operating costs of a full-scale production unit converting cornstarch into ethanol. The new technology is an FBR using immobilized *Zymomonas mobilis*, as devised by Oak Ridge National Laboratory (ORNL) (*1*). The microbes were immobilized at high cell densities in gel beads and placed in a column reactor for continuous nonsterile operation. Productivities of 50–80 g/L/h were measured at 99% conversion over 2 mo. This study addresses substituting this new technology into the ethanol production section of an existing corn wet-milling facility or using it for a new plant.

We have compared the processing steps required by the FBR with those processing steps used in conventional ethanol technology. For both technologies, we developed process flow schematics with material balances, then identified and priced the required equipment, and, finally, developed plant capital cost and operating estimates. These conceptual design results were then compared, allowing for an evaluation of the operating costs between the FBR and traditional technologies. The study also examines the consequences of several FBR design parameters, using a series of sensitivity analyses.

METHODS

This technology is based on previous laboratory-scale FBR experiments (*1*) at ORNL. From the reported parameters for an FBR contained in this article, we prepared a conceptual design for an ethanol fermentation unit and, using process descriptions available from open literature, a similar conceptual design based on traditional technology as a basis of comparison.

The next step was to set boundaries on the scope of the conceptual design. This was done by preparing block flow diagrams (BFDs) showing the limits of the ethanol production units within a typical corn wet-milling facility. The BFD for traditional bioreactor technology is presented in Fig. 1, and the BFD for the FBR technology is given in Fig. 2. Note that four FBRs are anticipated; each will be on-line for 6 wk and then off-line for 2 wk while being reloaded with fresh biocatalyst. A complete description of pilot-scale bioreactor installation is shown in another article in this proceeding (*2*). The scaled-up version of the FBR appropriate for a production unit is shown in Fig. 3. The same quantity of heat removal is required for each system. Biocatalyst production will be intermittently required for the FBR system and is described elsewhere (*1,2*). These were omitted from Fig. 2 for clarity.

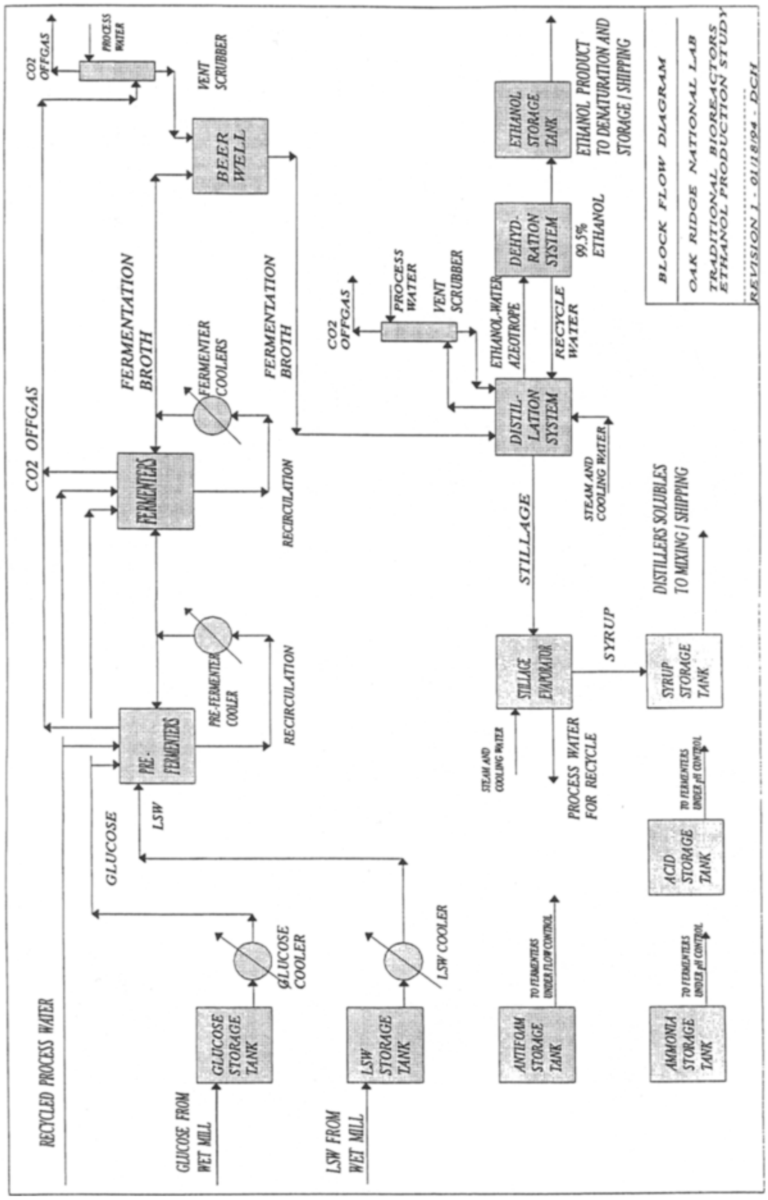

Fig. 1. Block flow diagram for traditional technologies using batch fermentation.

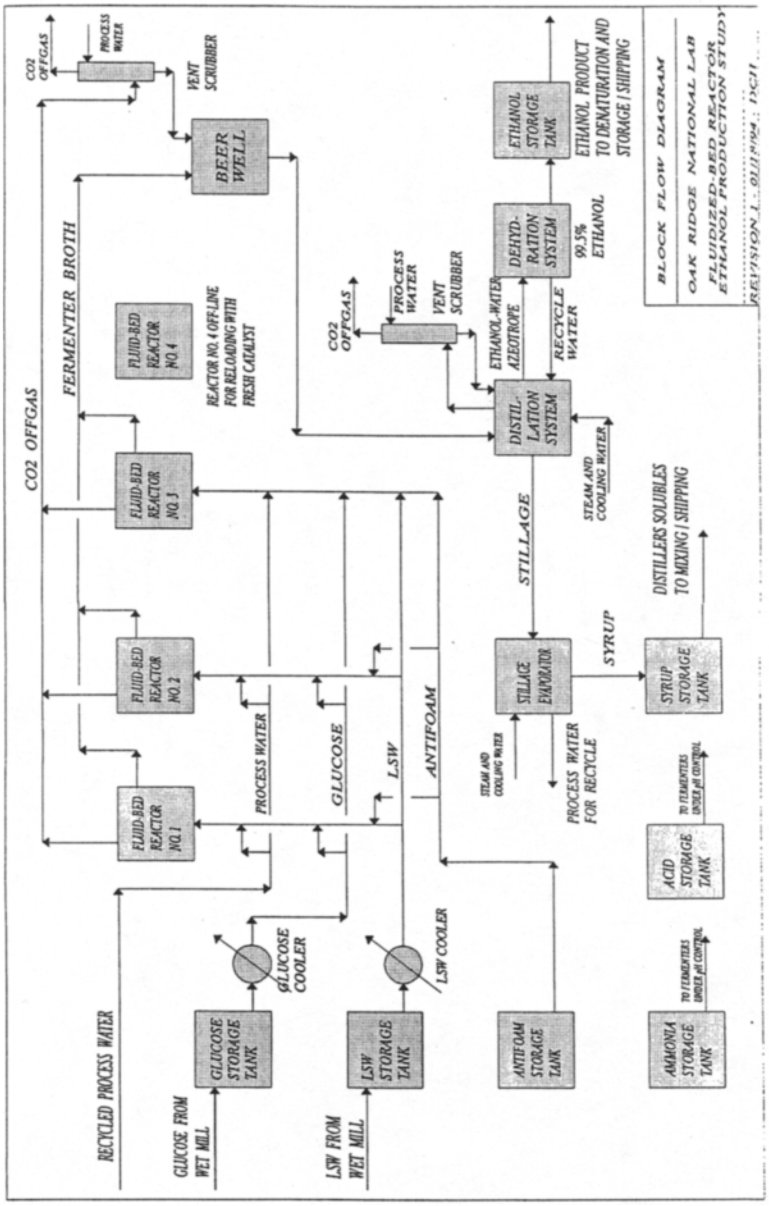

Fig. 2. Block flow diagram for FBR technology.

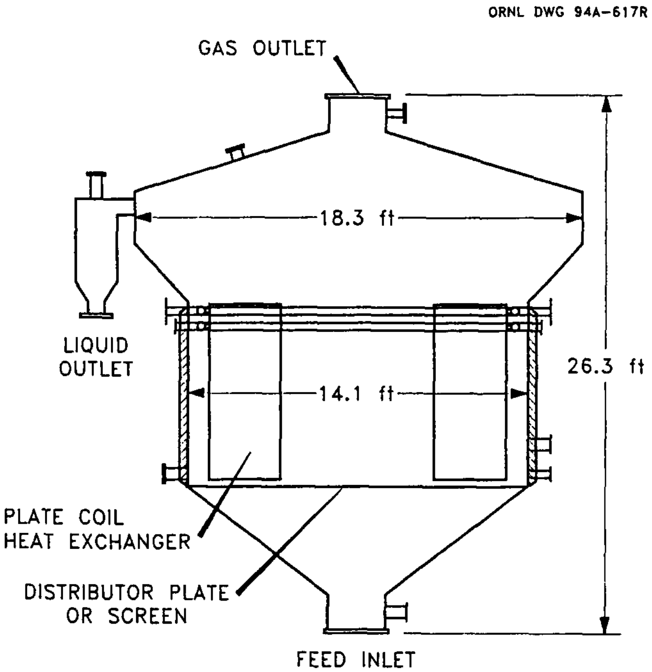

Fig. 3. Design for a single full-scale bioreactor.

Table 1
Design Basis
Base Case: Nominal 50 × 10^6 Gal/Yr Ethanol

Technology	Traditional	Fluidized bed
Operating mode	Fed batch	Continuous
Residence time	24-h fermentation	Nominal 20 min 30% Catalyst volume
Glucose feed conc.	15%	15%
Conversion	99.5%	99.5%
Yield	95.0%	98.0%
Bioreactors	1 Seed 3 Prefermenters 5 Main fermenters @56,000 gal	4 FBRs @9100 gal
Feed sterilization	Required	Not required
Aeration	Yes—for seed	Not required

Next, a design basis was set for the plant capacities to be evaluated. The details of the "Base Case" of a nominal 50 million gal (0.19 million m^3)/yr ethanol production are given in Table 1. Note that the expected glucose conversion is the same for both technologies, but ethanol yield is expected to be somewhat higher for the FBR. Also, sterilization of the light steep-water feed stream is required for the traditional technologies

Table 2
Conceptual Plant Cost Estimate[a,b] ($Millions)

	Costs		
Fermenter type	Fluidized-bed bioreactor	Batch bioreactor	Continuous batch bioreactor
Equipment	13.324	16.455	15.675
Installation	19.986	24.6825	23.5125
Estimated total installation	33.31	41.1375	39.1875
Scope development contingency	0	0	0
Forecast total installation	33.31	41.1375	39.1875
Construction management @5%	1.6655	2.056875	1.959375
Total field cost	34.9755	43.19438	41.14688
Design engineering @10%	3.49755	4.319438	4.114688
Know-how fees	0.4	0.4	0.4
Total project cost	38.87305	47.91381	45.66156

[a]Plant capacity, 50 × 10^6 gal/yr; glucose feed concentration, 15%; 1994 costs.
[b]Expected estimate accuracy: −15 to +25%.

only. An intermediate technology using a continuous well-mixed fermenter was also evaluated.

Using the information above to define the scope of the project, the mechanics of generating the conceptual plant cost estimates were then accomplished: material balances for the BFDs were generated, the major equipment items were sized based on the material balances, pricing for this equipment was obtained, and a factored capital cost estimate was prepared from the priced equipment lists. Also, utilities consumptions were estimated from the equipment sizing and material balances, allowing the estimation of operating costs.

DISCUSSION

The conceptual plant cost estimates for the base case of 50 million gal (0.19 million m^3)/yr, 15% glucose feed, 30% biocatalyst volume, and biocatalyst activity of 12 g ethanol/g dry cells/h, are tabulated in Table 2 both for FBR technology and for traditional batch and continuous well-mixed fermentations. The estimates were developed from factors applied to the equipment costs. This procedure is appropriate at this level of project definition. These factors are taken from experience with actual projects. The FBR plant cost of $38.9M is about 17% lower than that for traditional technology. The likely accuracy of this estimating procedure is in the range of plus 25% to minus 15%.

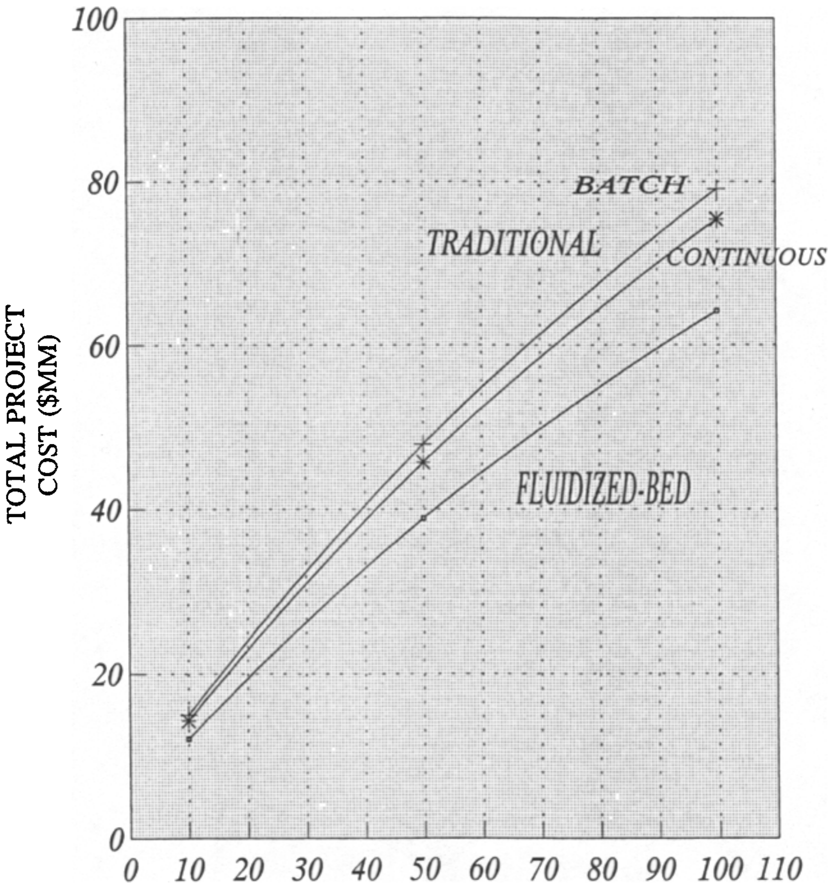

Fig. 4. Total project cost vs plant capacity using 15% glucose feed for traditional batch, (+) continuous well-mixed, (*) and fluidized-bed reactor (□) systems.

Additional estimates were prepared for other cases and are consolidated in Fig. 4 showing total project cost vs plant capacity for 15% glucose feed concentrations. Plant capacity covers the range of 10–100 million gal (0.038–0.380 million m^3)/yr.

From the conceptual plant cost estimates and the utility cost estimates developed from equipment evaluations, operating costs estimates were developed, an example of which is tabulated in Table 3. The data indicate that the FBR technology generates a savings of >$0.02/gal ethanol ($0.0053/L) based on operating costs alone, and a savings of >$0.06/gal ($0.016/L) if the capital to construct a new facility is considered. For a 50 million gal (0.19 million m^3)/yr plant, these differential savings calculate to be $1MM and $3MM/yr, respectively.

It is important to note that this analysis compares technologies with the stated assumptions. Thus, the comparative benefit is emphasized, **not** the absolute value, which will vary greatly with the assumptions,

Table 3
Operating Costs Summary[a]

Major cost component	Fluidized-bed reactor Units	$/hr	$/gal	Traditional batch reactor Units	$/hr	$/gal	Continuous bioreactor Units	$/hr	$/gal
Sugar @ $0.006/lb	82,385 lb/h[b]	4943	0.79	84,990 lb/h[b]	5099	0.815	84,990 lb/h[b]	5099	0.815
Plant utilities		1065	0.17		1076	0.172		1069	0.171
Bioreactor catalyst @ $20/ft^3	$192,480/yr	24	0.004	0			0		
Subtotal of noncapital costs			0.964			0.987			0.986
Capital burden @ 20% of project cost	$7,775,000/yr	972	0.155	$9,583,000/yr	1198	0.191	$9,132,000/yr	1142	0.182
Total—$/Gal			1.119			1.178			1.168

[a]Plant capacity, 50 × 10^6 gal/yr; glucose feed concentration, 15%; 1994 costs.
[b]91% on stream time.

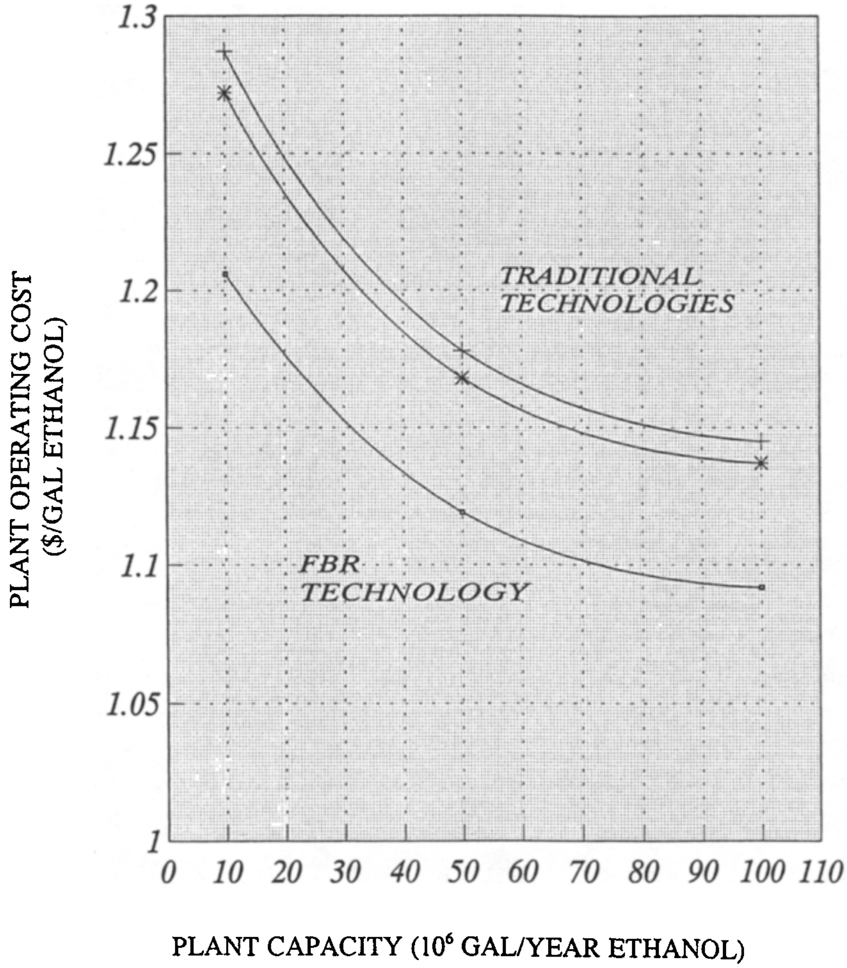

Fig. 5. Plant operating costs vs plant capacity comparing fluidized-bed reactor and traditional technologies as in Fig. 4.

such as the cost of sugar. This study shows benefits owing both to the microorganism and by tailoring a bioreactor system to that organism. Some economic advantages are solely process-based, such as the low amount of biomass in the reactor effluent. Busche et al. (3) also found that immobilized Z. *mobilis* in a fluidized bed offered comparative advantages over yeast batch technology. They estimated a larger benefit of almost $0.17/gal; however, this study did not perform a full fermentation plant design and cost estimate. The trends of these differential savings are expected to apply to other types of ethanol production plants and raw materials. For example, Kane and Reilly (4) found savings of between $0.06 and $0.20/gal of ethanol by the use of state-of-art batch equipment with improved energy efficiencies.

Several sensitivity analyses were conducted as part of this study. Of fundamental importance is the variation in operating costs with plant capacity. As shown in Fig. 5, the differential savings expected from the

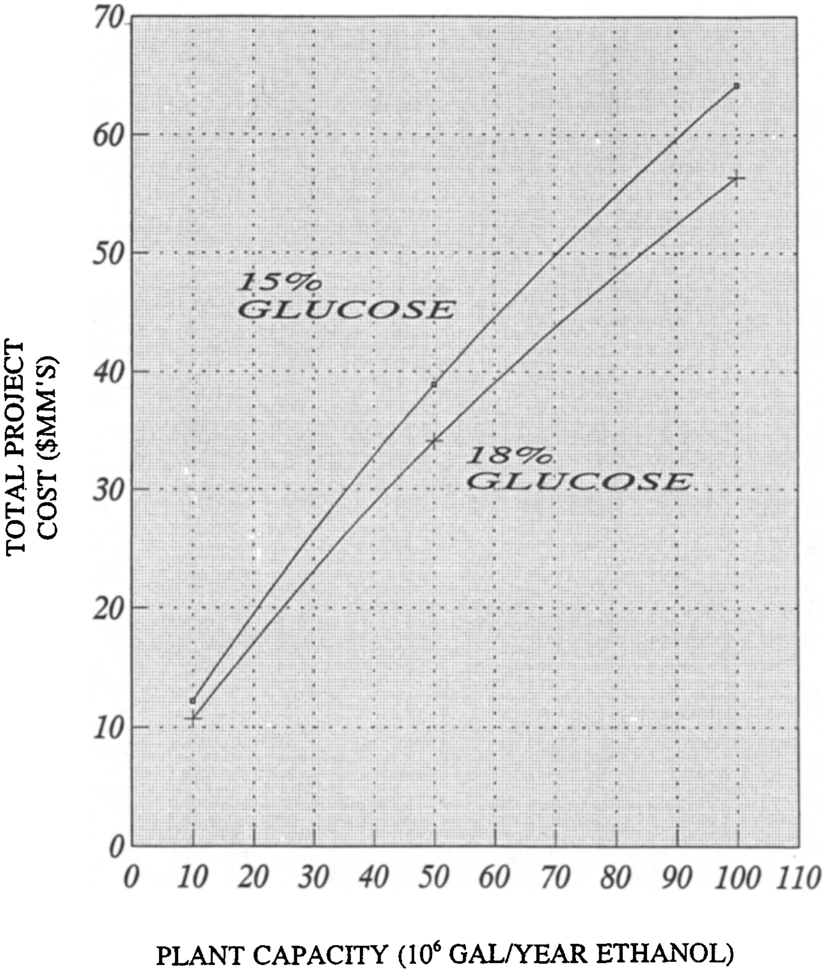

Fig. 6. Effect of feed concentration on total project cost vs plant capacity using FBR technology: 15% (□) and 18% (+) glucose.

FBR technology is essentially constant within the accuracy of these conceptual estimates.

Of similar interest is the possibility of increasing feed concentration from 15 to 18% glucose. The effect of this variation on total project cost in relation to plant capacity is shown in Fig. 6. Clearly, the more concentrated feed stream, and hence more concentrated fermentation broth, allows smaller equipment sizes and a lower cost plant. It is interesting that the FBRs are the same size for each concentration case. The liquid just moves through the column more slowly for the 18% case, to give the same alcohol yield.

Several evaluations were made based on the impact of a range of potential catalyst volumes and activities. For example, Fig. 7 shows the calculated bioreactor productivity in relation to a 50% variation in biocatalyst activity. It is interesting to note that, based on the catalyst costs

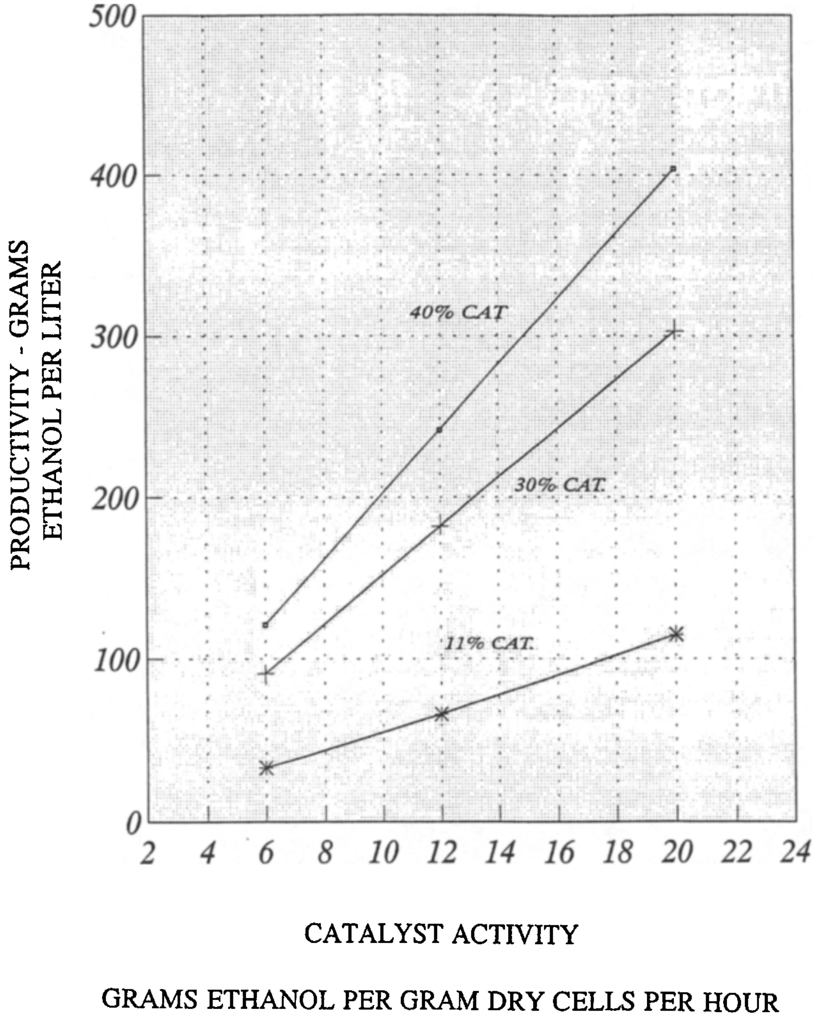

Fig. 7. Bioreactor productivity vs biocatalyst activity specific for each FBR. This is independent of plant capacity.

included in the utility and operating costs shown in Table 3, the calculations indicate that a 50% variation in catalyst costs will vary the production costs by about \$0.0015/gal (\$0.0004/L). This is quite secondary to the effects of other variables, and thus, this study did not emphasize the design of biocatalyst production equipment.

CONCLUSIONS

The study results show that the FBR technology can provide a significant reduction in the production costs of ethanol—a savings > \$0.02/gal (0.53 cents/L) savings if inserted into an existing plant, and a savings > \$0.06/gal (1.6 cents/L) if used at a new plant. These savings occur because of reduced operating and capital costs associated with the FBR technology: Operating costs are reduced through better feedstock utilization and a slightly lowered utilities consumption. Equipment costs for the FBR process are at least 50% lower compared to conventional fermentation equipment costs, providing a 15–20% reduction in total plant cost. This reduced capital cost burden also lowers production costs.

This economic assessment shows the operating costs to be sensitive to the activity of the biocatalyst, the feed sugar concentrations, and the volume of biocatalyst required in the FBR. The operating costs are less sensitive to plant scale and to variations in biocatalyst cost.

ACKNOWLEDGMENTS

This study was supported under subcontract through Martin Marietta Energy Systems, Inc., by the AICD-BCTR program of the US Department of Energy under contract DE-AC05-84OR21400.

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