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PRELIMINARY ECONOMIC EVALUATION OF A PROCESS FOR THE
PRODUCTION OF FUEL GRADE ETHANOL BY ENZYMATIC
HYDROLYSIS OF AN AGRICULTURAL WASTE

MASTER

Final Report

January 1978

Work Performed Under Contract No. EG-77-X-01-3891

SRI International
Menlo Park, California

U.S. Department of Energy

Solar Energy

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Prepared for:

Department of Energy
Fuels from Biomass Branch
Washington, D.C.

Purchase Order No. EG-77-X-01-3891

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Menlo Park, California 94025

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I INTRODUCTION

This report was prepared by SRI International under Purchase Order No. EG-77-X-01-3891 for the U.S. Department of Energy (formerly the Energy Research and Development Administration), Fuels from Biomass Branch, Mr. Roscoe F. Ward, Branch Chief.

This study concerns the preliminary economic feasibility of a process for converting agricultural waste (wheat straw) to fuel grade ethanol through enzymatic hydrolysis. The process described in this study is based mainly on publications by Professor C. R. Wilke and his associates at the University of California at Berkeley. Additional data were obtained from other reports, particularly those by the U.S. Army Natick Development Center at Natick, Massachusetts. Because the research used as a basis of the process design has only gone through bench scale development, many of the design assumptions have not been fully tested.

SRI developed a preliminary design for the process on the basis of research concepts described in the literature. Professor Wilke was consulted in the course of this work. The base case design is for a 25 million gal/yr plant for 95 vol% ethanol from wheat straw. The preliminary design included material and energy balances and major equipment specifications and sizing, which in turn were used for estimating the required capital investment. Estimates of process operating costs and required selling prices were based on typical industrial conditions. The sensitivity of product ethanol cost to changes in key operating variables was determined in order to indicate where future process improvements are needed and more R&D effort is warranted.

The research was conducted primarily by Mr. Wing S. Fong, Senior Chemical Engineer in SRI's Process Economics Program. Mr. Robert G. Muller, Director of SRI's Chemical Industries Center, was responsible for the overall direction of the project.

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II SUMMARY AND CONCLUSIONS

The process described in this study is based mainly on publications by Professor C. R. Wilke and his associates at the University of California at Berkeley. Additional data were obtained from reports by the U.S. Army Natick Development Center at Natick, Massachusetts. The base case is for the production of 25 million gal/yr of 95 vol% ethanol from a sugar solution obtained by enzymatically hydrolyzing an agricultural waste (wheat straw). The process may be divided into six operating sections: substrate pretreatment, enzyme recovery, hydrolysis, sugar solution concentration, enzyme production, and ethanol production. All sections are assumed to operate continuously except for the fermentation of the sugar to ethanol.

In substrate pretreatment, the straw is milled and then treated with a 1% sulfuric acid solution. The pretreatment produces xylose and arabinose, which are separated from the reactor effluent by filtration and become part of an aqueous acid extract solution containing also other solubles. A major portion of this solution is recycled to the first reactor, while the remainder is disposed of as a waste by-product. The wet filter cake from the filtration contains the cellulosic substrate for sugar production but it is conveyed to the enzyme recovery section, where it is used to adsorb and recover the enzyme contained in the aqueous sugar solution from the hydrolysis section. This recovery is carried out countercurrently in three mixing tanks, each followed by a filter. The sugar solution from the last filter is assumed to be relatively free of the enzyme and is sent to the ethanol production section of the plant. The wet cake, on the other hand, is sent to the hydrolysis section, where it is enzymatically hydrolyzed with an enzyme (cellulase) solution produced by *Trichoderma Viride* in the enzyme production section from a 1% cellulose (newsprint) slurry containing various salts, urea, and protease peptone. The production is carried out in

three lines of six fermenters connected in series. The slurry to these fermenters is sterilized by steam injection. The aerobic fermentation is maintained at 86°F with refrigeration, and at a pH of 4.8 with injection of acid or base. An enzyme solution and a wet cake are recovered from the fermenter effluent through centrifugation and then filtration. The enzyme solution is sent to the hydrolysis section of the plant, while about 65% of the slurry from the centrifuges is recycled to the first fermenters. The wet cake is disposed of as another waste by-product.

The enzymatic hydrolysis is carried out continuously with a 5% slurry in ten lines of four hydrolizers connected in series. The pH of the hydrolyzate is maintained at about 4.8 with a citrate solution. The aqueous sugar solution recovered from the hydrolyzate by filtration is sent to the enzyme recovery section of the plant. The wet cake from the filtration contains unhydrolyzed solids contaminated with enzyme and it too is disposed of as a waste by-product.

The relatively enzyme-free sugar solution from the enzyme recovery section of the plant is concentrated from about 4% to about 10.7% sugar content before it is fed to the batch fermenters for ethanol production. The anaerobic fermentation is carried out with yeast (e.g., *Saccharomyces cerevisiae*) cultivated aerobically from laboratory culture through a series of step-up culture tanks and prefermenters whenever necessary. The fermented broth is then continuously filtered to remove the yeast cells. The filtrate is then purified and concentrated to a 95 vol% ethanol through three distillation columns.

From a preliminary design prepared by SRI, an estimate was made of the required capital investment for the base case (25 million gal of 95% ethanol per year), constructed in the United States in December 1977, as follows:

	<u>\$ million</u>
Battery limits investment by plant section	
Substrate pretreatment	12.0
Enzyme recovery	3.5
Hydrolysis	19.2
Sugar solution concentration	4.4
Enzyme production	21.3
Sugar fermentation and alcohol distillation	<u>10.1</u>
Subtotal	70.5
Off-sites, including utilities, tankage, waste treatment, and general service facilities	<u>26.3</u>
TOTAL FIXED CAPITAL	96.8
Start-up cost	8.2
Working capital	<u>15.9</u>
<u>Total capital investment, excluding land</u>	120.9

The enzyme production and hydrolysis plant sections represent the most costly plant sections, accounting for 31% and 24% of the fixed capital investment respectively. All plant sections require tanks and reactors of very large volume because of the low dilution at which the reactions occur. Tank and reactor costs represent 69% of the battery limits investment.

The plant gate manufacturing cost for the production of 25 million gal/yr of 95 vol% ethanol is summarized as follows:

	<u>\$/Gal</u>
Total materials cost	2.04
Utilities cost	0.48
Capital cost	0.46
Labor cost, including overhead	<u>0.36</u>
Plant gate manufacturing cost*	3.34

* Plant gate cost includes raw materials, utilities, maintenance material and labor, operating labor and supplies, control laboratory, plant overhead, taxes, insurance, and depreciation and does not include any general and administrative, sales, and research costs, profit, and any by-product credits or disposal charges.

The major cost is for materials, which account for about 61% of the plant gate cost, with the agricultural waste accounting for about 12% and materials for enzyme production accounting for about 45%. Enzyme production accounts for 62% of the total plant gate cost, followed by substrate pretreatment at 12%, hydrolysis at 10%, and sugar fermentation and alcohol production at 10%.

For a 15% discounted cash flow rate of return on investment, after taxes, the selling price for the 95 vol% ethanol would have to be \$4.90/gal. This is based on a 15%/yr of fixed capital for general and administrative, sales, and research costs, a 15 year expected life of the plant, a 48% tax rate, and capacity production throughput, requiring no sales buildup over the years.

The sensitivity of the economics to the following factors on fixed capital and the plant gate cost was assessed:

- Cost of agricultural waste
- Cost of cellulose (newsprint for enzyme production)
- Cost of peptone (nutrient for enzyme production)
- Hydrolysis reactor size
- Fermentation tank size
- Conversion of hexosans in agricultural waste to sugar
- Labor costs or requirements
- Fixed capital costs
- Utilities costs or requirement
- Cellulose requirements and concentration in enzyme production
- Enzyme makeup requirements
- Substrate concentration in hydrolysis
- Acid and milling requirements in substrate pretreatment.

The results of these sensitivity studies confirm that the largest cost reductions can be obtained by finding ways (1) to recover more of the enzyme lost through adhesion to the unhydrolyzed solids in hydrolysis, thus reducing the makeup enzyme requirements, (2) to reduce the cellulose requirement for enzyme production, thus reducing the materials cost as well as equipment costs in enzyme production, (3) to use less expensive

cellulosic substrate and less expensive other nutrients (especially the peptone) in enzyme production, thus reducing the materials costs, and (4) to discover that "ideal" strain of microorganism that can produce the enzyme on "cheaper" substrates at a slightly elevated temperature (so that cooling water can be used to maintain the broth at fermentation temperature instead of refrigeration) and at a "faster" induction rate. It would probably also be economically beneficial to be able to use a fermentation medium that would allow a complete or near-complete recycle of the viable cells to the enzyme production after the cells are separated from the enzyme solution and washed.

Since the cost for agricultural waste, even at 0.45¢/lb (\$9.00/ton) accounts for about 39¢/gal 95 vol% ethanol or about 12% of the plant gate cost, it is essential that the agricultural waste used in the process have a relatively high convertibility to sugar. High conversion not only reduces substrate and pretreatment requirements and hydrolysis costs, it can also reduce the amount of unhydrolyzed solids, thus reducing the amount of enzyme that adheres to these solids and becomes lost. Pretreatment of the substrate with acid is relatively expensive. Although some credits may be allowable for the acid extract by-product containing the xylose and arabinose, this extract may need further processing before it can be marketed. Reducing the amount of acid and the pretreatment temperature, if possible, would make the pretreatment more economically attractive.

Excluding any political and social considerations, the production of ethanol from agricultural wastes such as wheat straw, which can be plowed back into the soil after the grain is harvested, does not appear to be economically attractive with current technology and present raw materials costs. The use of other solid wastes that present a disposal and environmental problem to some communities may make the process attractive, if sufficient negative values can be placed on these wastes. Even with such wastes, improvement on the enzyme recovery and production, and reduction in the makeup enzyme requirement remain essential. Moreover, an evaluation on the disposal and utilization of the by-products generated by the process must also be made before the process economics can be finalized.

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III PROCESS DESCRIPTION

The process described in this study is one to produce 25 million gal/yr of a 95 vol% ethanol from a sugar solution obtained by enzymatically hydrolyzing an agricultural waste (wheat straw). The process is divided into six operating sections: substrate pretreatment, enzyme recovery, hydrolysis, sugar solution concentration, enzyme production, and ethanol production. All sections are assumed to be operating continuously except for the fermentation of the sugar to ethanol. A schematic flow sheet containing the major stream flows is illustrated in Figure 1, and the major equipment list and utilities summary are presented in Table 1.

In the substrate pretreatment, the straw is milled and then treated with a 1% sulfuric acid solution at 212°F for an average residence time of about 1.1 hours. The pretreatment produces xylose and arabinose, which are separated from the reactor effluent by filtration and become part of an aqueous acid extract solution containing also other solubles. A major portion of this solution is recycled to the first reactor, while the remainder is disposed of as a waste by-product. The wet filter cake from the filtration contains the cellulosic substrate for sugar production but it is conveyed to the enzyme recovery section, where it is used to adsorb and recover the enzyme contained in the aqueous sugar solution from the hydrolysis section. This recovery is carried out countercurrently in three mixing tanks, each followed by a filter. The sugar solution from the last filter is assumed to be relatively free of the enzyme and is sent to the ethanol production section of the plant. The wet cake, on the other hand, is sent to the hydrolysis section, where it is enzymatically hydrolyzed with an enzyme (cellulase) solution produced by *Trichoderma Viride* in the enzyme production section from a 1% cellulose (newsprint) slurry containing various salts, urea, and protease peptone. The production is carried out at a dilution rate of about 0.02 hr^{-1} and an aeration rate of 0.015 vol/vol/min in three

lines of six fermenters connected in series. The slurry to these fermenters is sterilized by steam injection. The aerobic fermentation is maintained at 86°F with refrigeration, and at a pH of 4.8 with injection of acid or base. An enzyme solution and a wet cake are recovered from the fermenter effluent through centrifugation and then filtration. The enzyme solution is sent to the hydrolysis section of the plant, while about 65% of the slurry from the centrifuges is recycled to the first fermenters. The wet cake is disposed of as another waste by-product.

The enzymatic hydrolysis is carried out continuously with a 5% slurry feed at 122°F for an average residence time of about 40 hours in ten lines of four hydrolyzers connected in series. The pH of the hydrolyzate is maintained at about 4.8 with a citrate solution. A portion of the aqueous sugar solution recovered from the hydrolyzate by filtration is recycled to the first hydrolyzers, while the remainder is sent to the enzyme recovery section of the plant. The wet cake from the filtration contains unhydrolyzed solids contaminated with enzyme and it too is disposed of as a waste by-product.

The relatively enzyme-free sugar solution from the enzyme recovery section of the plant is concentrated from about 4% to about 10.7% sugar content before it is fed to the batch fermenters for ethanol production. The anaerobic fermentation is carried out at a pH of 4-5 and about 86°F for about 41 hours (batch cycle time of about 64 hours) with yeast (e.g., *Saccharomyces cerevisiae*) cultivated aerobically from laboratory culture through a series of step-up culture tanks and prefermenters whenever necessary. The fermented broth is then continuously filtered to remove the yeast cells. The filtrate is then purified and concentrated to a 95 vol% ethanol through three distillation columns.

Table 1

**ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)**

MAJOR EQUIPMENT AND UTILITIES SUMMARY

Capacity: 25 Million gal/yr 95 vol% Ethanol
at 0.9 Stream Factor

Equipment Number	Name	Size	Material of Construction		Remarks	
<u>Compressors</u>						
K-501	Aeration system	1,550 bhp	Carbon steel		Including filters and cooler.	
K-601	Aeration system	500 bhp	Carbon steel		Including filters and cooler.	
<u>Exchangers</u>						
E-101-105	Heat exchangers, each	200	16.80	Carbon steel	Carbon steel	
E-106-111	Heat exchangers, each	2,200	19.20	Carbon steel	304 ss	
E-112	Heat exchanger	1,100	51.00	Carbon steel	304 ss	
E-501-503	Heat exchangers, each	1,700	23.80	Carbon steel	304 ss	
E-504-506	Heat exchangers, each	400	2.20	Carbon steel	304 ss	
E-601-604	Plate exchangers, each	400	5.00	Carbon steel	Carbon steel	
E-605	Heat exchanger	7,000	41.50	Carbon steel	Carbon steel	
E-606	Heat exchanger	5,100	80.00	Carbon steel	Carbon steel	
E-607	Heat exchanger	200	0.20	Carbon steel	Carbon steel	
E-608	Heat exchanger	1,200	1.26	Carbon steel	Carbon steel	
<u>Tanks, Hoppers, and Bins</u>						
T-151	Sulfuric acid storage tank	75,000	Carbon steel			
T-101	Feed hopper	60,000	Carbon steel		With feed screw conveyor.	
T-102-106	Reactors, each	120,000	304 ss		With agitator and heat transfer coil.	
T-201-203	Mixing tanks, each	125,000	Carbon steel		With agitator.	
T-301-305	Citrate solution tanks, each	1,000	Carbon steel		With agitator.	
T-306-310	Feed hoppers, each	200	Carbon steel		With feeder.	
T-311-350	Hydrolyzers, each	540,000	Carbon steel		With agitator.	
T-401	Surge tank	150,000	Carbon steel		Not shown.	
T-402	Sugar solution surge tank	600,000	Carbon steel			
T-501	Cellulose bin	350,000	Carbon steel		With feed conveyors to mills.	
T-502	Urea bin	6,000	Carbon steel		With feed conveyor. Not shown.	
T-503	Ammonium sulfate bin	30,000	Carbon steel		With feed conveyor. Not shown.	
T-504	Phosphate bin	40,000	Carbon steel		With feed conveyor. Not shown.	
T-505	Calcium chloride bin	6,000	Carbon steel		With feed conveyor. Not shown.	
T-506	Magnesium sulfate bin	6,000	Carbon steel		With feed conveyor. Not shown.	
T-507	Protease peptone bin	15,000	Carbon steel		With feed conveyor. Not shown.	
T-508	Feed hopper	6,000	Carbon steel		With feed conveyor.	
T-509	Medium makeup tank	70,000	304 ss		With agitator.	
T-610	Antifoaming agent tank	1,000	Carbon steel			
T-511	Acid tank	3,500	Carbon steel			
T-512	Base tank	3,500	Carbon steel			
T-513-530	Fermenters, each	530,000	304 ss		With agitator and coil.	
T-531	Enzyme solution surge tank	30,000	304 ss		With coil.	
T-601-602	First yeast tanks, each	350	304 ss		Equipped with agitator and heat transfer coils.	
T-603-604	Second yeast tanks, each	1,700	304 ss		Equipped with agitator and heat transfer coils.	
T-605-608	Final yeast tanks, each	8,500	304 ss		Equipped with agitator and heat transfer coils.	
T-609-612	Prefermenters, each	50,000	Carbon steel		Equipped with agitator and heat transfer coils.	
T-613-618	Fermenters, each	560,000	Carbon steel			
T-619	Surge tank	6,500	Carbon steel			
T-620	Surge tank	250	Carbon steel			
T-621	Surge tank	4,000	Carbon steel			
T-651	Fusel oils storage tank	11,000	Carbon steel		Not shown.	
T-652	Ethanol storage tank	2,300,000	Carbon steel		Not shown.	
<u>Columns</u>						
C-601	Beer column	54	15.0	Carbon steel	Carbon steel	23 sieve trays, 24 in. spacing, with reboiler.
C-602	Heads column	50	7.5	Carbon steel	Carbon steel	20 sieve trays, 24 in. spacing, with heating coils.
C-603	Rectifying column	75	11.5	Carbon steel	Carbon steel	30 sieve trays, 24 in. spacing, with heating coils.

Table 1 (Concluded)

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)

MAJOR EQUIPMENT AND UTILITIES SUMMARY

Capacity: 25 million gal/yr 95 vol% Ethanol
at 0.9 Stream Factor

Equipment Number	Name	Size	Material of Construction	Remarks
<u>Miscellaneous Equipment</u>				
M-101	Mills		Carbon steel	12 hammer mills, each with 150 hp motor.
M-102	Mills		Carbon steel	12 air-swept pulverizers, each with 150 hp motor and collection system.
M-103	Conveyor systems		Carbon steel	12 belt conveyors to M-101, 12 screw conveyors from M-101 to M-102.
M-104-109	Rotary filter, each	800 sq ft	304 ss	
M-110	Conveyor systems		Carbon steel	For conveying filter cake to enzyme recovery section. Not shown.
M-201	Conveyor systems		Carbon steel	For conveying filter cake to mixing tanks.
M-202	Conveyor systems		Carbon steel	For conveying filter cake to hydrolysis section.
M-203-208	Rotary filters, each	800 sq ft	Carbon steel	
M-301-304	Rotary filters, each	860 sq ft	Carbon steel	
M-305	Conveyor systems		Carbon steel	For conveying unhydrolyzed wastes from hydrolysis section. Not shown.
M-401	Multieffect evaporator	70,000 sq ft	Carbon steel	Ten-effect.
M-501	Mills		Carbon steel	Two air-swept pulverizers each with 150 hp motor and collection system.
M-502-507	Centrifuges, each	65 hp	304 ss	
M-508	Rotary filter	350 sq ft	304 ss	
M-509	Conveyor system		Carbon steel	For conveying filter cake from enzyme production section. Not shown.
M-510	Scrubber	16,000 cfm	Reinforced plastic	Not shown.
M-601	Scrubber	5,000 cfm	Reinforced plastic	Not shown.
M-602-607	Rotary filters, each	850 sq ft	Carbon steel	Not shown.

Pumps

100 Section: 32, including 23 operating, 9 spares; 1,103 operating bhp
 200 Section: 14, including 10 operating, 4 spares; 442 operating bhp
 300 Section: 79, including 64 operating, 15 spares; 660 operating bhp
 400 Section: 6, including 3 operating, 3 spares; 134 operating bhp
 500 Section: 50, including 38 operating, 12 spares; 480 operating bhp
 600 Section: 51, including 37 operating, 14 spares; 212 operating bhp

Utilities Summary

	Battery Limits Total	100 Section	200 Section	300 Section	400 Section	500 Section	600 Section
<u>Average Consumptions</u>							
Cooling water (gpm)	17,055	1,120	0	160	0	7,215	8,560
Refrigeration (tons) at 40°F	3,100	0	0	0	0	1,900	1,200
Process water (gpm)	3,706	1,900	0	915	0	891	0
Electricity (kw)	25,653	4,311	623	8,937	80	8,093	3,609
Steam at 250 psig (lb/hr)	348,500	80,000	0	0	80,000	70,000	118,500
<u>Peak Utility Demands</u>							
Cooling water (gpm)	20,466	1,344	0	192	0	8,658	10,272
Refrigeration (tons) at 40°F	3,720	0	0	0	0	2,280	1,440
Process water (gpm)	4,447	2,280	0	1,098	0	1,069	0
Electricity (kw)	26,326	4,311	623	8,937	80	8,505	3,870
Steam at 250 psig (lb/hr)	418,200	96,000	0	0	96,000	84,000	142,200

Note: The battery limits figures include electricity and cooling water requirements of refrigeration.

Figure 1

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS OF AGRICULTURAL WASTES (WHEAT STRAW)

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Figure 1 (Concluded)

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)

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IV PROCESS DISCUSSION

The described process is based essentially on data published by Professor C. R. Wilke and his associates at the University of California at Berkeley (1-8). Additional data, such as the recipe for the enzyme production medium, were obtained from other reports, particularly those by the U.S. Army Natick Development Center at Natick, Massachusetts (9-10)*. Many of these data are from laboratory and bench scale experiments and many of the design assumptions, therefore, have not yet been tested in a larger, continuous unit.

The wheat straw was assumed to contain 34% hexosans, 17% pentosans, and 13% lignins (1). About 81% of the pentosans in the milled agricultural waste is assumed to be converted to xylose and arabinose in the acid pretreatment. Also formed is an acid extract by-product, the utilization and value of which probably require further study.

About 0.624 lb of solids for the enzymatic hydrolysis is also assumed to be obtainable from a lb of the straw and about 45% of the hexosans present in the waste is assumed to be converted to sugars fermentable to ethanol in hydrolysis.

The amount of cellulose required to produce a lb of enzyme has been reported to be from 3 to 9 lb; these data are based on the use of purified cellulose (Solka-Floc®) or newsprint and sugar as substrates. Newsprint is assumed to be the substrate in this study and about 4.35 lb of the newsprint/lb of enzyme production is assumed to be needed for the makeup mycelial growth. The fermentation medium is based on a 1% cellulose concentration and contains the relatively expensive protease peptone, a low priced phosphate, and other nutrients (ammonium sulfate, urea, calcium chloride, and magnesium sulfate). A medium containing a higher

* References 11-37 and 39 were used also but they are not cited specifically.

substrate concentration and a less expensive peptone-equivalent may be developed for industrial production.

About 65% of the cells is recycled to the fermenters in the enzyme production and about 66% of the enzyme needed in the hydrolysis is produced to make up for the enzyme loss through adsorption on the unhydrolyzed solids.

The sizes of the enzyme fermenters and the hydrolyzers are assumed to be about 530,000 and 540,000 gal respectively. This is based on the fact that fermenters up to this size range reportedly have been used in ethanol fermentation. These capacities may not be the optimum sizes for the enzyme production or the hydrolysis in large scale production.

In the design case, a 5% solids concentration is used in the feed to the hydrolysis to produce a hydrolyzate with 4% sugar concentration. It may be possible to increase the solids concentration to 7.5%, provided that the slurry can still be effectively agitated to keep the slurry uniformly blended and can still be pumped through the lines.

The fermentable sugar in the hydrolyzate is concentrated by a conventional method, multieffect evaporation. Other methods such as osmosis may eventually prove to be feasible and economical.

By-products containing unhydrolyzed and unfermented solids are produced from the hydrolysis and enzyme production. They are disposed of as wastes. These by-products may be used as fuel for steam generation, but their fuel values will have to be established because they also contain a large quantity of water. The aqueous effluent from the distillation column in ethanol fermentation from molasses is normally dried to produce a "distillers feed." However, the sugar solution obtained through enzymatic hydrolysis may contain contaminants objectionable for such utilization. Further study may be needed to determine the disposition of this by-product.

V COST ESTIMATES

The cost estimates for the annual production of 25 million gal of 95 vol% ethanol from wheat straw is based on the process described in Section III and on the following assumptions:

- The cost for the straw is set at 0.45¢/lb (\$9.00/ton), a price that is at the low end of a range of collection and transportation (within a 10 mile radius of point of collection) costs estimated by J. H. Sloneker (38) and SRI (40). It does not include any compensation to the farmers for not having the straw to plow back into the soil.
- The cost for the cellulosic substrate for the enzyme production is set at 16¢/lb, a price quoted by the Wall Street Journal for newsprint, effective February 1978.
- Ammonium phosphate at 0.9¢/lb is used for the medium in enzyme production instead of potassium acid phosphate, which is currently quoted at about 43¢/lb (technical grade).
- A protease peptone at \$3.00/lb is used for the medium in enzyme production.
- The battery limits investment is estimated from the battery limits major equipment cost by PEPCOST, a computerized costing program designed by SRI and based on the Hirsch and Glazier method (41).
- General service facilities investment is set at 20% of the sum of the battery limits investment and the utilities and tankage investment, and it includes a 5% allowance for waste treatment.
- The onstream factor is set at 0.90, or 330 days/year and 24 hours/day (7,920 hours/year).
- The plant gate manufacturing cost includes raw materials, utilities, maintenance material and labor, operating labor and supplies, control laboratory, plant overhead, taxes, insurance, and depreciation. It does not include any general and administrative, sales, and research costs, profit, and any by-product credits or disposal charges.
- Maintenance material and labor costs are each set at 3%/yr of the battery limits investment, plus 1.5%/yr of the refrigeration investment.

- Operating supplies are set at 10% of operating labor cost.
- Operating labor cost is set at \$11.65/man-hour; this includes fringe benefits and shift overlap.
- Control laboratory cost is set at 20% of operating labor cost.
- Plant overhead is set at 80% of total labor cost, which includes operating labor, maintenance labor, and control laboratory costs.
- Taxes and insurance costs are set at 2%/yr of the total fixed capital.
- Depreciation is set at 10%/yr of the total fixed capital.

On the basis of the preceding assumptions, the capital investments for the 25 million gal 95 vol% ethanol plant constructed in December 1977, are presented in Table 2 and summarized as follows:

	<u>\$ Million</u>
Battery limits investment by plant section	
Substrate pretreatment	12.0
Enzyme recovery	3.5
Hydrolysis	19.2
Sugar solution concentration	4.4
Enzyme production	21.3
Ethanol production	<u>10.1</u>
Subtotal	70.5
Off-sites investment, including utilities	
Tankage, waste treatment and general service facilities	<u>26.3</u>
TOTAL FIXED CAPITAL	96.8
Start-up cost	8.2
Working capital	<u>15.9</u>
TOTAL CAPITAL INVESTMENT, not including land	120.9

The distributions of capital and battery limits equipment costs are summarized in Table 3. The most expensive operating sections of the plant are enzyme production and hydrolysis, with the former accounting for slightly less than one-third of the total fixed capital and the latter accounting for slightly less than one-fourth. In equipment, the cost for tanks is predominant, accounting for about 69% of the battery limits equipment cost.

The plant gate manufacturing costs for the production of 25 million gal of 95 vol% ethanol are presented in Table 4 and summarized as follows:

	<u>\$/gal</u>
Total materials cost	2.04
Utilities cost	0.48
Capital cost	0.46
Labor cost, including overhead manufacturing	<u>0.36</u>
Plant gate manufacturing cost	3.34

The major cost is for materials, which account for about 61% of the plant gate manufacturing cost, with the straw accounting for about 11.6% and materials for enzyme production accounting for about 44.5%. The cellulose and the high priced protease peptone account for about 17% and 24% of the plant gate manufacturing cost and about 29% and 41% of the total raw material cost. The effect of the prices of cellulose, wheat straw, and peptone on the plant gate manufacturing cost is presented in Figure 2. If the price for the straw must also include compensation to the farmer, the price might increase, for instance, from 0.45¢/lb (\$9/ton) to 1.5¢/lb (\$30/ton). The plant gate manufacturing cost would thus be raised from \$3.34/gal to \$4.25/gal, a 27% increase. On the other hand, if a \$1.90/lb peptone^{*} can be used to replace quantitatively the \$3.00/lb protease peptone[†], the plant gate manufacturing cost can be reduced to about \$3.05/gal, about a 9% reduction.

In the base case a production of 0.45 lb of sugar for each lb of hexosans in the straw is assumed. The effect of this conversion on plant gate manufacturing cost is illustrated in Figure 3. If, for example, 0.6 lb of sugar can be obtained from a lb of hexosan in the straw, the plant gate manufacturing cost can be reduced from \$3.34/gal to about \$3.14/gal, a 6% reduction.

* Gunther'sTM Soy-Peptone-SF by A. E. Staley Mfg Co., Decatur, Ill.

† "Pharmatone" by American Laboratories, Omaha, Nebraska.

Table 2

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)

TOTAL CAPITAL INVESTMENT

Capacity: 25 Million gal/yr 95 vol% Ethanol
at 0.9 Stream Factor
PEP Cost Index: 285

	Total			Substrate Pretreatment			Enzyme Recovery			Hydrolysis		
	Capacity Exponent			Capacity Exponent			Capacity Exponent			Capacity Exponent		
	Cost	Up	Down	Cost	Up	Down	Cost	Up	Down	Cost	Up	Down
Battery limits equipment, f.o.b.												
Columns	\$ 373,200											
Vessels and tanks	17,628,500			\$ 895,600	0.64	0.64	\$ 188,400	0.63	0.63	\$ 6,634,300	0.95	0.94
Exchangers	853,400			451,200	0.86	0.53						
Compressors	796,000											
Miscellaneous equipment	4,618,600			1,881,000	0.94	0.68	538,600	0.95	0.45	352,800	0.93	0.45
Pumps	1,286,500			408,900	0.89	0.85	83,700	0.95	0.95	335,200	0.95	0.95
Total	\$25,556,200	0.78	0.71	\$ 3,636,700	0.85	0.67	\$ 810,700	0.88	0.54	\$ 7,322,300	0.95	0.92
BATTERY LIMITS INVESTMENT	\$70,460,000	0.76	0.68	\$11,976,000	0.83	0.67	\$ 3,489,000	0.84	0.49	\$19,256,000	0.91	0.88
Off-sites												
Cooling tower	\$ 1,356,700			89,100	0.95	0.83				\$ 12,700	0.95	0.83
Process water treatment	230,000			117,900	0.77	0.77				56,800	0.77	0.77
Steam generation	3,841,800			881,900	0.95	0.95						
Refrigeration	2,436,600											
Tankage	648,700			60,600	0.65	0.65						
Utilities and tankage investment	\$10,216,000	0.90	0.90	\$ 1,380,000	0.92	0.90				\$ 83,000	0.82	0.78
General service facilities	16,135,000*											
OFF-SITES INVESTMENT	\$26,351,000											
TOTAL FIXED CAPITAL	\$96,811,000	0.78	0.71									
Start-up cost	8,166,000											
Working capital	15,943,000											
TOTAL CAPITAL INVESTMENT, not including land	\$120,920,000											

*\$4,033,750 for waste treatment is included in General Service Facilities.

Table 2 (Concluded)

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)

TOTAL CAPITAL INVESTMENT

Capacity: 25 Million gal/yr 95 vol% Ethanol
at 0.9 Stream Factor
PEP Cost Index: 285

	Sugar Solution Concentration			Enzyme Production			Ethanol Production		
	Cost	Capacity Exponent		Cost	Capacity Exponent		Cost	Capacity Exponent	
		Up	Down		Up	Down		Up	Down
Battery limits equipment, f.o.b.									
Columns							\$ 373,200	0.90	0.68
Vessels and tanks	\$ 178,100	0.65	0.65	\$ 8,168,900	0.64	0.63	1,563,200	0.60	0.56
Exchangers				231,700	0.56	0.52	170,500	0.78	0.60
Compressors				568,300	0.74	0.74	227,700	0.75	0.75
Miscellaneous equipment	775,200	0.73	0.73	562,600	0.86	0.45	508,400	0.44	0.44
Pumps	37,200	0.95	0.95	275,400	0.95	0.95	146,100	0.80	0.74
Total	\$ 990,500	0.72	0.72	\$ 9,806,900	0.66	0.63	\$ 2,989,100	0.65	0.58
BATTERY LIMITS INVESTMENT	\$ 4,381,000	0.66	0.68	\$21,269,000	0.63	0.60	\$10,042,000	0.62	0.56
Off-sites									
Cooling tower				574,000	0.95	0.83	680,900	0.95	0.83
Process water treatment				55,300	0.77	0.77			
Steam generation	881,900	0.95	0.95	771,700	0.95	0.95	1,306,300	0.95	0.95
Refrigeration				1,493,400	0.84	0.95	943,200	0.84	0.95
Tankage							588,100	0.84	0.63
Utilities and tankage investment	\$ 1,058,000	0.95	0.95	\$ 3,473,000	0.90	0.92	\$ 4,222,000	0.88	0.87

Table 3

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)

DISTRIBUTION OF CAPITAL AND BATTERY LIMITS EQUIPMENT COSTS

Capacity: 25 Million gal/yr 95 vol% Ethanol
at 0.9 Stream Factor
PEP Cost Index: 285

	Capital Cost Distribution (%)		
	Battery Limits Investment	Utilities and Tankage Investment	Total Fixed Capital
Substrate pretreatment	17.0	13.5	16.6
Enzyme recovery	5.0	0	4.3
Hydrolysis	27.3	0.8	24.0
Sugar solution concentration	6.2	10.4	6.7
Enzyme production	30.2	34.0	30.7
Ethanol production	<u>14.3</u>	<u>41.3</u>	<u>17.7</u>
Total	100.0	100.0	100.0

	Battery Limits Equipment Cost Distribution (%)						
	Substrate Pretreatment	Enzyme Recovery	Hydrolysis	Sugar Solution Concentration	Enzyme Production	Ethanol Production	Total
Columns	0	0	0	0	0	1.5	1.5
Tanks	3.5	0.7	26.0	0.7	32.0	6.1	69.0
Exchangers	1.8	0	0	0	0.8	0.7	3.3
Compressors	0	0	0	0	2.2	0.9	3.1
Miscellaneous	7.4	2.1	1.4	3.0	2.2	2.0	18.1
Pumps *	<u>1.6</u>	<u>0.3</u>	<u>1.3</u>	<u>0.1</u>	<u>1.1</u>	<u>0.6</u>	<u>5.0</u>
Total	14.3	3.1	28.7	3.8	38.3	11.8	100.0

* Including spares.

Table 4

ETHANOL PRODUCTION FROM ENZYMATIC HYDROLYSIS
OF AGRICULTURAL WASTES (WHEAT STRAW)

PLANT GATE MANUFACTURING COST¹

Capacity: 25 Million gal/yr 95 vol% Ethanol
at 0.9 Stream Factor
PEP Cost Index: 285

			¢/gal 95 vol% Ethanol						
	Units/Gal	Unit Cost	Total	Substrate Pretreatment	Enzyme Recovery	Hydrolysis	Sugar Solution Concentration	Enzyme Production	Ethanol Production
Materials *									
Agro-wastes, wheat straw	86.26 lb	0.45¢/lb [†]	38.82						
Sulfuric acid	2.803 lb	2.67¢/lb	7.48	7.48					
Cellulose, newsprint	3.494 lb	16.0¢/lb [‡]	55.90					55.90	
Protasec peptone	0.264 lb	\$3.00/lb [§]	79.20					79.20	
Phosphate	0.699 lb	9.0¢/lb**	6.29					6.29	
Ammonium sulfate	0.505 lb	3.0¢/lb	1.51					1.47	0.04
Urea	0.105 lb	8.4¢/lb	0.88					0.88	
Magnesium sulfate	0.105 lb	8.5¢/lb	0.89					0.89	
Miscellaneous	0.325 lb ^{††}	10.0¢/lb ^{††}	3.25			2.00		1.25	
Total raw materials			194.22	7.48 ^{††}		2.00 ^{††}		145.88 ^{††}	0.04 ^{††}
Maintenance material	3%/yr of battery limits cost, plus 1.5%/yr of refrigeration investment		8.63	1.44	0.42	2.31	0.52	2.66	1.28
Operating supplies	10% of operating labor		0.94	0.21	0.08	0.16	0.04	0.21	0.24
Total materials			203.79	9.13	0.50	4.47	0.56	148.75	1.56
Utilities									
Cooling water	323 gal	3¢/1,000 gal	0.97	0.07		0.01		0.41	0.48
Steam	110 lb	275¢/1,000 lb	30.22	6.93			6.94	6.07	10.28
Process water	70.1 gal	40¢/1,000 gal	2.80	1.44		0.69		0.67	
Electricity	8.09 kwh	1.75¢/kwh	14.16	2.38	0.34	4.93	0.04	4.48	1.99
Total utilities			48.15	10.82	0.34	5.63	6.98	11.63	12.75
VARIABLE COST			251.94	19.95	0.84	10.10	7.54	160.38	14.31
Operating labor	23 men/shift at \$11.65/man-hr		9.39	2.04	0.82	1.63	0.41	2.04	2.45
Maintenance labor	3%/yr of battery limits cost, plus 1.5%/yr of refrigeration investment		8.63	1.44	0.42	2.31	0.52	2.66	1.28
Control laboratory	20% of operating labor		1.88	0.41	0.16	0.33	0.08	0.41	0.49
Total direct labor			19.90	3.89	1.40	4.27	1.01	5.11	4.22
TOTAL DIRECT COST			271.84	23.84	2.24	14.37	8.55	165.49	18.53
Plant overhead	80% of total labor		15.92	3.11	1.12	3.42	0.81	4.09	3.37
Taxes and insurance	2%/yr of fixed capital		7.74	1.28	0.34	1.86	0.52	2.37	1.37
Depreciation	10%/yr of fixed capital		38.72	6.41	1.68	9.28	2.61	11.87	6.87
PLANT GATE MANUFACTURING COST			334.22 ^{§§}	34.64 ^{††}	5.38 ^{††}	28.93 ^{††}	12.49 ^{††}	183.82 ^{††}	30.14 ^{††}

* At prices quoted in the Chemical Marketing Reporter, Nov. 28, 1977, unless stated otherwise.

[†] Priced at low end of the range of collection and transportation costs estimated by J. H. Sloneker (38) and SRI International (40).

[‡] Bowater's newsprint price, effective February 1978 (Wall Street Journal, Nov. 14, 1977). Solka-Floc[®], a pure, finely divided cellulose produced by Brown Company and used in most of the reported laboratory enzyme production experiments, is priced at about 38¢/lb (SW-40, BW-20, BW-40), 30-50 lb bags, carload, f.o.b., Berlin, New Hampshire, effective Sept. 1, 1977.

[§] American Laboratories, Inc.'s "Pharmatone" (a high protease peptone made from pork).

**Ammonium phosphate price. References (2) and (10) cited potassium acid phosphate as the phosphate nutrient in the medium; potassium acid phosphate costs about 43¢/lb in 100 lb bags, minimum 20,000-24,000 lb lot.

^{††} Allowed for miscellaneous chemicals.

^{†††} Not including the cost for the agricultural waste substrate.

^{§§} Not including G&A, sales, and research costs, profit, and any by-product credits or charges for the acid extract from the substrate pretreatment and the aqueous stream, fusel oils and others from the ethanol production.

Figure 2

EFFECT OF AGRICULTURAL WASTE, CELLULOSE, AND PEPTONE PRICES ON PLANT GATE MANUFACTURING COST

* For Enzyme Production

Figure 3

EFFECT OF HEXOSAN CONVERSION TO SUGAR
AND CHANGES IN LABOR, CAPITAL AND UTILITIES COST
OR REQUIREMENT ON PLANT GATE MANUFACTURING COST

The utilities and capital costs each account for about 14% of the plant gate manufacturing cost, and the labor cost, 11%. The effect of these labor, capital, and utilities costs on plant gate manufacturing cost is also illustrated in Figure 3. For example, if the wet cake by-products from enzyme production and hydrolysis are used as fuel for steam generation, the steam unit cost would be reduced from about 2.74¢/1,000 lb to about \$0.39/1,000 lb of steam, and the utilities cost from 48.15¢/gal of 95 vol% ethanol to about 22.22¢/gal, or a 54% reduction from that in the base case. The plant gate manufacturing cost would thus be reduced from \$3.34/gal to about \$3.08/gal, about an 8% reduction.

The largest equipment expense is for tanks. Doubling the hydrolyzers and enzyme fermenter sizes from the base case 540,000 and 530,000 gal to 1,080,000 and 1,060,000 gal (while assuming the same installation factor for the cost estimation) would reduce the total fixed capital from \$96.8 million to about \$88.7 million, about an 8% reduction, and the plant gate manufacturing cost from \$3.34/gal to about \$3.28/gal, about a 2% reduction. On the other hand, if smaller hydrolyzers and enzyme fermenters are found to be necessary in scale-ups and 270,000 gal hydrolyzers and 265,000 gal enzyme fermenters are used, the total fixed capital would be increased to about \$107 million, about an 11% increase, and the plant gate manufacturing cost would be increased from \$3.34/gal to about \$3.44/gal, about a 3% increase.

Excluding the cost for the straw, the distribution of the plant gate manufacturing cost is as follows:

<u>Plant Section</u>	<u>%</u>
Substrate pretreatment	12
Enzyme recovery	2
Hydrolysis	10
Sugar solution concentration	4
Enzyme production	62
Ethanol production	<u>10</u>
Total	100

As in capital investment, enzyme production is the largest cost factor in plant gate manufacturing cost. The effect of cellulose and enzyme makeup requirements, cellulose concentration in the feed to the enzyme fermenters, and peptone cost in enzyme production on plant gate manufacturing cost and total fixed capital are presented in Figures 4, 5, and 6. Reducing the cellulose requirement, for example, from 4.35 lb/lb of enzyme produced to about 2 lb/lb reduces the total fixed capital from \$96.8 million to about \$84.9 million, a 12% reduction, and the plant gate manufacturing cost from \$3.34/gal to about \$2.44/gal, a 27% reduction. If the peptone price can be reduced from \$3.00/lb to about \$1.00/lb at the same time, the plant gate manufacturing cost can be reduced to about \$2.19/gal, a 34% reduction.

On the other hand, if the enzyme makeup requirement is reduced from 66% to about 33% (see Figure 5), the total fixed capital will be reduced from \$96.8 million to about \$85.9 million, an 11% reduction, and the plant gate manufacturing cost from \$3.34/gal to about \$2.45/gal, a 27% reduction. Again, if the peptone price is reduced from \$3.00/lb to about \$1.00/lb at the same time, the plant gate manufacturing cost will be reduced to about \$2.18/gal, about a 35% reduction.

The total fixed capital and plant gate manufacturing cost can also be reduced by increasing the concentration of the slurry fed to the enzyme fermenters, provided the dilution rate and enzyme production can be maintained unchanged. For example, if the cellulose can be increased from 1% to 2% (see Figure 6), the fixed capital and plant gate manufacturing cost can be reduced from \$96.8 million and \$3.34/gal to about \$88.9 million, about an 8% reduction, and to \$3.25/gal, about a 3% reduction. And if the peptone price is reduced from \$3.00/lb to about \$1.00/lb at the same time, the plant gate manufacturing cost will be further reduced to about \$2.72/gal, about a 19% reduction.

The substrate pretreatment section has a lower capital requirement but a higher plant manufacturing cost^{*} than does the hydrolysis section.

^{*} Without any credit or disposal charge on the acid extract by-product.

Figure 4

EFFECT OF CELLULOSE REQUIREMENT AND PEPTONE COST
IN ENZYME PRODUCTION ON PLANT GATE MANUFACTURING COST
AND TOTAL FIXED CAPITAL

Figure 5

EFFECT OF ENZYME MAKEUP REQUIREMENT AND PEPTONE COST
IN ENZYME PRODUCTION ON PLANT GATE MANUFACTURING
COST AND TOTAL FIXED CAPITAL

Figure 6

EFFECT OF CELLULOSE CONCENTRATION IN FEED TO ENZYME
PRODUCTION FERMENTER ON PLANT GATE MANUFACTURING
COST AND TOTAL FIXED CAPITAL

This is mainly because an acid (sulfuric acid) is used in a relatively dilute solution to treat the substrate at a relatively high temperature (212°F), requiring steam heating. The milling required is assumed at about 25 hp-hr/ton of substrate and has a lesser effect on the plant gate manufacturing cost than does the acid treatment. Reducing the amount of acid (while maintaining a 1% acid solution in the feed) and reducing the amount of milling required would affect the total fixed capital and plant gate manufacturing cost as follows:

	<u>Base Case</u>	<u>(A)</u>	<u>(B)</u>
Lb acid/gal ethanol	2.8	2.8	1.4
Milling energy required (hp-hr/ton)	25	12.5	12.5
Total fixed capital (\$ million)	96.8	95.3	90.7
Plant gate manufacturing cost (\$/gal ethanol)	3.34	3.31	3.19
% reduction			
Total fixed capital	0	1.5	6.3
Plant gate manufacturing cost	0	0.9	4.5

The enzymatic hydrolysis section has the second highest capital investment requirement, next to enzyme production, and accounts for about 10% of the plant gate manufacturing cost, excluding the cost of the straw. Increasing the substrate concentration in the feed to the hydrolyzers reduces the required volume of the tanks and the evaporation requirement to concentrate the hydrolyzate for the ethanol production, if a corresponding increase in the sugar concentration in the hydrolyzate is obtained at the same time. The effect of the substrate concentration in the feed on plant gate manufacturing cost and total fixed capital is presented in Figure 7. If the substrate concentration is raised from 5% to about 7.5%, for example, and the sugar concentration in the resulting hydrolyzate is also raised from 4% to 6% without adversely affecting the sugar yield and conversion rate, the fixed capital will be reduced from \$96.8 million to about \$88.4 million, about a 9% reduction, and the plant gate manufacturing cost will be reduced from \$3.34/gal to about \$3.24/gal, about a 3% reduction.

Figure 7

EFFECT OF SUBSTRATE CONCENTRATION IN THE SLURRY FEED
TO THE HYDROLYZERS ON THE PLANT GATE MANUFACTURING
COST AND TOTAL FIXED CAPITAL

On the basis of 15%/yr of fixed capital for general and administrative, sales, and research costs, a 15 year expected life of the plant, and a 48% tax rate, the selling prices for the ethanol would have to be \$4.90 and \$4.50/gal of 95 vol% ethanol, for a discounted cash flow return on investment, after taxes, of 15% and 10%.

About 330 million lb/yr of sugar is produced for the ethanol production. The fixed capital and plant gate manufacturing cost for the production of the sugar solution is summarized as follows:

	<u>Sugar Concentration in Solution</u>			
	<u>4%</u>		<u>10.7%</u>	
Total fixed capital (\$ million)	73.1		79.6	
	<u>¢/lb</u>	<u>%</u>	<u>¢/lb</u>	<u>%</u>
Plant gate manufacturing cost *				
Total materials	15.3	69	15.3	66
Total labor	1.1	5	1.2	5
Total utilities	2.2	10	2.7	12
Plant overhead	0.9	4	1.0	4
Taxes and insurance	0.4	2	0.5	2
Depreciation	<u>2.2</u>	<u>10</u>	<u>2.4</u>	<u>11</u>
Total	22.1	100	23.1	100

The effect of the prices of straw, cellulose, and peptone on the plant gate manufacturing cost is illustrated in Figure 8.

* Same basis as for ethanol production.

Figure 8

EFFECT OF AGRICULTURAL WASTE, CELLULOSE AND PEPTONE PRICES ON THE PLANT GATE MANUFACTURING COST IN THE PRODUCTION OF THE SUGAR SOLUTION

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