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Publication Date

1977-08-01

Submitted to Biotechnology and Bioengineering

uc-61

LBL-5963 c.1
Preprint

Energy and Environment Division

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August 1977

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Prepared for the U.S. Energy Research and Development Administration under Contract No. W-7405-ENG-48

Revised March 10, 1977

PROCESS DESIGN & ECONOMIC STUDIES OF ALTERNATIVE FERMENTATION METHODS FOR THE PRODUCTION OF ETHANOL

by

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ABSTRACT

A cell recycle and vacuum fermentation process are described for the continuous production of ethanol. Preliminary process design studies are employed to make an economic comparison of these alternative fermentation schemes with continuous and batch fermentation technologies. Designs are based on a production capacity of 78,000 gallons per day of 95% ethanol employing molasses as the fermentation substrate. The studies indicate that a 57% reduction in fixed capital investment is realized by continuous rather than batch operation. Further decreases in required capital investment of 68% and 71% over batch fermentation were obtained for cell recycle and vacuum operation respectively. However, ethanol production costs were dominated by the cost of molasses, representing over 75% of the total manufacturing cost. But, when a reasonable yeast by-product credit was assumed, the net production cost for 95% ethanol was estimated at 82.3 and 80.6 cent/gal, for the cell recycle and vacuum processes respectively.

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INTRODUCTION

Presently, 9.8×10^5 tons per year of industrial ethanol are produced in this country for use as a solvent and a chemical feed stock. Over 98% of this industrial ethanol is produced from the catalytic conversion of ethylene. However, with the impending petroleum shortage there has been renewed interest in the production of ethanol via fermentation. The overwhelming advantage of fermentation is that the raw materials are renewable. Any fermentable sugar can be used. The recent developments in acid and enzymatic hydrolysis of cellulose to fermentable sugars may possibly allow the economic production of fermentation ethanol from the vast and renewable quantities of cellulose on the earth.(1,2) Ethanol could then serve not only as a chemical feed stock but as a liquid fuel.(3)

The renewed interest in ethanol fermentation has led to the optimization of old fermentation processes, and to the proposal of several new innovative fermentation schemes.(4,5) The aim of this paper is to provide an economic comparison of these new fermentation technologies with conventional fermentation processing.

Traditionally, ethanol fermentations have been operated batchwise, even though continuous fermentation would produce substantial savings by eliminating fermentor down time between the batch fermentations. The two main reasons continuous fermentations have not been more extensively employed are possible yeast mutations and the problem of maintaining a high fermentation rate during continuous fermentation. The problem of deleterious mutations is particularly serious for the beverage industry. The slightest change in fermentation products can impart noxious flavors in fermented beverages. This is not a problem for the production of industrial ethanol. In fact, continuous ethanol fermentations have been maintained in the laboratory in excess of sixty days without any signs of deleterious mutations.(6) During these extended experiments ethanol yields of over 90% of the theoretical yield were obtained - although the product did have a noxious taste.

The low fermentation rates sometimes obtained in continuous ethanol fermentations has been shown by numerous workers to be due to a lack of oxygen.(5,7,8) Even though ethanol fermentation is a anerobic process, trace amounts of oxygen are required for biosynthesis. The oxygen requirement, however, can be eliminated by adding an unsaturated lipid, ergosterol, to the fermentation broth,(16) but the cost of ergosterol is prohibitive for industrial scale processes. Recent work using Saccharomyces cerevisiae (ATCC # 4126) has shown that an oxygen tension of 0.07 mmHg was optimal for ethanol production.(4) As shown in Fig. 1, below an oxygen tension of 0.07 mmHg the yeast became oxygen starved and the fermentor ethanol productivity (gram of ethanol produced)/(liter of fermentor volume-hour) decreased. Whereas, at high oxygen tensions the yeast metabolism began to shift from anaerobic to aerobic and less ethanol was produced with a corresponding increase in cell mass production. As a result, if the oxygen tension was maintained at 0.07 mmHg by constantly sparging a small amount of air through the fermentor, high fermentation rates were obtained with continuous culture. If, however, air was not continuously sparged through the fermentor and only an air saturated feed was used, the oxygen tension dropped to zero. Under these conditions complete fermentation of even an 8.9% glucose feed was not possible with continuous operation.

Fermentor ethanol productivities in both batch and continuous culture are limited by two factors: ethanol inhibition and a low cell mass concentration. This is illustrated in Fig. 2 for continuous culture.(4) As the sugar feed concentration was increased, the specific ethanol productivity (grams ethanol produced/(gram cells-hour)) decreased because more ethanol was produced at high sugar concentrations and ethanol inhibition increased. At low sugar concentrations ethanol inhibition was lessened, but the cell mass concentration decreased. These two counter-balancing affects produced an optimum fermentor productivity at 10% sugar feed. At low sugar feeds, the fermentor productivity was limited by a low cell density, while at high sugar feeds the productivity was limited by ethanol inhibition.

To overcome the low cell density limitation a cell recycle system can be employed. A portion of the cells are separated from the fermented beer and returned to the fermentor. This increases the cell density in the fermentor and produces higher ethanol productivities. The results of a cell recycle fermentation are shown in Fig. 3.(5) The cell density was increased 4 times over simple continuous operation resulting in a 4-fold increase in ethanol productivity.

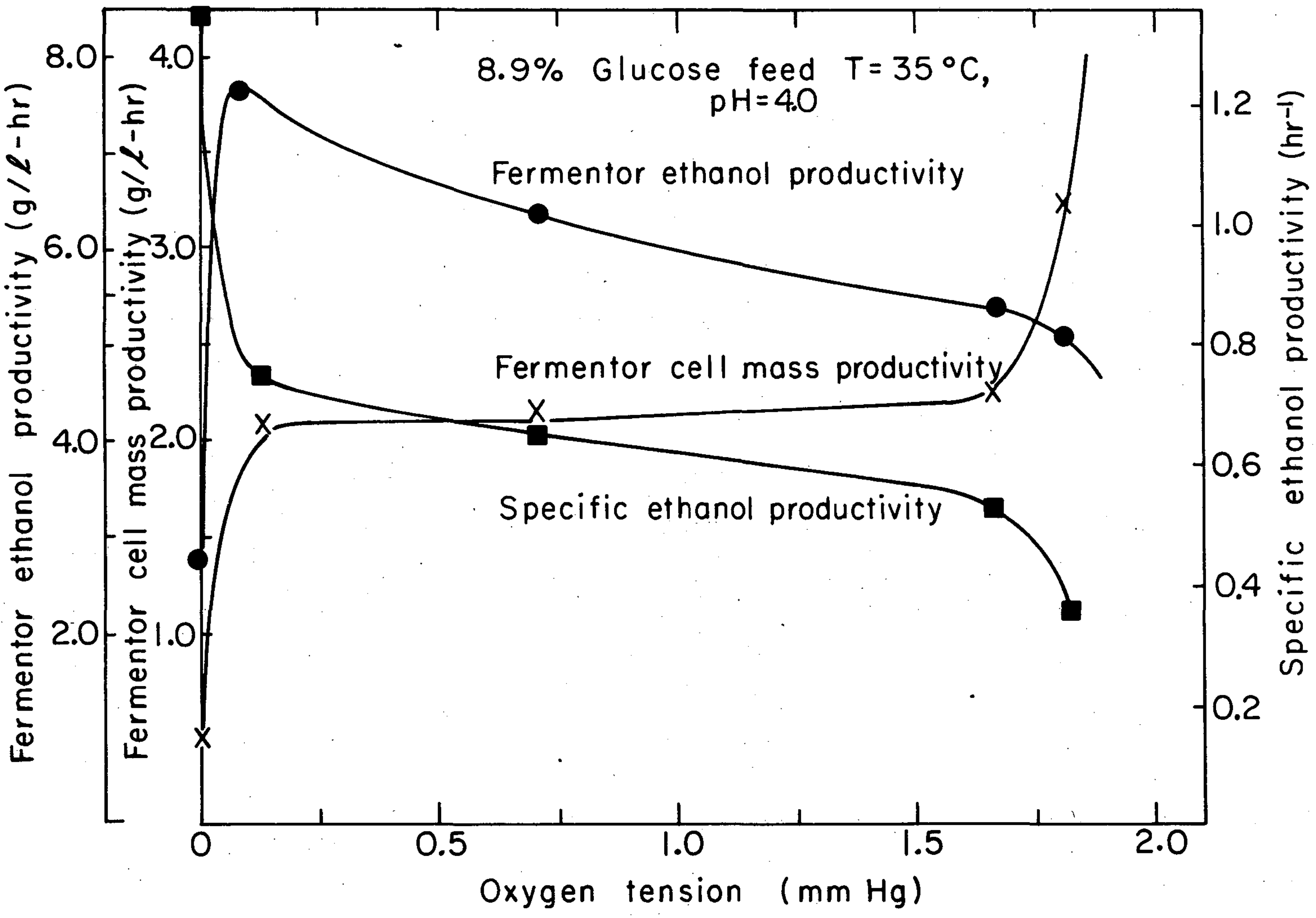

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Fig. 1. Productivities as a function of oxygen tension at a dilution rate of 0.22 hr^{-1}.

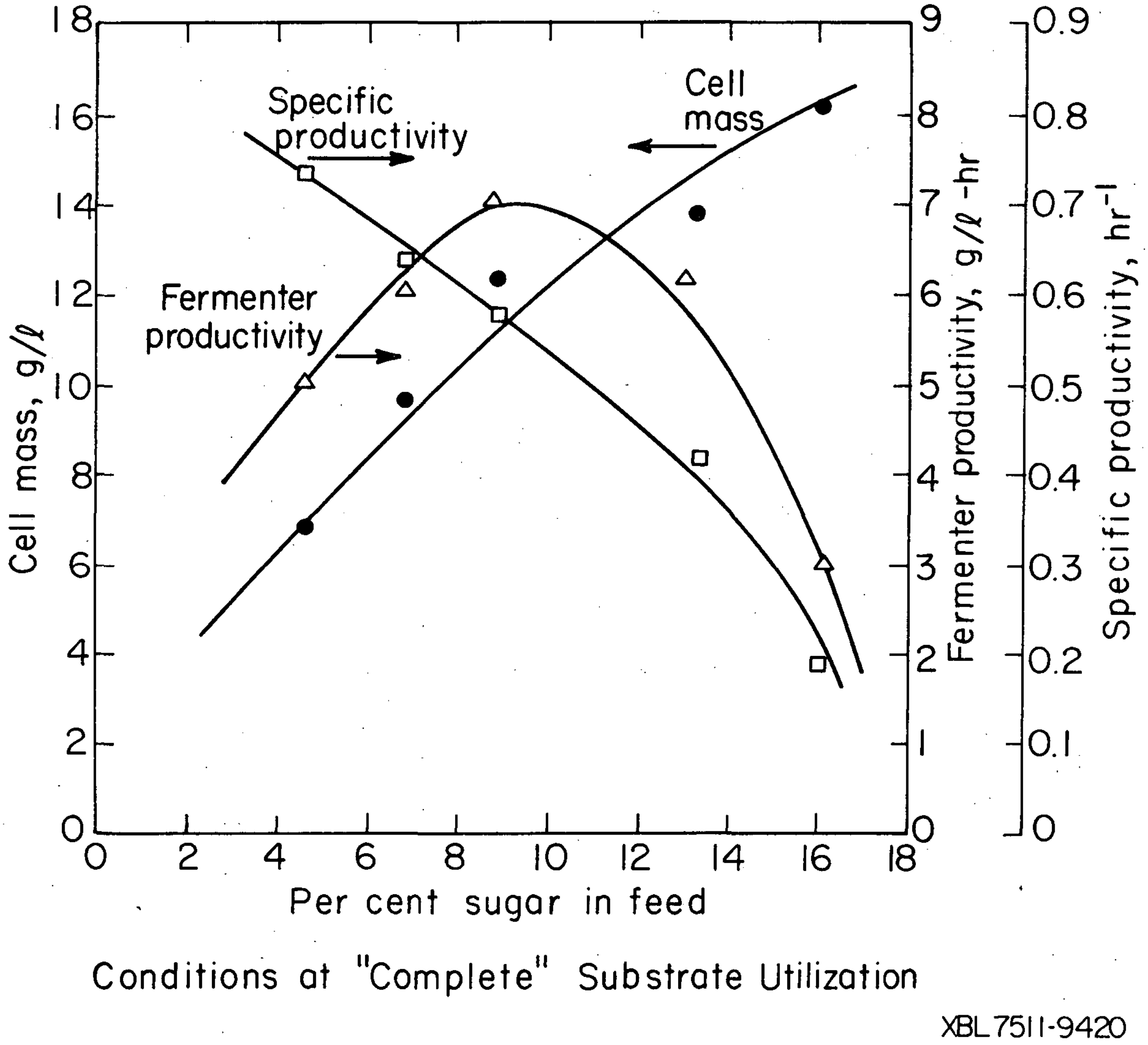

Fig. 2. Effect of glucose concentration on continuous fermentation.

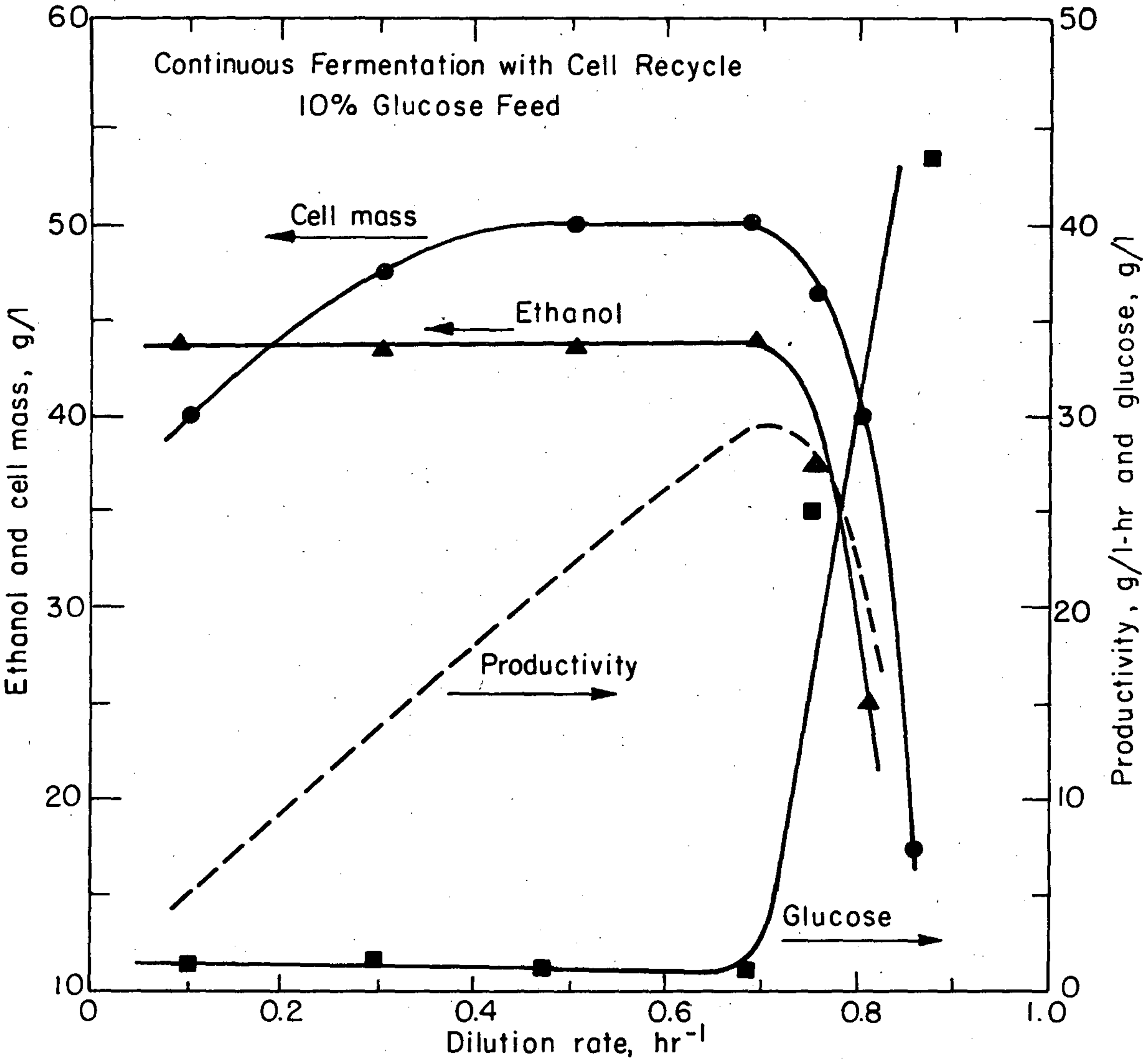

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Fig. 3. Effect of increasing cell density by use of cell recycle in continuous fermentation.

In order to eliminate ethanol inhibition, ethanol must be removed from the fermentation broth as it is formed. This is easily done by taking advantage of ethanol's high volatility and boiling off the ethanol from the fermentation broth. But the fermentation must be run under a sufficient vacuum to obtain boiling at a temperature compatible with the yeast. It is then possible to combine vacuum and cell recycle operation and eliminate both limitations of conventional continuous fermentation. The results of a vacuum-cell recycle fermentation are shown in Fig. 4.(5) Here a 33.4% glucose feed was fermentated to less than 0.3% residual glucose. This was not possible with atmospheric operation due to ethanol inhibition. A final cell density of 124g dry wt/ℓ was obtained in the vacuum-cell recycle system producing an ethanol productivity of 82g/ℓ-hr or almost 12 times that obtained with simple continous operation.

Yeast viability was not effected by vacuum operation as long as sufficient oxygen was present. But to supply the required trace amounts of oxygen, pure oxygen has to be sparged through the fermentor. The only discernible difference noted with vacuum fermentations was a 50% lower cell yield factor as compared to atmospheric pressure fermentations. The lower yield factor may be a result of higher maintenance energy requirements of the yeast in a vacuum.

A summary of optimum values of parameters and maximum ethanol productivities for each of the above modes of operation is shown in Table 1. Complete details of the laboratory fermentation systems and a full discussion of experimental results is given elsewhere.(4-6)

GENERAL PROCESS DESIGN BASES

Preliminary process designs of industrial scale ethanol fermentation plants were made employing the aforementioned modes of operation: batch, continuous, continuous with cell recycle and vacuum with cell recycle. Each plant was based on a production capacity of 78,000 gal/day of 95% ethanol using cane molasses as the fermentation substrate. Molasses was assumed delivered to the fermentation plants as a 50% sugar solution with 97% of the sugar fermentable.(9)

The laboratory fermentation kinetics described above were used for the process design studies. In each design optimum fermentation condition of temperature, pH, and oxygen tension have been assumed.

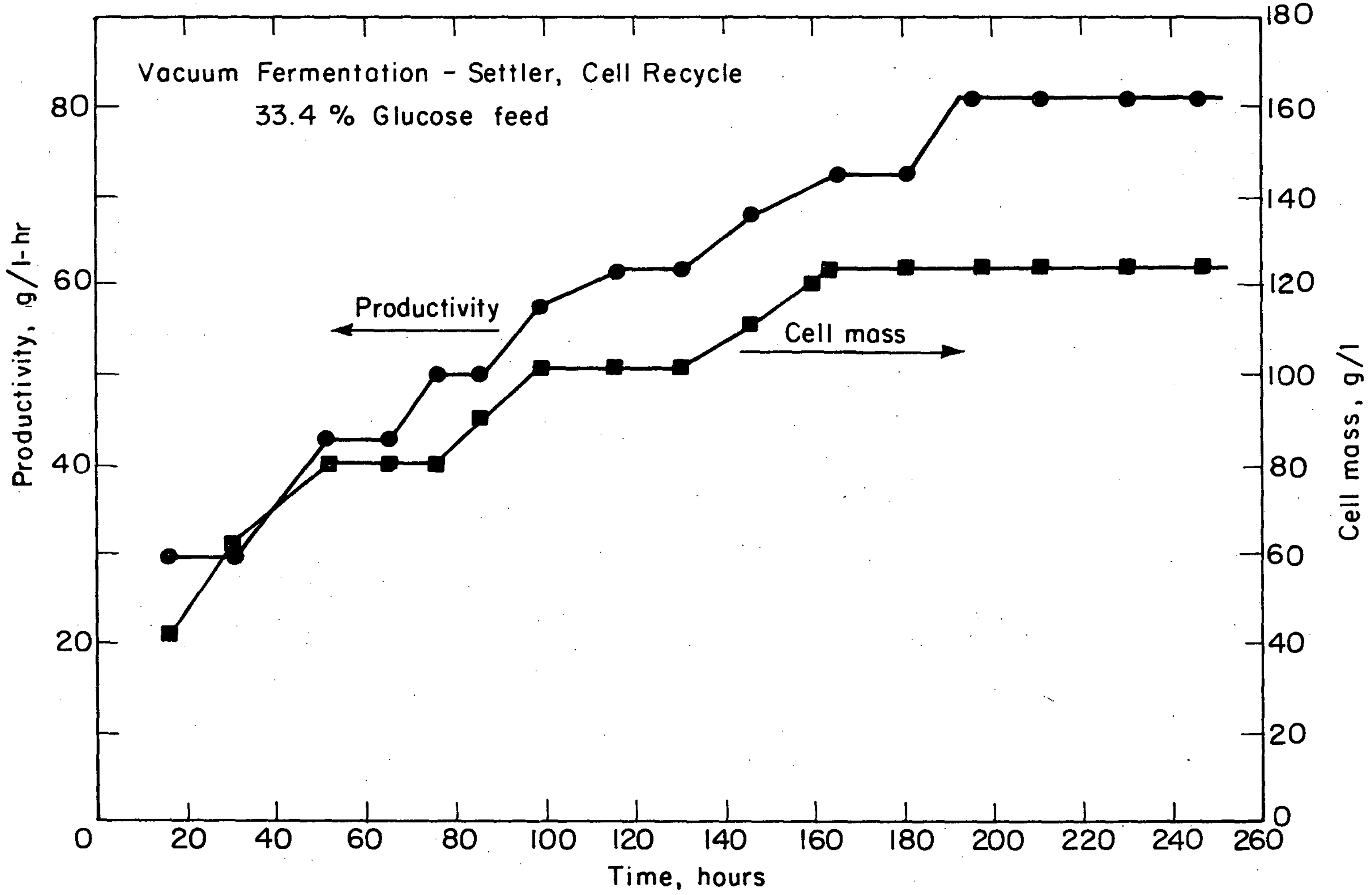

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Fig. 4. Effect of increasing cell density by use of cell recycle in vacuum fermentation. (P = 50 mmHg; T = 35°C).

TABLE 1. SOME RESULTS OF THE LABORATORY FERMENTATION SYSTEMS. (OPTIMUM pH = 4.0 AND OPTIMUM TEMPERATURE = 35°C IN ALL CASES)

FERMENTATION SYSTEM	OPTIMUM OXYGEN TENSION, MMHG	OPTIMUM SUGAR CONCENTRATION, %	CELL MASS CONCENTRATION AT OPTIMUM CONDITIONS, g DRY WT, LITER	MAXIMUM ETHANOL PRODUCTIVITIES, g/ℓ-HR
BATCH	*	-	5.6[†]	2.2[‡]
CONTINUOUS	0.07	10.0	12.0	7.0
CONTINUOUS WITH CELL RECYCLE	0.07	10.0	50.0	29.0
VACUUM WITH CELL RECYCLE	**	-	124.0	82.0

[*] - OPTIMUM PROCEDURE WAS TO INITIALLY AIR SATURATE BROTH AND USE AN AEROBICALLY GROWN 2.0% INOCULUM WITH NO AIR SPARGING DURING FERMENTATION.

[**] - OXYGEN TENSION COULD NOT BE DETERMINED. OPTIMUM PROCEDURE WAS TO SPARGE PURE OXYGEN THROUGH THE FERMENTOR AT A RATE OF 0.10 VVM AT STP.

[‡] - ASSUMES 6 HOUR FERMENTOR DOWN TIME BETWEEN 16 HOUR BATCH FERMENTATION.

[†] - AT END OF BATCH FERMENTATION.

Assuredly, optimal laboratory conditions cannot be expected in industrial operations. However, designs based on laboratory data should yield a valid comparison between the various processing schemes, although the absolute magnitude of the cost figures may be optimistic. This is especially true with regard to the fermentation substrate. Analytical grade glucose was used in the laboratory experiments while molasses is proposed in the industrial scale processes. It is not suggested that fermentation kinetics obtained with glucose will be identical with results obtained with molasses. Rather, that the extent the kinetics, or ethanol productivities are changed by employing molasses will be equally reflected in each fermentation system and a relative comparison between each system remains valid. Further, each design is the result of a computer process model and represents an optimum design. Thus, economic comparisons are based on the optimum design for each mode of operation.

The ethanol produced in each fermentation process was concentrated to 95 wt% by a single distillation step. Since only one distillation is performed, the distillate product will contain approximately 0.5% fusel oil.(10) The fusel oil has no effect on the product value if the ethanol is used as a liquid fuel. Also, the obnoxious taste imparted by the fusel oil may eliminate the need for addition of denaturants.

Economics. F.O.B. process equipment costs were estimated from two main sources, Peters(11) and Guthrie,(12) and Marshell-Stevens indices used to up-date the cost figures. The total fixed capital cost was estimated as a multiple of the F.O.B. purchased cost of the principal items of equipment. In the present case a multiplier of 3.1 was used, except in the case of the fermentors for which the multiple was increased to 4.24 to reflect the additional instrumentation, piping and installation costs associated with fermentors.

Plant operating costs were divided into fixed charges and direct production costs. A summary of the fixed charges is shown in Table 2. Here a 10 year straight line depreciation was assumed and local taxes have been included. The total fixed charges amount to 19.0% of the fixed capital investment per year.

Direct production costs were estimated according to Peters.(11) A base labor rate of $5.60 per man hour and a 8,500 hour year was assumed through-out the cost calculations. The base utility rates are shown in Table 3. Electric power requirements were calculated assuming an 80% efficiency of electric to mechanical power conversion. Also, an 80% efficiency was taken for adiabatic gas compression and pumps.

TABLE 2

FIXED OPERATING COSTS

	PER CENT OF FIXED CAPITAL INVESTMENT PER YEAR
DEPRECIATION	10.0%
TAXES	4.0%
INSURANCE	1.0%
MAINTENANCE & REPAIR	3.0%
OPERATING SUPPLIES	1.0%
TOTAL	19.0%

TABLE 3

BASE UTILITY RATES

COOLING WATER	$0.128/10^3$ GAL
ELECTRIC POWER	3 CENT/KW**
STEAM	$2.81/10^3$ LB*

* SELF GENERATED FROM LOW SULFUR FUEL OIL.

**BOUGHT FROM PUBLIC UTILITY.

PROCESS DESCRIPTIONS

Continuous Fermentation. The design basis of the continuous fermentation process is shown in Table 4. Figure 5 shows a schematic process flow diagram of the continuous fermentation process to produce 78,000 gal/day of 95% ethanol. The principal items of equipment corresponding to the flow sheet are listed in Table 5.

The molasses is first diluted to a 10% sugar solution and mineral supplements are added. Sterilized by steam injection, the molasses solution is distributed to eight 1.89×10^5 liter continuous fermentors*, each operating at a dilution rate of $0.17\ hr^{-1}$. A low flow of air (2.5×10^{-2} vvm) is sparged through each fermentor to maintain the oxygen tension at the optimum level of 0.07 mmHg. The fermented beer then passes to four continuous centrifuges and the yeast is removed. (Only two centrifuges are shown in Fig. 4.) The yeast is subsequently dried and stored for sale as a protein feed supplement. The clarified beer from the centrifuges is next distilled to concentrate the ethanol to 95 wt%. An absorber, using the distillate bottoms as the absorbing liquid, is employed to recover ethanol lost in the exit gases (air and CO_2) from the fermentor. The ethanol rich stream from the absorber is also fed to the main distillation unit for final ethanol recovery.

Continuous Fermentation with Cell Recycle. The cell recycle process is identical to the continuous process described above except that a portion of cell concentrate from the centrifuges is returned to the fermentors. This increases the cell mass concentration in the fermentors permiting a higher volumetric ethanol productivity. As a result, the total fermentation volume is reduced in the cell recycle process requiring only 3 fermentors of 1.22×10^5 liters in volume to produce 78,000 gal/day of 95% ethanol. The reduction in fermentation volume is offset somewhat by an increased load on the centrifuges. Seven centrifuges are needed in the cell recycle fermentation to maintain a yeast cell concentration of 50 g dry wt/l in the fermentors. All other process equipment is the same as that listed in Table 5 for conventional continuous operation. A summary of the design basis of the cell recycle process is listed in Table 6.

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*Working volume of each fermentor is taken at 80% of total fermentor volume.

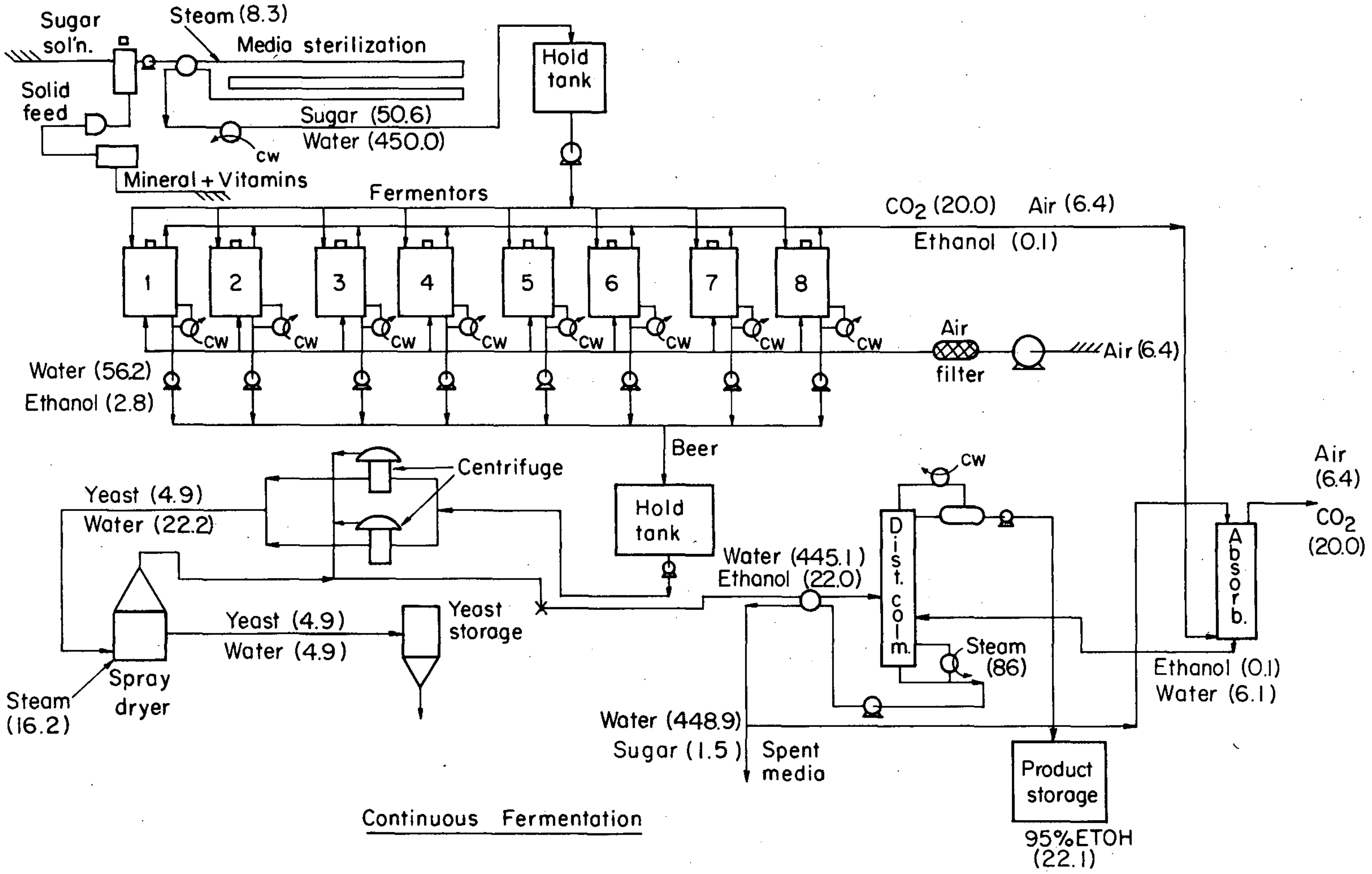

Fig. 5. Flow diagram and mass balance for continuous fermentation. Capacity 78,000/gal/day of 95% ethanol (flows in 10^3 lb/hr) cw = cooling water.

TABLE 4

CONTINUOUS FERMENTATION DESIGN BASIS

SUGAR CONCENTRATION	10%
DILUTION RATE	0.17 HR^{-1}
TEMPERATURE	35°C
CELL YIELD FACTOR, $Y_{X/S}$	0.10
ETHANOL YIELD FACTOR, $Y_{P/S}$	0.45
CELL CONCENTRATION IN FERMENTOR	10.0 DRY WT/L

Table 5 Major items of equipment for continuous ethanol fermentation plant (Capacity 78,000 gal/day of 95% ethanol).

Item	Unit Specification	Number of Units	Cost/Unit $*
Ethanol Fermentation		Total	1,856,700
Fermentor	Vol 1.89×10^5 liters, stainless steel Construction	8	90,500
Agitator	14 HP, stainless steel construction	8	6,500
Air Compressor	91 HP, centrifuger type, 30 psig	1	38,000
Air Filter	0.4×0.3 meters, glass fiber	8	210
Media Sterilizer	8.7×1.2 meters, insulated stainless pipe	1	11,700
Preheat Exchanger Coupled with Sterilizer	10,000 ft^2, stainless steel construction	1	112,500
Cooler Exchanger Coupled with Sterilizer	4,100 ft^2, stainless steel construction	1	64,000
Heat Removal Exchanger Coupled with Fermenter	410 ft^2, stainless steel construction	8	14,500
Solid Feeders	Screw conveyor, 4 ton/day	4	1,600
Nutrient Mixing Tank and Agitator	Vol 1.03×10^5 liters, stainless steel construction	1	45,300

Table 5 Continued.

Item	Unit Specification	Number of Units	Cost/Unit $*
Sugar Solution Storage Tank	Vol 2.48×10^6 liters, stainless steel construction	1	270,000
In Plant Beer Storate	Vol 4.14×10^5 liters, stainless steel construction	1	26,700
Centrifuge	Nozzle type bowl, 40 HP	4	62,000
Yeast Spray Dryer	18 ft dia stainless steel construction	2	31,100
Product Alcohol Storage Tank	Vol 5.9×10^5 liters, carbon steel construction	1	21,600
Yeast Storage Tank	Vol 1.0×10^4 liters, stainless steel construction	1	7,900
Pumps and Drivers		10	4,800
<u>Ethanol Recovery</u>		Total	299,400
Distillation Column	11.2 ft dia 45 sieve trays, carbon steel construction	1	76,200
Condenser	4,700 ft^2 carbon steel construction	1	69,900
Reboiler	2,600 ft^2 carbon steel construction	1	47,800
Preheat Exchanger	4,200 ft^2 carbon steel construction	1	64,500

Table 5 Continued.

Item	Unit Specification	Number of Units	Cost/Unit $*
Reflex Tank	Vol 1.13×10^3 carbon steel construction	1	3,800
Ethanol Absorber	7.2 ft dia, 26 ft high, 1 in. reasching rings	1	25,700
Pumps and Drivers		5	2,300

*Costs are estimated for the second quarter 1975, Marshell Stevens Index = 445.6.

TABLE 6

CONTINUOUS FERMENTATION WITH CELL RECYCLE DESIGN BASIS

SUGAR CONCENTRATION	10%
DILUTION RATE	0.7 HR^{-1}
TEMPERATURE	35°C
CELL YIELD FACTOR, $Y_{X/S}$	0.10
ETHANOL YIELD FACTOR, $Y_{P/S}$	0.45
CELL CONCENTRATION IN FERMENTOR	50.0G DRY WT/L

Batch Fermentation. The batch fermentation process parallels the continuous process shown in Fig. 5, however, the fermentors are operated batchwise instead of continuously. A 16 hr fermentation time was assumed with an additional 6 hr required to fill, drain, and sterilize each fermentor. The net result is that 26 fermentors of 1.85 x 10^5 liters in volume are required for the batch production of 78,000 gal/day of 95% ethanol. In addition, two 4.9 x 10^4 liter seed fermentors are required to produce a 2% inoculum for the main fermentors. All other processing equipment is identical to that listed in Table 5 for continuous operation. The design basis of the batch fermentation is shown in Table 7.

Vacuum Fermentation with Cell Recycle. Figure 6 shows a schematic flow diagram of a vacuum fermentation process to produce 78,000 gal/day of 95% ethanol. The design basis of the vacuum process is listed in Table 8. The principal items of equipment corresponding to Fig. 6 are shown in Table 9.

Full strength molasses is first mixed with mineral supplements. The medium is sterilized by steam injection and fed to a single 1.89 x 10^5 liter vacuum fermentor operating at a total pressure of 55 mmHg and 35°C. Pure oxygen is sparged through the fermentor at a rate of 0.1 vvm at S.T.P. to satisfy the trace oxygen requirement of the yeast. As the fermentation proceeds, ethanol and water are boiled away from the fermentation broth. The vapor from the fermentor is compressed to 340 mmHg and condensed in the fermentor reboiler to supply the energy for the vaporization of ethanol and water in the fermentor. After the vapor recompression cycle, the uncondensable gases (carbon dioxide and oxygen) are compressed to 760 mmHg and cooled to 35°C to condense additional ethanol and water. The fermentation gases are finally fed to an absorber where the last traces of ethanol are removed. The fermented beer is pumped to atmospheric pressure and fed to two continuous centrifuges where the yeast concentrate is removed. A portion of the yeast concentrate is returned to the fermentor. The remaining yeast is spray dried and packaged for sale. The clarified beer from the centrifuges and the condensation products are fed to a distillation column where the ethanol is concentrated to 95%. A portion of the bottoms product from the distillation column is cooled and fed to the absorber.

TABLE 7

BATCH FERMENTATION DESIGN BASIS

SUGAR CONCENTRATION	10%
FERMENTATION TIME	16 HR
FERMENTOR DOWN TIME PER CYCLE	6 HR
TEMPERATURE	35°C
CELL YIELD FACTOR, $Y_{X/S}$	0.056
ETHANOL YIELD FACTOR, $Y_{P/S}$	0.477

TABLE 8

VACUUM-RECYCLE FERMENTATION DESIGN BASIS

SUGAR CONCENTRATION	50%
DILUTE RATE	0.18 HR^{-1}
TEMPERATURE	35°C
PRESSURE	55 MMHG
CELL YIELD FACTOR, $Y_{X/S}$	0.058
ETHANOL YIELD FACTOR, $Y_{P/S}$	0.475

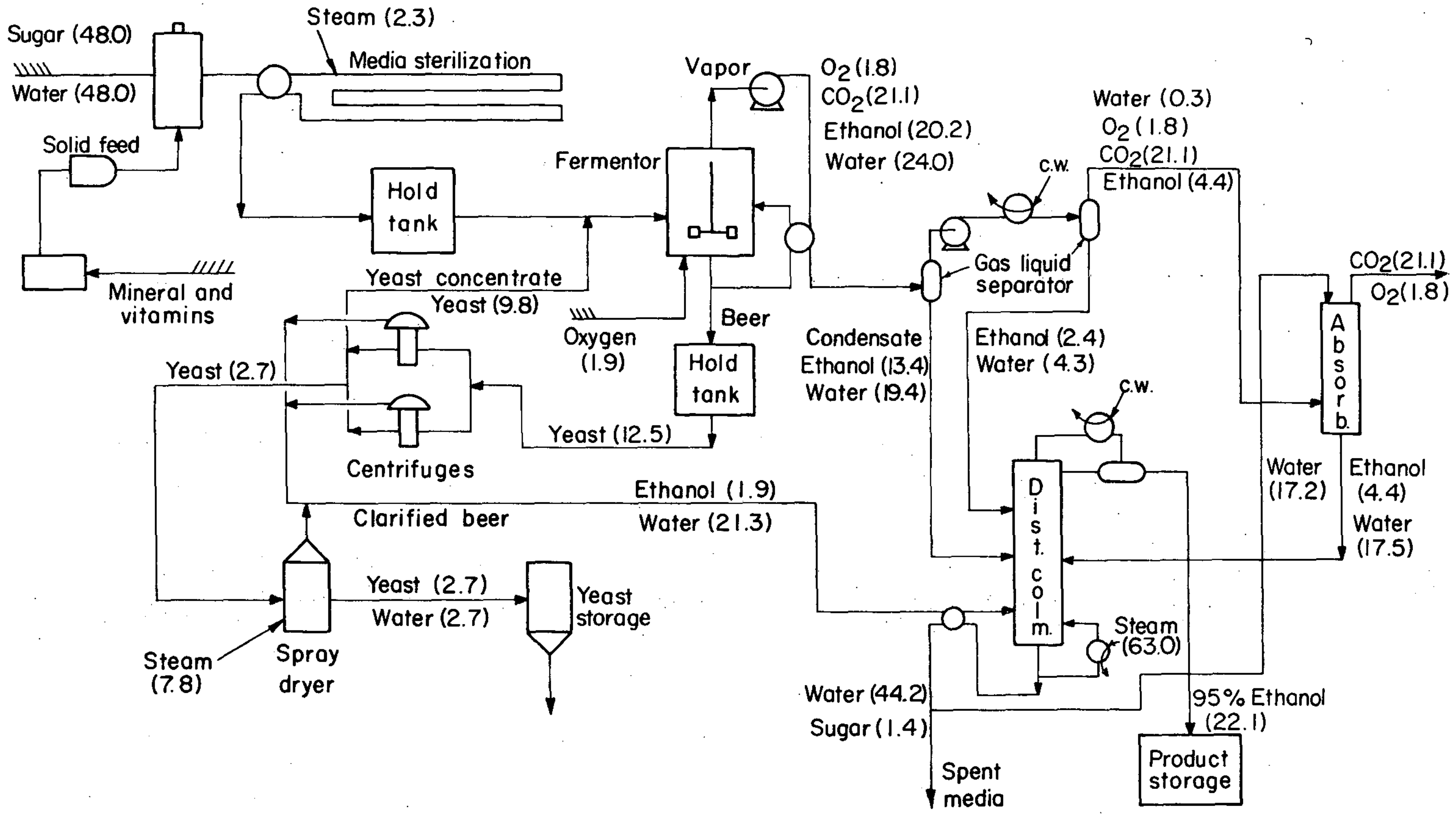

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Fig. 6. Flow diagram and mass balance for continuous vacuum fermentation with cell recycle. Capacity 78,000 gal/day of 95% ethanol (flows in 10^3 10^3 lb/hr) cw = cooling water.

Table 9 Major items of equipment for vacuum ethanol fermentation plant (capacity 78,000 gal/day of 95% ethanol).

Item	Unit Specification	Number of Units	Cost/Unit $*
Ethanol Fermentation		Total	1,382,300
Fermentor	Vol 1.89×10^5 liters, stainless steel construction	1	95,500
Agitator	110 HP, stainless steel construction	1	16,400
Compressor for Vapor Recompression	3,000 HP, centrifuger type	1	523,800
Compressor for CO_2 Compression	500 HP, centrifuger type	1	122,000
Fermentor Reboiler	4,400 ft^2, stainless steel construction	1	66,500
Oxygen Filter	0.5×0.3 meters, glass fiber	1	360
Media Sterilizer	8.7×0.64 meters, insulated stainless steel pipe	1	5,500
Preheat Exchanger Coupled with Sterilizer	2,800 ft^2, stainless steel construction	1	50,500
Cooler Exchanger Coupled with Sterilizer	1,200 ft^2, stainless steel construction	1	28,900
Solid Feeders	Screw conveyors, 4 ton/day	4	1,600
Nutrient Mixing Tank with Agitator	Vol 2.9×10^5 liters, stainless steel construction	1	27,200

Table 9 Continued.

Item	Unit Specification	Number of Units	Cost/Unit $*
Sugar Solution Storage Tank	Vol 7.09×10^5 liters, stainless steel construction	1	121,000
In Plant Beer Storage Tank	Vol 1.18×10^5 liters, carbon steel construction	1	11,900
Gas Liquid Separators	Vol 1.5×10^3 liters, carbon steel construction	2	3,600
Secondary Vapor Condenser	100 ft^2 stainless steel construction	1	25,800
Centrifuge	Nozzle type bowl, 40 HP	2	62,000
Yeast Spray Dryer	18 ft dia, stainless steel construction	2	31,100
Yeast Storage Tank	Vol 1.0×10^4 liters, stainless steel construction	1	7,900
Product Alcohol Storage Tank	Vol 5.9×10^5 liters, carbon steel construction	1	21,600
Pumps and Drivers		12	4,800
<u>Ethanol Recovery</u>		Total	265,800
Distillation Column	10.2 ft dia 51 sieve trays, carbon steel construction	1	74,300
Condenser	3,700 ft^2, carbon steel construction	1	59,700
Reboiler	1,900 ft^2, carbon steel construction	1	39,400
Preheat Exchangers	200 ft^2, carbon steel construction	2	9,100

Table 9 Continued.

Item	Unit Specification	Number of Units	Cost/Unit $*
Reflex Tank	Vol 1.13×10^3 liters, carbon steel construction	1	3,800
Ethanol Absorber	9.5 ft dia, 70 ft high, 1 in. rasching rings	1	58,900
Pumps and Drivers		5	2,300

*Costs are estimated for the second quarter 1975, Marshell Stevens Index = 445.6.

PROCESS ECONOMICS

Table 10 compares the fixed capital investment required for the various fermentation processes to produce 78,000 gal/day of 95% ethanol from molasses. As shown in Table 10, a substantial decrease in capital investment is experienced in going from batch to continuous processing. A batch fermentation process requires 225 dollars of capital per gallon of ethanol produced each day. This figure is cut in half for continuous fermentation requiring only 96 dollar/gal/day. The vacuum process requires the lowest total capital expenditure of only 5.2 million dollars or 66 dollar/gal/day. Whereas, the continuous-cell recycle process requires the lowest capital expenditure for the fermentation equipment, this is offset by an increased expenditure for centrifuges used for yeast recovery to maintain a high cell density in the fermentors.

Although the vacuum system requires only one fermentor, a higher capital expenditure is needed for the fermentation equipment in the vacuum system than in the cell recycle fermentation. This is due to the large compressors and fermentor reboiler needed in the vacuum process. The increased fermentation equipment cost is, however, balanced by a reduction in the size of auxiliary equipment (media sterilizer, storage and mixing tanks, centrifuges and distillation column) because a more concentrated sugar solution (50%) is used in the vacuum process.

ETHANOL PRODUCTION COSTS

Ethanol production costs excluding the cost of sugar and medium supplements are shown in Tables 11 and 12. As to be expected, reduction of capital investment is reflected in the production costs. The largest decrease in production cost is achieved by using continuous operation rather than batch. Batch ethanol production costs are 27.5 cent/gal while only 17.3 cent/gal is required for continuous fermentation. A further decrease of production cost to 16.1 cent/gal and 12.7 cent/gal is obtained in the continuous-cell recycle and vacuum fermentations, respectively. As shown in Table 12, the low fermentation cost of the continuous-cell recycle process is partially offset by an increased cost for yeast recovery.

TABLE 10. REQUIRED FIXED CAPITAL INVESTMENT FOR DIFFERENT MODES OF OPERATION. PLANT CAPACITY 78,000 GAL/DAY OF 95% ETHANOL.

	FIXED CAPITAL INVESTMENT, 10^3 DOLLARS			
	BATCH	CONTINUOUS	CONTINUOUS CELL RECYCLE	VACUUM CELL RECYCLE
FERMENTATION	14,900	4,808	2,484	3,366
ETHANOL RECOVERY	928	928	928	824
YEAST RECOVERY	962	962	1,362	794
STORAGE	811	811	811	233
TOTAL	17,601	7,509	5,585	5,217

TABLE 11

ETHANOL PRODUCTION COSTS FOR DIFFERENT MODES OF OPERATION PLANT CAPACITY 78,000 GAL/DAY OF 95% ETHANOL FROM 50% "CANE" MOLASSES SUGAR SOLUTION

	PRODUCTION COST CENT/GAL			
	BATCH	CONTINUOUS	CONTINUOUS CELL RECYCLE	VACUUM CELL RECYCLE
INVESTMENT RELATED COSTS	10.3	4.9	4.0	3.5
OPERATING LABOR	3.2	0.9	0.5	0.4
SUPERVISION & CLERICAL	0.2	0.1	0.1	0.1
UTILITIES				
WATER	0.6	0.6	0.6	0.4
POWER	1.2	0.6	0.9	0.6
STEAM	10.1	9.5	9.5	6.8
OXYGEN	-	-	-	0.5
LABORATORY CHANGES	0.1	0.1	0.1	0.1
PLANT OVERHEAD	1.8	0.6	0.4	0.3
TOTAL	27.5	17.3	16.1	12.7

TABLE 12. ETHANOL PRODUCTION COSTS FOR DIFFERENT MODES OF OPERATION. PLANT CAPACITY 78,000 GAL/DAY OF 95% ETHANOL.

	PRODUCTION COST CENT/GAL			
	BATCH	CONTINUOUS	CONTINUOUS CELL RECYCLE	VACUUM CELL RECYCLE
FERMENTATION	16.8	6.6	5.0	4.8
ETHANOL RECOVERY	8.1	8.1	8.1	6.7
YEAST RECOVERY	2.0	2.0	2.4	1.0
STORAGE	0.6	0.6	0.6	0.2
TOTAL	27.5	17.3	16.1	12.7

Almost 3.5 cent/gal can be saved with the vacuum system compared to conventional continuous fermentation. The advantage of the vacuum process is twofold. The 50% molasses solution must not be diluted and the ethanol distillation cost (as reflected by the steam cost) is reduced.

The reduced distillation cost in the vacuum process is due to the preliminary concentration of ethanol achieved in the vapor recompression cycle used to maintain the fermentor vacuum. The ethanol concentration is increased from a mole fraction of 0.03 in the fermentation broth to 0.21 in the condensed vapor. The resulting increased ethanol concentration in the feed to the distillation column allows the use of a lower reflux ratio for the final concentration of ethanol to 95%. By decreasing the required reflux ratio (i.e., moles reflux per mole of product) from 7.33 for atmospheric fermentations to 5.66 for vacuum fermentation an overall steam savings of 17% is obtained. This includes the steam required for compressor operation in the vacuum system.

As discussed above, another advantage of the vacuum fermentation scheme is elimination of end product inhibition by boiling-off ethanol as it is produced. However, by changing the fermentation pressure, the equilibrium ethanol concentration is altered and the ethanol concentration in the fermenting broth may be adjusted to any desired level. Figure 7 shows the affect of ethanol concentration on production costs for the vacuum system. When the ethanol concentration of the broth is low, the equilibrium vapor concentration is also low. A high boil up rate is thus necessary to remove the ethanol produced during fermentation. This increases the vapor compression costs in the recompression cycle and production costs increase. At high ethanol concentrations the compression costs are reduced, but fermentation costs increase because the yeast becomes inhibited by the ethanol. As shown in Fig. 7, these two competing affects produce a rather flat production cost curve between ethanol concentrations of 5.0% and 8.0%.

The production cost of vacuum fermentation without recycle is also shown in Fig. 7. Production costs without cell recycle rise more rapidly with increased ethanol concentration than when cell recycle is employed. This stems from the overall mass balances. When the ethanol concentration is high the boil up rate necessary to remove the required amount of ethanol is low and, from the mass balance, a large bleed rate from the fermentor is necessary. But, a substantial amount of cell mass is removed with the bleed stream and the yeast concentration in the fermentor decreases. Since the cell mass concentration

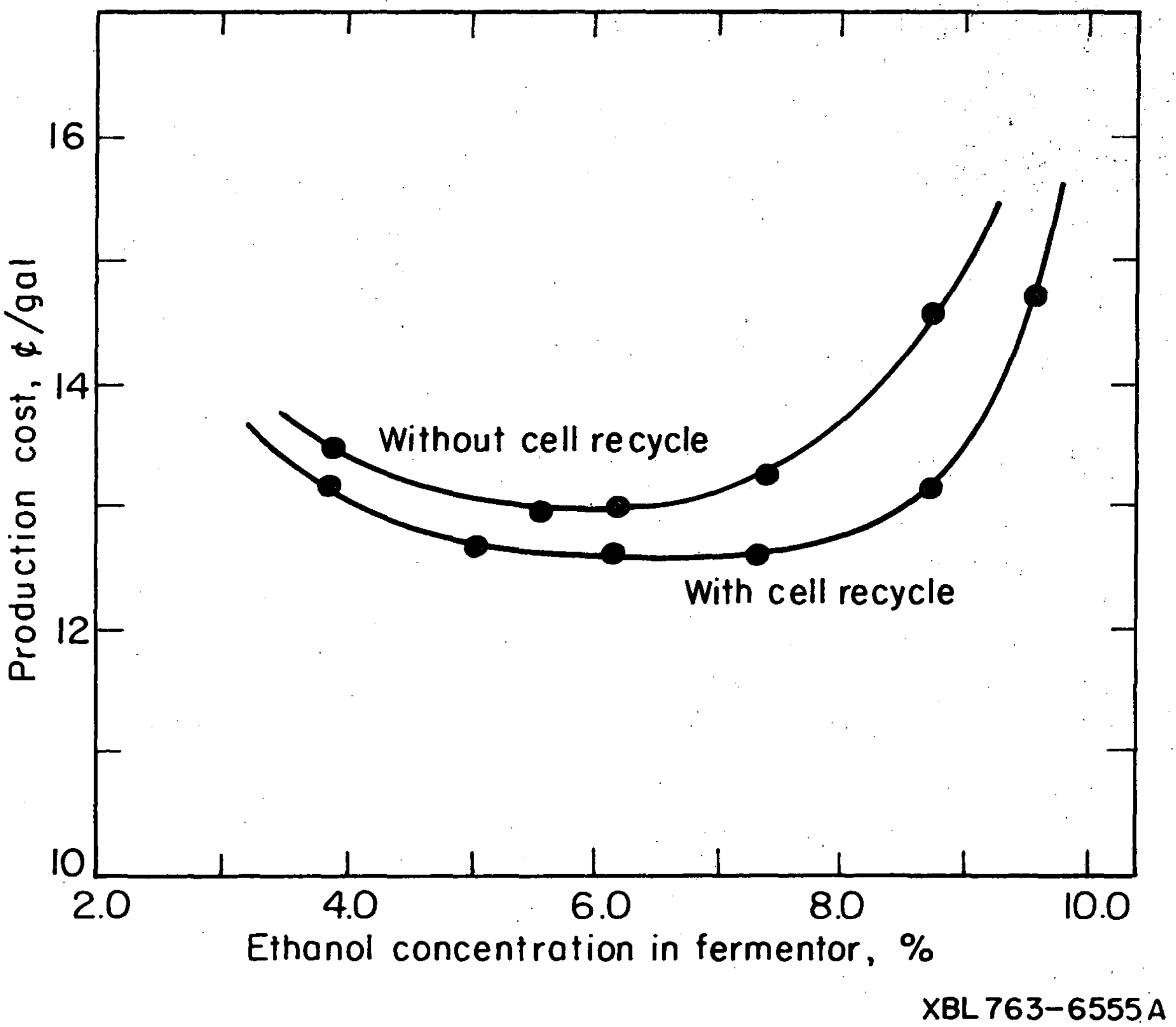

Fig. 7. Effect of ethanol concentration in vacuum fermentor on ethanol production costs.

decreases, the fermentation rate per unit volume decreases and the fermentation costs increase. This, of course, is not the case when cell recycle is employed because the biomass concentration in the fermentor is maintained at a high level by returning a portion of the yeast to the fermentor.

EFFECT OF FEED SUGAR CONCENTRATION ON ETHANOL PRODUCTION COSTS

Ethanol production costs are plotted against the feed concentration of fermentable sugar in Fig. 8 for conventional continuous fermentation. There is a definite optimum production cost at 10% sugar feed. Above a 10% sugar concentration ethanol inhibition slows the fermentation rate. As a result, a larger fermentation volume must be used and as shown in Fig. 8, the fermentation costs increase. Below 10% sugar feed, the cell mass concentration decreases, lowering the fermentor ethanol productivity which again increases the fermentation costs. Also, at low feed sugar concentrations dilute solutions of ethanol are produced. This increases the distillation cost because more energy is required to concentrate these dilute solutions to 95% ethanol.

An optimum sugar concentration of 10% also exists for continuous cell recycle fermentations, however, the fermentation cost curve differs from that shown in Fig. 8. When cell recycle is employed the cell mass concentration in the fermentor is not a function of sugar concentration. Therefore, at sugar concentrations below 10% the productivity does not decrease but rather increases because of less ethanol inhibition. This increased productivity is somewhat counter balanced by an increased centrifugation requirement since higher flow rates through the centrifuges are required for low sugar concentrations. The net effect is that the fermentation cost curve gradually decreases with decreasing sugar concentrations below 10%. But, distillation costs sharply increase in this region as shown in Fig. 8. Hence, total ethanol production cost increases as the sugar concentration decreases below 10%. Above 10% sugar, ethanol inhibition becomes the controlling factor and drives up the fermentation cost, and the total production cost in the recycle system increases.

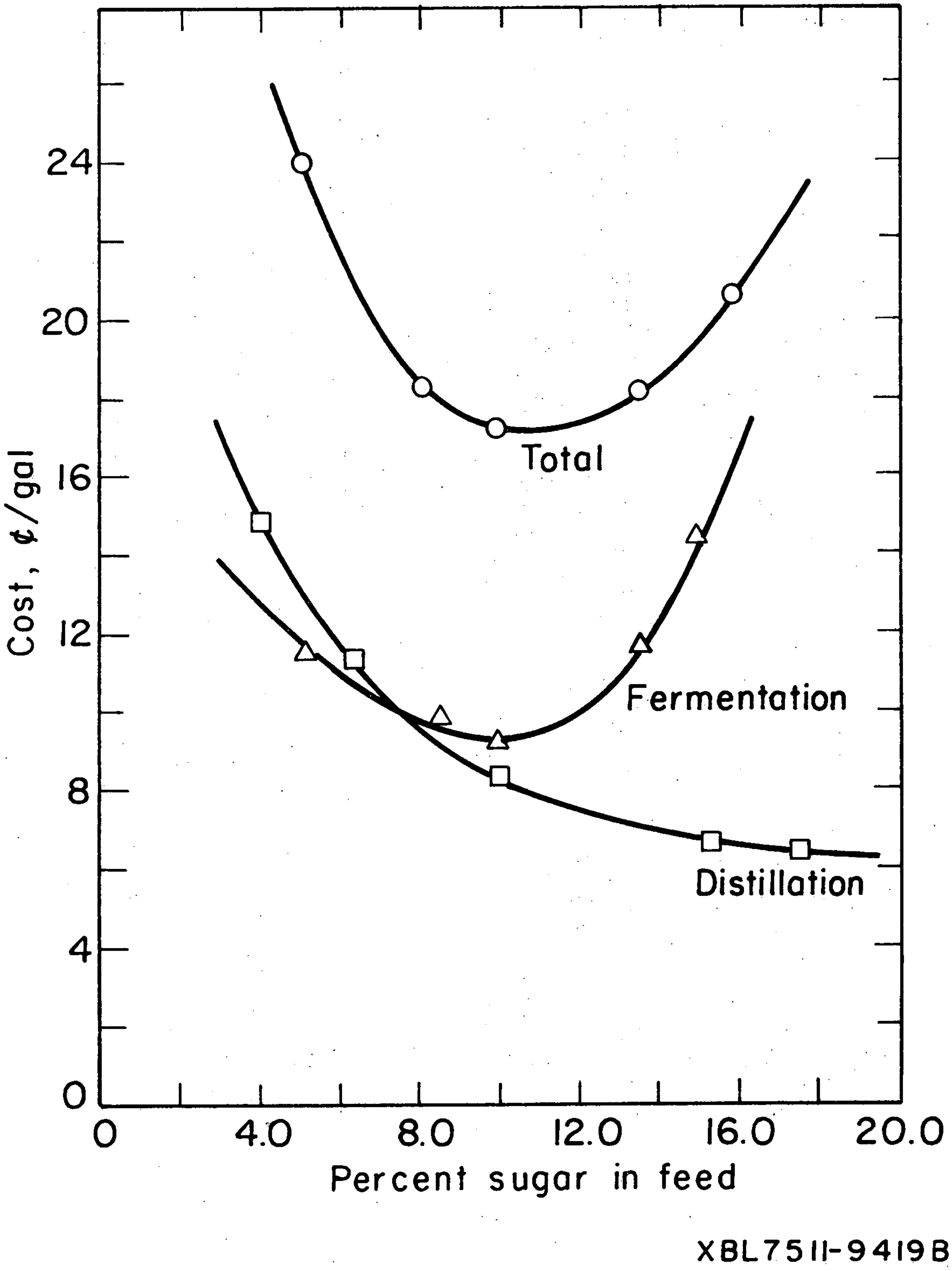

Fig. 8. Effect of sugar concentration on ethanol production costs for continuous fermentation.

The effect of sugar concentration on ethanol production cost for the vacuum fermentation process is illustrated in Fig. 9. The production costs shown are exclusive of any sugar concentration costs. As the sugar concentration increases, the fermentation cost steadily declines since ethanol inhibition is not a problem in the vacuum fermentation and high sugar concentrations allow a reduction in the size of process equipment. However, there is a practical limit to the sugar concentration which may be employed. Extremely concentrated solutions are difficult to pump because of high viscosity. Also, as the sugar is concentrated, so are non-volatile constituents such as minerals and salts. At high concentrations these components may become toxic to the yeast. In absence of knowledge of the exact optimum, a total sugar concentration of 50%, equal to that of full strength cane molasses, was set in the vacuum system. It should be realized, however, that molasses may contain substances (i.e., sulfur dioxide, hydroxymethylfurfural, potassium inidodisulphonate) which inhibit fermentation, depending on the source and manufacturing process of the molasses.(9,13) Hence, more work is required to characterize fermentation kinetics on full strength molasses before a design can be finalized. In this respect, the vacuum fermentation process design must be viewed as a tentative, illustrating the maximum potential of vacuum operation.

TOTAL ETHANOL PRODUCTION COSTS

The total ethanol production cost includes the cost of molasses and any medium supplements that are required. Based on simple stoichiometry, every cent per pound of fermentable sugar costs adds 14.3 cents to the manufacturing cost of 1 gallon of 95% ethanol. Thus, it is easily seen, if sugar costs are above 2 to 3 cent/lb the sugar cost will dominate the economics of ethanol production. Unfortunately, this is the present situation.

A comparison of total ethanol production costs between continuous-cell recycle and vacuum-cell recycle fermentations is given in Table 13. The cost of molasses was taken at 5.0 cents/lb of sugar(14) and 97% of the sugar was assumed fermentable.(9) The medium supplement cost was based on a representative composition of cane molasses and the mineral composition of the yeast.(9) The medium costs are summerized in Table 14. The only additions required are mineral nitrogen, magnesium and phosphorus. Sufficient quantities of other minerals and biotin are present in the raw molasses. A by-product credit of 10 cents/lb of yeast was subtracted from the total production cost. The yeast credit was reduced from the

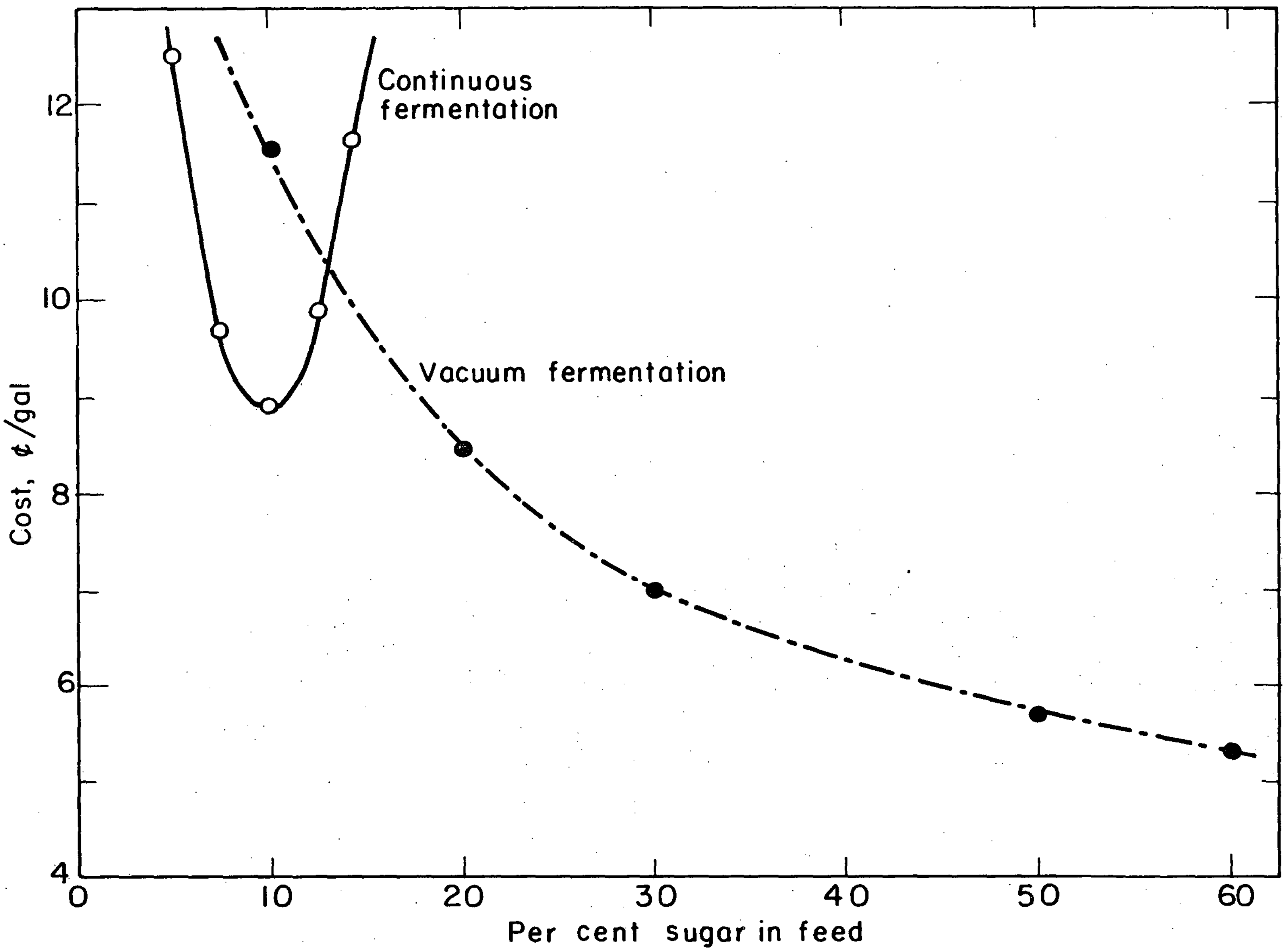

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Fig. 9. Effect of sugar concentration on ethanol production costs for vacuum fermentation.

TABLE 13. TOTAL ETHANOL PRODUCTION COSTS, CENTS/GALLON OF 95% ETHANOL.

	CONTINUOUS CELL RECYCLE	VACUUM CELL RECYCLE
FERMENTATION	5.0	4.8
ETHANOL RECOVERY	8.1	6.7
YEAST RECOVERY	2.4	1.0
STORAGE	0.6	0.2
SUGAR	73.7	71.4
MEDIUM SUPPLEMENTS	5.8	2.7
TOTAL PRODUCTION COSTS	95.6	86.8
YEAST CREDIT	13.3	6.2
NET PRODUCTION COSTS	82.3	80.6

TABLE 14

MEDIUM SUPPLEMENT COSTS FOR CONTINUOUS - CELL RECYCLE OPERATION ($Y_{X/S}$ = 0.10)

COMPONENT	GM/LITER OF RAW MOLASSES	$/TON	TONS/DAY
AMMONIUM	21.1	90	22.1
POTASIUM PHOSPHATE	6.6	120	6.9
MAGNESIUM SULFATE	1.5	110	1.6

current selling price of 40¢/lb for S. cerevisiae(15) to reflect added costs for marketing and distribution. But more important, if industrial ethanol was produced entirely by fermentation the tremendously increased supply of yeast would drive down the selling price. Hence, in absence of a complete marketing study, a conservative price of 10¢/lb of yeast was assumed.

As shown in Table 13, the total ethanol production cost for the continuous cell recycle system is 95.6 cents/gal and for the vacuum system is 86.8 cents/gal. However, after the yeast credit has been subtracted the continuous-cell recycle fermentation appears more attractive requiring only 82.3 cents/gal as compared to 80.6 cents/gal for the vacuum fermentation. Thus, the net production costs are almost identical for the recycle and vacuum systems, even though total production costs are less in the vacuum system. This is due to the lower cell yield factor and hence, reduced yeast by-product credit obtained in the vacuum fermentation (see Tables 6 and 8).

The cost of sugar does indeed dominate the ethanol production cost, representing over 75% of the total manufacturing cost. However, the net production costs of 80.6 and 82.3 cents/gal, after the yeast credit has been subtracted, compares favorably with the current selling price for 95% ethanol of $1.10/gal.(15)

Since the processing costs represent about only 16% of the total ethanol produciton costs, the effect of property taxes and labor rates on the final ethanol cost is minor. This is shown in Table 15 along with the effect of sugar costs.

CONCLUSIONS

The cost of molasses represents over 75% of the total ethanol production cost and thus will dictate the selling price of fermentation ethanol. Viewed from this point, fermentation process improvements have a minor effect on total production costs. However, the process improvements described in this work have a substantial effect on required fixed capital investment and will thus appreciably change the profitability of ethanol production via fermentation. The simple return on investment (ROI) before taxes for the various fermentation processes is shown in Table 16. The current selling price of $1.10/gal of 95% ethanol was assumed, and working capital, consisting of one months operating expenses and a one month surplus of product ethanol, was included in the total fixed capital investment used for the ROI calculations. The ROI for each process is shown both for the case when a 10¢/lb yeast by-product credit is taken and for the case when the yeast by-product credit is neglected.

TABLE 15. INCREMENTAL EFFECT OF VARIABLES ON ETHANOL PRODUCTION COST.

	CENT/GAL INCREASE OF ETHANOL COST
\$5.60/HR → \$10.0/HR INCREASE IN LABOR COSTS	0.5
4.0% → 12% INCREASE IN TAXES	3.6
5.0 CENT/LB → 8.0 CENT/LB INCREASE IN MOLASSES SUGAR COSTS	44.2

TABLE 16. COMPARISON OF RETURN ON INVESTMENT BEFORE TAXES BETWEEN THE VARIOUS FERMENTATION PROCESSES. SELLING PRICE OF 95% ETHANOL TAKEN AT 1.10/GAL.

	PERCENT RETURN ON INVESTMENT*	
FERMENTATION PROCESSES	YEAST CREDIT TAKEN AT 10¢/LB	NO YEAST CREDIT
BATCH	18.5	3.3
CONTINUOUS	55.6	27.9
CONTINUOUS WITH CELL RECYCLE	69.7	36.5
VACUUM WITH CELL RECYCLE	81.5	64.3

$$* - \% \text{ RETURN ON INVESTMENT} = \frac{\text{YEARLY PROFIT}}{\text{TOTAL CAPITAL INVESTMENT}} \times 100$$

With a yeast credit of 10¢/lb batch fermentation yields only 18.5% return on investment (ROI). Since batch fermentation is the currently accepted technology for ethanol fermentation, this low ROI impart explains why ethanol is not presently manufactured by fermentation. But if either of the continuous processes are considered the ROI ranges from 55.6% to 81.5%. In this light, fermentation process improvements have a pronounced affect and could lead to the profitable production of fermentation ethanol.

In conclusion, although the economic analyses presented here are based on preliminary (and tentative) process designs, ethanol production via continuous fermentation processes appears presently profitable and will become more profitable as the price of petroleum increases.

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