370
3-5-82
(88)

(2)

ch. 319

DOE/ET/23135-T1
(DE82005495)

**AN EVALUATION OF THE NATICK ENZYMATIC HYDROLYSIS PROCESS
FOR USE IN THE PRODUCTION OF ETHANOL FROM MUNICIPAL SOLID
WASTE OR FROM WOOD**

Final Report

**By
J. L. Jones
W. S. Fong
A. K. Chatterjee**

**October 1979
(Revised and Published 1981)**

MASTER

Work Performed Under Contract No. AC03-79ET23135

**SRI International
Menlo Park, California**

U.S. Department of Energy

Solar Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A05
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts*, (ERA); *Government Reports Announcements and Index* (GRA and I); *Scientific and Technical Abstract Reports* (STAR); and publication, NTIS-PR-360 available from (NTIS) at the above address.

**AN EVALUATION OF THE NATICK
ENZYMATIC HYDROLYSIS PROCESS
FOR USE IN THE PRODUCTION
OF ETHANOL FROM MUNICIPAL
SOLID WASTE OR FROM WOOD**

Final Report

October 1979
(revised and published 1981)

By: J. L. Jones
W. S. Fong
A. K. Chatterjee

Prepared for:

FUELS AND BIOMASS SYSTEMS BRANCH
U.S. DEPARTMENT OF ENERGY
600 E. St. N.W.
Washington, D.C. 20545

Contract No. DE-AC03-79ET23135

SRI Project PYU 8760

Approved by:

R. C. Phillips, Director
Chemical Engineering Laboratory

G. R. Abrahamson, Vice President
Physical Sciences Division

SRI International
Menlo Park, California

CONTENTS

LIST OF ILLUSTRATIONS	iii
LIST OF TABLES	v
INTRODUCTION	1
Background	1
Scope of the Analysis	2
THE "NATICK" ENZYMATIC HYDROLYSIS PROCESS	5
Bases and Assumptions	6
Process Design	6
Ethanol Fermentation and Recovery	8
Feedstock Requirements	9
General Economic and Design Bases	11
PRODUCTION OF ETHANOL FROM MUNICIPAL SOLID WASTE	13
Process Description	13
Feedstock Characteristics	13
Process Flowsheet and Design	15
Mass Flows and Operating Requirements	23
Thermal Efficiency	26
Process Economics	27
Investment Cost Estimates	27
Operating Costs and Revenue Requirements	27
Production of Cellulosic Substrate from MSW	27
Production of Ethanol from Substrate	35
Cost Sensitivity Analysis	39
Availability of the Technology	40
PRODUCTION OF ETHANOL FROM WOOD	45
Process Description	45
Feedstock Characteristics	45
Process Flowsheet and Design	45
Mass Flows and Operating Requirements	48
Thermal Efficiency	48
Process Economics	50
Investment Cost Estimates	50
Operating Costs and Revenue Requirements	50
Cost Sensitivity Analysis	54
Availability of the Technology	57

SUMMARY AND DISCUSSION OF RESULTS	59
CONCLUSIONS	63
Status of the Technology	63
MSW Feedstock Cases	63
Wood Feedstock Cases	63
APPENDICES	
A. Process Description and Design for Ethanol Fermentation and Recovery Facilities	A-1
B. General Economic and Design Basics	B-1

FIGURES

1. Flow Diagram for MSW Processing Plant Showing Detailed Operations for One Process Train	17
2. Approximate Mass Flows for Major Feedstocks, Product and By-Products from Enzymatic Hydrolysis and Fermentation Facilities (MSW-derived feedstock case)	21
3. Approximate Overall Mass Flow Balance for Major Process Streams (MSW feedstock case)	24
4. Plant Gate Price for Cellulosic Substrate for Hydrolysis versus Tipping Fee for Municipal Solid Waste	33
5. Plant Gate Ethanol Price versus the Cost of the MSW-Derived Cellulosic Substrate for Hydrolysis	38
6. Block Flow Diagram with Approximate Mass Flows for Major Feedstocks, Product, and By-Products from Enzymatic Hydrolysis and Fermentation Facilities (wood feedstock) . . .	46
7. Plant Gate Ethanol Price versus the Cost of Wood Chips	55

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

TABLES

1. Summary of Design Bases and Assumptions for Enzymatic Hydrolysis Using the Natick Process	6
2. Refuse Composition for New York City	14
3. Summary of Calculations to Establish MSW Plant and Individual Processing Train Capacities	16
4. Description of Steam and Electric Power Generation Facilities for MSW Processing Case	19
5. Summary of Operating Requirements (MSW feedstock case) . . .	25
6. Estimated Total Capital Investment for Production of Cellulosic Substrate for Enzymatic Hydrolysis from MSW . . .	28
7. Plant Facilities Investments for Ethanol Production Facilities Using the Natick Enzymatic Hydrolysis Process with an MSW Derived Cellulosic Substrate	29
8. Total Capital Investments for Ethanol Production Facilities Using the Natick Enzymatic Hydrolysis Process with an MSW Derived Cellulosic Substrate	30
9. Production of Cellulosic Substrate for Hydrolysis from MSW, Estimated Annual Operating Costs and Revenue Requirements for a Regulated Private Venture	31
10. Production of Cellulosic Substrate for Hydrolysis from MSW, Estimated Annual Operating Costs and Revenue Requirements for a Municipally Owned and Operated Facility	34
11. Production of Ethanol from an MSW-Derived Cellulosic Substrate Using the Natick Enzymatic Hydrolysis Process, Estimated Annual Operating Costs and Revenue Requirements	36
12. Sensitivity of Plant Gate Ethanol Prices to Variations in Various Parameters for the MSW Derived Substrate Cases . .	41
13. Typical Composition of Hardwood (dry basis)	47
14. Summary of Operating Requirements (wood feedstock case) . . .	49
15. Estimated Plant Facilities Investments for Ethanol Production from Wood Using the Natick Enzymatic Hydrolysis Process . . .	51

16.	Estimated Total Capital Investments for Ethanol Production from Wood Using the Natick Enzymatic Hydrolysis Process	52
17.	Production of Ethanol from Wood Using the Natick Enzymatic Hydrolysis Process, Estimated Annual Operating Costs and Revenue Requirements	53
18.	Sensitivity of Plant Gate Ethanol Price to Variations in Various Parameters for the Wood Feedstock Cases	56
19.	Summary of Economic Data for Selected Ethanol Production Options	60

INTRODUCTION

Background

Ethanol production from renewable resources for use as a fuel is currently a subject of extensive research and some commercial activity in the United States. The commercial production of ethanol by fermentation is based on the conversion of six-carbon sugars (C_6 sugars) by yeast under anaerobic conditions. The C_6 sugars may be produced by hydrolysis of sucrose* (cane sugar juice, other sugar crop juices, or molasses) or by hydrolysis of starch (from corn or other starch crops). The hydrolysis of cellulose in lignocellulosic materials represents another option, but one that is not currently being used commercially in the United States. The potential use of lignocellulosic substrates is considered attractive because of the lower value of such materials as compared with sugar crops or starch crops. Some of the lignocellulosic materials that are potentially available in large tonnages include agricultural crop residues (wheat straw and corn stover), wood, and the organic portion of municipal solid waste (MSW).

The production of ethanol from glucose or other C_6 sugars derived from lignocellulosics may be accomplished by a number of techniques, but at a cost that to date has been unattractive in free market systems. The hydrolysis processes that have been developed for actual or potential use on a commercial scale may be classified, based on the type of hydrolyzing agent:

- Dilute mineral acid processes (sulfuric acid)
- Concentrated mineral acid processes
 - Sulfuric acid
 - Hydrochloric acid
- Enzymatic hydrolysis processes.

* Sucrose, a 12-carbon sugar, is readily hydrolyzed by the enzyme sucrase and then fermented to ethanol by yeast.

The hydrolysis of cellulose in mineral acid solutions has been a subject of research for over 150 years. In contrast, enzymatic hydrolysis processes have been the topic of extensive research only during the last several decades.

Strong acid processes have problems concerned with acid recovery and materials of construction costs. In dilute acid processes, the high temperature required to achieve acceptable rates of conversion of cellulose to sugar increases the rate of decomposition of the sugars and increases the rate of corrosion of the equipment. Both the hydrolysis reactions and the sugar decomposition reactions exhibit first order rates. A major potential advantage to use of enzymatic hydrolysis is that the decomposition of the product sugars is not a problem. In enzymatic hydrolysis processes, however, the costs to date for producing enzymes have been high and the conversion of cellulose often quite low, unless the material undergoes extensive pretreatment.

Much of the pioneering work in the development of an enzyme system to hydrolyze cellulosic materials to fermentable C₆ sugars has been done by the U.S. Army Natick Research and Development Command at Natick, Massachusetts. At present, one of the most frequently used enzyme systems employed for the hydrolysis of cellulosic materials reported in literature is produced from Trichoderma reesei, an enzyme system developed at Natick and named after one of Natick's researchers, Dr. E. T. Reesei. Among the many published papers by Natick staff, several papers recently reported:

- Significant advances concerned with enzyme productivity.
- The use of roll milling as a pretreatment for the substrate to increase the initial substrate concentration in the hydrolyzing medium and the substrate reactivity toward the enzyme.
- A reduction in the hydrolysis time.

Scope of the Analysis

The Department of Energy (DOE) contracted in July 1979 for SRI International to prepare a technoeconomic evaluation of the Natick Enzymatic Hydrolysis Process. SRI was instructed to use a consistent set

of economic and design bases previously developed by SRI for use on other DOE-funded projects. The technoeconomic analysis includes:

- Consideration of facilities capable of producing 542.5 tons/day of C₆ sugars from a wood feedstock and from processed municipal solid waste for use in production of 25 million gallons/year of fuel grade ethanol.
- Consideration of production of ethanol by both batch and continuous fermentation.
- Preparation of a process description and analysis section with:
 - Feedstock characteristics.
 - Process design considerations and block flowsheet.
 - Mass flows, and utility and operating requirements.
 - A calculation of process efficiency.
 - Plant investment cost estimates.
 - Estimates of revenue requirements for both an industrial venture and a regulated utility venture.
 - A cost sensitivity analysis to demonstrate the effects of feedstock cost (or tipping fee) operating hours, and plant facilities investment cost on product price.
 - A discussion of the current status of the technology and the availability of the process for commercialization.

This report presents economic evaluations of a conceptual, large-scale, commercial ethanol production facility using the enzymatic hydrolysis technology developed by Natick staff members. The conceptual process design for the enzymatic hydrolysis section is based on yield and operating data provided to SRI by the U.S. Army Natick Research and Development Command and on certain design assumptions made by SRI. The designs and cost estimates for the mechanical processing sections and the ethanol fermentation and recovery sections have been prepared by SRI staff members.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

THE "NATICK" ENZYMATIC HYDROLYSIS PROCESS

General Process Description

The features of the Natick process, based on information available in mid-1979 are:

- (1) A pretreatment of the substrate by two-roll milling.
- (2) A relatively high enzyme productivity of about 100-125 IU/liter/hr in the enzyme production area.*
- (3) A relatively high initial substrate concentration (20 wt%) in the hydrolysis medium.
- (4) A relatively short batch hydrolysis cycle time of about 24 hours.

The overall process, however, retains the conventional operating sections of substrate pretreatment, enzyme production, and hydrolysis.

The enzyme is produced under aerobic conditions using a strain of Trichoderma reesei in the presence of a carbon source (such as a mixture of lactose and unhydrolyzed solids from the hydrolysis reactors) and some nutrients (such as ammonium sulfate, potassium monobasic phosphate, magnesium sulfate, calcium chloride, and trace metals). The batch fermentation is conducted in two stages: (1) at a temperature of about 32°C, a pH of about 4, and an aeration rate of about 0.4 volume/volume/min; (2) at a temperature of about 28°C, a pH of about 3.5, and an aeration rate of about 0.2 v/v/min. In about 112 hours, the fermentation is completed and an enzyme solution is recovered from the fermented broth by centrifugation and sent to the hydrolysis. A wet cake (~ 50 wt% H₂O) is obtained from the recovery, and about 40% of it is recycled to the next fermentation batch as inoculum; the rest is exported to the boiler plant for use as fuel.

Before enzymatic hydrolysis, the substrate is first pretreated by roll milling. The roll milling increases the bulk density of the substrate, making it possible to prepare a hydrolysis feed slurry with an initial substrate concentration of about 20 wt%. The overall average

* One international unit (IU) is the amount of enzyme that produces under standard (usually optimal) conditions, 1 μ mole of product per minute.

total substrate concentration in the hydrolysis mixture is further increased by adding more substrate to the medium during the hydrolysis. The roll milling also improves the ease of hydrolysis of the substrate by the enzyme.

The hydrolysis (in a batch fed reactor) is carried out at a temperature of about 50°C and a pH of about 4.8 in the presence of the enzyme solution. The hydrolysis reactor cycle time is about 24 hours. The amount of enzyme required is at an equivalence of about 10 IU/gram of substrate. At the end of the hydrolysis, the resulting sugar solution is separated from the unhydrolyzed solids and sent to the ethanol fermentation section. A portion of the unhydrolyzed solids, in the form of a wet cake (50 wt% H₂O), is sent to the enzyme production section to be used as a portion of the carbon source for enzyme production while the remainder is exported to the steam boiler as fuel.

Bases and Assumptions

Process Design

The bases and assumptions used for the process design are summarized in Table 1.

Table 1

SUMMARY OF DESIGN BASES AND ASSUMPTIONS FOR ENZYMATIC HYDROLYSIS USING THE NATICK PROCESS*

Substrate pretreatment:

- Roll milling with energy input as follows:

<u>Feedstock Sources</u>	<u>Energy Input</u>
Municipal solid waste	0.5 kWh/dry kg (0.23 kWh/dry lb)
Wood	0.7 kWh/dry kg (0.32 kWh/dry lb)

Enzyme production:

- Substrate: Mixture of 50% lactose and 50% solids in the wet cake by-product from the hydrolysis section.
- Fermentation: A two-stage, batch, aerobic process with the following operating conditions:

* Much of the information is based on personal communication with staff members of the Army Natick Research and Development Command.

	<u>1st Stage</u>	<u>2nd Stage</u>
- Temperature, °C	32	28
- pH	4	3.5
- Aeration rate, vol/vol/min	0.4	0.2
- Fermentation time, hr	70	42
- Cycle time, hr	20	120

- Enzyme productivity: about 125 IU/liter/hr, based on medium volume in the fermenter, including allowance for enzyme loss during processing.
- Pasteurization temperature for water fed directly to the fermenter: 90°C.
- Wet cake by-product from enzyme production: 40% is recycled to the next fermentation batch as inoculum while the remainder is exported as fuel to the steam boiler.
- Fresh start-up of fermentation batch from laboratory culture about every 6-8 batches.
- Fermenter size: 757,000 liters (200,000 gallons).

Hydrolysis:

- Initial substrate concentration in medium: 20 wt%.
- Enzyme to substrate weight ratio: 10 IU/gram.
- Hydrolysis conditions:
 - Temperature, 50°C
 - pH, 4.8
 - Nonaseptic
 - Hydrolysis time, 22 hr
 - Cycle time, ~ 24 hr
- Hydrolyzable content in substrate: 75%
- C₆ sugars yield (MSW-derived feedstock and wood feedstock): 45% of theoretical conversion of hydrolyzable material (cellulose and hemicellulose).
- C₅ sugars yield (MSW feedstock):* 4.4% of hydrolyzable material.
- C₅ sugars yield (wood feedstock):* 12.2% of hydrolyzable material.
- C₅ sugar concentration does not change during ethanol fermentation (yeast does not metabolize C₅ sugars under anaerobic conditions).
- Hydrolyzer size: 1,892,500 (500,000 gal).

* Calculated based on xylose concentrations reported by Natick staff.

Ethanol Fermentation and Recovery Facilities

The ethanol fermentation plants will be assumed to operate ~ 330 days/year and to produce 25 million gal/year of 199° proof (99.5 vol%) ethanol. The properties of the 199° proof ethanol are as follows:

- Specific gravity @ 60°F: 0.7962
- Pounds per gallon: 6.642
- Concentration:
 - Vol% EtOH: 99.5
 - Wt% EtOH: 99.19
 - Mol% EtOH: 97.95
- Heat of Combustion:
 - Anhydrous EtOH: 12,800 Btu/lb: 84,747 Btu/gal
 - 199° proof EtOH: 84,060 Btu/gal

The plant output of denatured alcohol will be slightly higher than 25 million gal/yr. One gallon of gasoline will be used to denature each 100 gal of 199° proof ethanol. Therefore, the heating value of the denatured alcohol will be approximately 84,470 Btu/gal. The total product output will be approximately 76,500 gal/operating day or 6.46×10^9 Btu/day.

The microorganisms used industrially for ethanol fermentation are almost exclusively yeast, specifically various acclimated strains of Saccharomyces cerevisiae. These yeast strains have a relatively high fermentation efficiency (high conversion of C₆ sugar to ethanol) and can tolerate relatively high ethanol concentrations (generally 6 to 8 vol% ethanol or higher). Other known yeasts and certain bacteria also produce ethanol from C₆ sugars, but not as efficiently or from as high a concentration of sugar.

Large-volume ethanol fermentation plants now use batch fermentation technology. For the ethanol production options considered here, each base case plant will have a conventional batch fermentation operation. We will, however, illustrate the effect on plant gate ethanol price of

using a continuous fermentation process. The continuous fermentation system design is adapted from a previous SRI study for DOE.*

Appendix A contains a discussion of the fermentation plant designs and the ethanol recovery section.

Feedstock Requirements

The amount of C_6 sugar required to produce 25 million gal/yr of 199° proof ethanol may be calculated based on the assumed stoichiometry. The work "assumed" is used because a number of complex reactions actually occur and the formation of by-products and yeast cells can vary, depending on the specific components other than C_6 sugars contained in the feed solution and on the fermenter operating conditions. The basic equation that describes the overall reaction is as follows:

This equation is used as the basis for fermentation efficiency calculations with 2 moles of ethanol per mole of C_6 sugar assumed as being 100% efficient. Because of cell formation plus by-products production, 100% efficiency cannot be attained. In the previous SRI studies, we have assumed a 90% efficiency or 1.8 moles of ethanol produced per mole of C_6 sugar as illustrated below:

The CH_2O in the above equation is intended to represent the formation of yeast cells and by-products such as fusel oils,[†] which are predominantly amyl(pentyl) alcohols and smaller amounts of n-propyl and

* Jones, J. L., et al., "Alcohol Fuels Production Technologies and Economics," Draft report prepared by SRI International for the U.S. Department of Energy (November 1978).

[†] Fusel is a German word meaning inferior liquor.

isobutyl alcohols. The formation of the alcohol by-products (recovered as the fusel oil stream) is typically equivalent to about 4 or 5 gal per 1000 gal of 199° proof ethanol (or < 0.5 wt% of the ethanol produced). The estimated production of yeast cells using the above formula, is equivalent to ~ 0.2 lb cells per pound of ethanol, or 1.3 lbs (dry cell basis) per gallon of 199° proof ethanol. If the fermentation efficiency were increased to 95%, the yeast cell production could theoretically be lower, as shown below:

The cell production in this example would be approximately 0.1 lb cells per pound of ethanol. (Ash content of yeast cells has been ignored.)

However, because not all of the sugar is fermented and the product distribution may differ, in actual practice the relative yields of ethanol, CO₂, cells, and by-products are not always as described in either of the above equations.

For this analysis, the above relationship for a 90% fermentation efficiency (Equation 2) is assumed to be adequate, with one exception: We assume that yeast production will be 0.1 lb/lb of ethanol. Thus, production of 25 million gal/yr of 199° proof ethanol will require the following quantity of C₆ sugar per day:

$$\begin{array}{c}
 \left(\frac{25 \times 10^6 \text{ gal/yr } 199^\circ \text{ proof EtOH}}{330 \text{ days/yr}} \right) \left(\frac{6.642 \text{ lbs}}{\text{gal}} \right) (0.9919^*) = \frac{542.5 \text{ ton/day}}{\text{C}_6 \text{ sugar}} \\
 \hline
 \left(\frac{0.46 \text{ lb EtOH}}{\text{lb C}_6 \text{ sugar}} \right) \left(\frac{2000 \text{ lbs}}{\text{ton}} \right)
 \end{array}$$

* Lbs EtOH/lb 199° proof EtOH.

The quantity of yeast by-product will be:

$$\frac{499,100 \text{ lb/day EtOH}}{2000 \text{ lb/ton}} \times 0.1 \cong 25 \text{ tons/day}$$

The quantity of fusel oil has been estimated as follows:

$$\frac{75,758 \text{ gal } 199^\circ \text{ proof EtOH}}{\text{day}} \times \frac{4.5 \text{ gal fusel oil}}{100 \text{ gal EtOH}} = 341 \text{ gal/day}$$

The quantity of CO₂ generated is ≥ 239 tons/day.

The effect of by-product sales on the ethanol price will be discussed for each feedstock/process combination to be considered.

General Economic and Design Bases

All costs presented in this report are presented in mid-1979 U.S. dollars. The general economic and design bases used in the analysis are summarized in Appendix B. These are essentially the same economic and design bases that were used by SRI for another DOE-supported project, "Preparation of a Cost Data Bank for DOE/Biomass Energy Systems Branch" (Contract No. EY-76-C-03-0115/PA 141). Because the same bases are used, it will be possible to compare the estimated economics of the Natick Process with the estimated economics of other processes being evaluated by SRI for the DOE. Such a comparison is contained in "Discussion of Results" section of this report.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

PRODUCTION OF ETHANOL FROM MUNICIPAL SOLID WASTE

Process Description

Feedstock Characteristics

The reporting of "average" municipal solid waste (MSW) composition information is of questionable value because of the wide variations by day, by season, by city, and by region. Most reported "average" composition data must be considered only a rough approximation of the composition.

For this analysis, we selected a reported "average" MSW composition for New York City (see Table 2). The MSW from a densely populated metropolitan area such as New York City will differ considerably from the reported "average" composition for the United States. For example, it will contain more paper and food wastes and less yard wastes than MSW generated by smaller, less densely populated cities. Large cities like New York, Boston, or Philadelphia, however, generate the required tonnages of wastes within a reasonable radius for a proposed conversion facility.

Based on calculations that appear later in the report, it is estimated that 1.59×10^6 tons/yr (436 tons/day for 365 days/yr, ~ 5400 tons/day for 294 operating days) of MSW must be available to produce 25 million gal/yr of ethanol. Assuming an average MSW generation rate of 3.5 lbs/capita/day, generation of 5400 tons/operating day of MSW would require servicing a population of about 3.0 million people. Collection, transportation, and processing of 5400 tons/operating day of material at one site, however, is probably unreasonable, even for very large cities. Traffic congestion, hauling costs, and land availability will probably limit the capacity of any one facility to no more than 3000 t/day. (The largest MSW processing or conversion plant currently being operated in the United States is located at Hempstead, N.Y. The plant is in the startup phase and will ultimately process 2000 t/day of MSW.)

Table 2
REFUSE COMPOSITION FOR NEW YORK CITY

<u>Category</u>	<u>Percent by Weight (dry basis)</u>
Combustibles	
Food waste	18.1
Textiles	0.7
Paper products	52.5
Plastics	3.2
Leather and rubber	0.6
Yard waste	4.9
Wood	<u>0.8</u>
Total	80.8
Noncombustibles	
Glass and ceramics	8.1
Metals	7.5*
Ash, rock, dirt	2.6
Miscellaneous	<u>1.0</u>
Total	19.2
Moisture content: 30%	
Heating value: 11.55 GJ/Kg or 5000 Btu/lb	

* Estimated breakdown: Ferrous - 6.58% wt
Aluminum - 0.57% wt
Other nonferrous - 0.35% wt

Source: Leonard F. O'Reilly, "Planning for Resource Recovery in the Big Apple," Proceedings of 1978 National Waste Processing Conference, ASME, New York, NY, p. 512 (1978).

Process Flowsheet and Design

Two mechanical processing facilities have been designed to process an average of ~ 2700 tons/day of MSW. (Table 3 shows how the design capacity was calculated.) The enzymatic hydrolysis and fermentation facility have been assumed to be located on the same site as one (Plant A) of the MSW processing facilities. The product from the other MSW processing facility would have to be hauled (~ 10 miles one way) by trucks to the hydrolysis and fermentation facility.

The MSW-derived organic feedstock for enzymatic hydrolysis must be pretreated before hydrolysis. Milling tests have been conducted at the Natick Laboratory, using a dry product from the Black Clawson hydropulping operation at Franklin, Ohio. The efficiency of milling in terms of hydrolysis yields reportedly decreases as the moisture content of the organic feedstock increases. Based on conversations with Natick Laboratory staff, we decided to design the facility so as to produce a feedstock for milling with a moisture content of < 25 wt%. If a hydropulping process were used, the hydropulped product would contain about 50 wt% moisture. Installation of dryers prior to the mills would be required to reduce the moisture content.

In addition, the hydropulping process does not normally separate plastics from the fiber product. It appears to be preferable to use a dry separation process that will not increase the moisture content of the as-received MSW and that also will remove plastics. A proprietary separation device developed by Imax International, Inc. (Duxbury, Massachusetts) has been reported by the developers to produce a low plastics content (< 2 wt%) organic fraction from MSW. Natick Laboratory staff suggested that we consider this device for use in our conceptual process design. To the best of our knowledge, Imax International is the only company that now offers such a separation device.

The block flow diagram for the mechanical processing of the MSW is shown in Figure 1. We have specified conventional equipment up to the point of the Imax International separation equipment. Imax International provided SRI with a performance specification for their equipment

Table 3

SUMMARY OF CALCULATIONS TO ESTABLISH MSW PLANT
AND INDIVIDUAL PROCESSING TRAIN CAPACITIES

- Basis:
- Input of 1350 dry metric tons/operating day for hydrolysis facility (1450 dry tons/day) of MSW-derived cellulosic substrate to the hydrolysis facility
 - 330 days of operation/year for hydrolysis facility
 - Moisture content of MSW-derived substrate ≤ 25 wt%.

Calculations

$$\left(\frac{1350 \text{ dry metric tons}}{\text{day}} \right) / \left(\frac{0.75 \text{ unit dry material}}{1.0 \text{ unit moist material}} \right) = \begin{matrix} 1800 \text{ metric tons/day} \\ \text{moist cellulosic} \\ \text{substrate} \end{matrix}$$

$$1800 \text{ metric tons/day} \left(\frac{330 \text{ days}}{\text{year}} \right) = \begin{matrix} 594,000 \text{ metric tons/year} \\ \text{moist cellulosic substrate} \end{matrix}$$

$$\left(\frac{594,000 \text{ metric tons/year}}{\text{moist cellulosic substrate}} \right) / \left(\frac{0.40 \text{ unit moist substrate}}{\text{unit as received MSW}} \right)^* \approx 1.49 \times 10^6 \begin{matrix} \text{metric} \\ \text{tons/year MSW} \end{matrix}$$

$$\frac{(1.49 \times 10^6 \text{ metric tons/year MSW})}{(6 \text{ days/week}) (49 \text{ weeks/year})} \approx \frac{5068 \text{ metric tons MSW}^\dagger}{\text{day}}$$

$$\frac{5068 \text{ metric tons/day MSW}}{2 \text{ plants}} \approx \frac{2534 \text{ metric tons/day MSW}}{\text{plant}} \text{ or } (2700 \text{ tons/day})$$

$$\begin{aligned} \frac{2534 \text{ metric tons/day plant MSW}}{3 \text{ processing trains per plant}} &= \frac{845 \text{ metric tons/day}}{\text{processing train}} \\ &= \frac{992 \text{ metric tons/day (design)}}{\text{processing train}} \text{ or } (1000 \text{ t/day}) \end{aligned}$$

* Based on information supplied to SRI International by Imax International, Duxbury, Mass.

† MSW processing plant is assumed to operate 294 days/year at 90% of design capacity. This is equivalent to a stream factor of 0.81 and a capacity utilization factor of 0.72. The plant will operate two shifts each operating day.

* MSW processing plants designed to operate 294 days/year, ethanol production facility operates 330 days/year

* Proprietary separation equipment, IMAX International, Duxbury, Massachusetts

- ① MSW AS - discarded basis, 38% moisture
- ② Primary shredded MSW, -15.2 cm (-6 inch) size particles
- ③ Ferrous free primary shredded MSW
- ④ Trommel oversize, +10 cm (+4 inch) size organic rich MSW fraction
- ⑤ Fine shredded organic rich MSW, -3.8 cm (-1.5 inch) size particles
- ⑥ Cellulosic substrate (<2 wt% plastics), +0.63 cm to -1.9 cm (+1/4 inch to -3/8 inch) size fraction
- ⑦ Cellulosic substrate feed to hydrolysis plant, 1755 metric tons (1933 tons)/day for 330 operating days/year

SA-8760-1

FIGURE 1 FLOW DIAGRAM FOR MSW PROCESSING PLANT SHOWING DETAILED OPERATIONS FOR ONE PROCESSING TRAIN

and an estimate of the FOB equipment cost. We have no performance data for the Imax International equipment and specification of their equipment in this conceptual design should not be construed as an endorsement by either SRI, the DOE, or the Natick Laboratory.

Each of the MSW processing plants (Plants A & B) have been designed with three trains of mechanical processing equipment. The MSW processing operations are designed to recover ferrous metals, aluminum, a mixed glass fraction, a cellulosic substrate for hydrolysis (mainly paper fiber with little plastics, textiles, or ash content) and a second organic fraction containing most of the plastics and textiles plus other organics (some paper, food wastes, etc.). The latter organic fraction is to be utilized as a fuel for steam and electric power generation. Plants A & B are designed to generate all of their own electrical power requirements and sell the excess to the local electric utility company. A portion of the steam and electricity from Plant A is to be sold to the adjacent ethanol production facility. The boiler plant within Plant A has been designed to burn the wet waste cake (50% H₂O) from the enzymatic hydrolysis operation as a fuel for steam and power generation. The value of the wet cake has been estimated to be \$9.75/wet ton on the basis of its fuel value (dry basis) and moisture content assuming a value of \$1.25 per million Btu of net fuel value. The steam and electric power generation facilities are described in Table 4. The plant designs include all required feedwater treatment, feedwater preheating, air pollution control, and wastewater treatment facilities.

The steam pressure and temperature conditions for the boilers have been selected based on data for the mass burning, water-wall boilers now operating in Dusseldorf, Federal Republic of Germany. This installation has two such boilers, one constructed in 1965 and the second in 1972. Most boilers in the United States that burn processed MSW (or refuse-derived fuel) are coal-fired, electric utility boilers with only a portion of the fuel demand ($\leq 15\%$ of fuel input) met by firing the processed MSW. United States installations that burn MSW alone produce lower pressure and temperature steam for industrial process use or for district heating systems. Because corrosion of tubes is a problem in

Table 4

DESCRIPTION OF STEAM AND ELECTRIC POWER
GENERATION FACILITIES FOR MSW PROCESSING CASE

MSW Processing Plant A (located adjacent to the ethanol production facility)

Two spreader stoker power-steam boilers designed to produce 181,820 kg/hr (each) ($\sim 400,000$ lbs/hr) of steam at 8.618×10^6 Pa (1250 psig) and 510°C (950°F); all of the steam will be used in condensing steam power cycles with a combined output of 70 MW electric.

One process steam boiler designed to produce a maximum of 68,180 kg/hr ($\sim 150,000$ lbs/hr) of saturated steam at $1,723 \times 10^6$ Pa (250 psig), for sale to the ethanol production facility.

MSW Processing Plant B

One spreader stoker power-steam boiler designed to produce 209,090 kg/hr (460,000 lbs/hr) of steam at 8.618×10^6 Pa (1250 psia) and 510°C (950°F). All of the steam will be used in a condensing steam power cycle with an output of 41.4 MW electric.

MSW-fired, water-wall boilers, various design features must be included to minimize corrosion problems. Such design features include covering tubes in the hottest part of the combustion zone with plastic refractory, locating the superheater in the lower temperature region, and decreasing gas velocity through the tube banks in the convective sections.

Ethanol is produced from the processed MSW in two steps: Enzymatic hydrolysis of the cellulosic materials separated from processed MSW and fermentation of the resulting C_6 sugars to ethanol by yeast. The

hydrolysis and fermentation processes have been described in the previous section of this report. Figure 2, a schematic flow sheet including the approximate mass flows for the major feedstocks, product and by-products for the operations.

The substrate for hydrolysis is pretreated by roll milling using four units of a four-stack, 22- x 60-in. roll machine. About 120,560 dry lb/hr of the substrate is milled and conveyed to the feed hopper for the hydrolyzers.

The hydrolysis is carried out in batches. Four 500,000-gal hydrolyzers are used, each producing about 271,250 lbs of C_6 fermentable sugars in 24 hours. About 78% of the total substrate (about 565,000 dry lb) is dispersed into the aqueous medium in the hydrolyzer at start-up, giving an initial substrate concentration in the suspension of about 20 wt%. The remainder of the substrate is added to the hydrolyzer during the hydrolysis. The enzyme solution for the hydrolysis is produced in the enzyme production section of the plant and is charged into the hydrolyzer in an amount equivalent to about 10 IU/gram of substrate. During the hydrolysis, the temperature of the medium is kept at about 50°C by circulating cooling water through the internal coils. The reactor pH is kept at about 4.8 by the addition of an aqueous caustic soda solution. The hydrolysis is terminated at 22 hours and the hydrolyzate is transferred to a surge tank, freeing the hydrolyzer for the next hydrolysis batch.

A sugar solution is then recovered from the hydrolyzate by centrifugation and sent to ethanol fermentation. A 50% moisture wet cake (about 918,900 lb) is also collected by the centrifuge; about 2.8 wt% of this is sent to the enzyme production as a second carbon source and the remainder of the cake is exported to the Plant A steam boiler as fuel.

FIGURE 2 BLOCK FLOW DIAGRAM WITH APPROXIMATE MASS FLOWS FOR MAJOR FEEDSTOCKS, PRODUCT AND BY-PRODUCTS FROM ENZYMATIC HYDROLYSIS AND FERMENTATION FACILITIES (MSW Feedstock Case)

Enzyme for the hydrolysis is produced in fermentation batches under aerobic and aseptic conditions in two stages. In fresh start-up, laboratory culture is cultivated through a series of step-up fermenters ranging up to about 20,000 gal to produce the seed culture needed for the enzyme production, which is carried out in eight 200,000-gal fermenters. For each fermentation batch, an aqueous solution containing the nutrients* (about 10,000 lb) and lactose (about 31,625 lb) is made up in a smaller vessel and sterilized by steam injection. The solution is then cooled to the fermentation temperature through a series of two heat exchangers and charged into the fermenter with the wet cake (about 63,250 lb) from hydrolysis and the seed culture from the final step-up vessel. Water added directly to the fermenter is first pasteurized at a temperature of about 90°C and air for the aeration is sterilized by filtration before being fed into the fermenter. Refrigeration is needed for cooling, because of the relatively low fermentation temperatures: about 32°C (first stage) and 28°C (second state). In about 112 hours, about 8.19×10^9 IU of enzyme activity is produced and an enzyme solution is recovered from the fermented broth through centrifugation and sent to the hydrolysis operation. A 50% moisture wet cake is also produced from the enzyme solution recovery; about 40% of it is recycled to the next fermentation batch as inoculum and the remainder is sent to the steam boiler as fuel. The recycling of the wet cake as inoculum to the next fermentation batch reduces the frequency of fresh inoculum start-up (from laboratory culture) to about once every six to eight batches. Each fermentation produces about 110,375 lb of wet cake as by-product.

The anaerobic filters for wastewater treatment have been designed for a loading of 0.55 lb/ft³/day of chemical oxygen demand (COD). A conversion of 92% of the COD has been assumed. The 1.1 million gal/day of effluent liquid from the filters (with a COD of 1000 mg/l and a suspended solids concentration of 2200 mg/l) is discharged to the municipal sewer system.

* Nutrients (such as ammonium sulfate, potassium monobasic phosphate, magnesium sulfate, calcium chloride) and trace metals (such as iron, manganese, and zinc sulfates, and cobalt chloride). Tween® may also be included as an additive.

Mass Flows and Operating Requirements

The mass flows used for design purposes are shown in Figures 2 and 3. The flows have been presented on an annual basis in Figure 3 because of the differences in the operating schedules for the MSW processing plants versus the ethanol production plants. The mechanical processing lines will operate two shifts per day, six days/week, 294 days/year. The hydrolysis and fermentation facilities will operate 24 hours/day, 330 days/year.

The operating requirements for the mechanical processing plants and the hydrolysis and fermentation facilities are summarized in Table 5. It should be noted that the total electric power requirements shown in Table 5 are very high for the MSW processing and the grinding (two roll mills) of the cellulosic substrate prior to enzymatic hydrolysis. The selection of electric drives rather than steam drives for some of the mechanical equipment may not be optimal, but there are numerous reasons not to select steam drives, including:

- Investment costs for steam drives are much higher than for electric motors; gear reducers and condensate collection systems are required.
- Equipment with steam drives often is also equipped with electric motors to ensure reliability in plant operation.
- Steam drives require much more maintenance than do electric motor drives.

In addition, more refuse-derived fuel is available than would be required by steam drives and process uses; therefore, electric power generation facilities would be included in the plant design whether or not steam drives are used.

If it appears warranted, based on energy cost considerations, future evaluations may consider the use of steam drives. However, further evaluation of steam drives is beyond the scope of this effort.

SA-8760-3A

FIGURE 3 APPROXIMATE OVERALL MASS FLOW BALANCE FOR MAJOR PROCESS STREAMS (MSW Feedstock Case)

Table 5

SUMMARY OF OPERATING REQUIREMENTS
(MSW Feedstock Case)

Facility	Labor (men/shift)	Average Electric Power* (kW)	Operating Requirements				Other
			Average Steam*		Average Purchased Water		
			(kg/hr)	(lb/hr)	(l/hr)	(gal/min)	
MSW Processing Plant A	21	10,000	}		12,615 [‡]	3,333 [‡]	
Steam and power plants	4						
MSW Processing Plant B	21	10,000					
Steam and power plant	4						
Ethanol Production Facility							
Enzymatic hydrolysis [†]	8	40,078	6,273	13,800	3,260	847	
Batch fermentation and recovery	7	3,490	}	80,000			
Continuous fermentation and recovery	4	1,700					
Lactose and nutrients							1.26 dry metric t/hr
Gasoline (denaturant)							119.5 l/hr (31.58 gal/hr)

* Provided by steam and power generation facilities at Plant A. Plant B also uses power generated onsite. Excess power is sold to electric utility.

[†] Mainly for mills.

[‡] Mainly for steam and power plant.

Note: Facilities have been designed to provide peak demand for utilities. For example, peak steam demand would be 56% greater than the average usage reported above.

Thermal Efficiency

The overall thermal efficiency of the system is calculated based on the higher heating value or energy content of all energy products (denatured ethanol, electric power, and methane), divided by the higher heating value of all inputs (MSW and gasoline for denaturing the ethanol). Fuel use for transport of the MSW to the conversion sites was not included in estimates for this study. The overall thermal efficiency, ~ 22.8%, was calculated as follows:

<u>Input</u>		<u>(10⁹ Btu/yr)</u>
$\left(2 \times 793,800 \frac{\text{tons MSW}}{\text{year}} \right) \left(10 \times 10^6 \frac{\text{Btu}}{\text{ton}} \right)$	=	15,876
$\left(250,000 \frac{\text{gallons gasoline}}{\text{year}} \right) \left(0.125 \times 10^6 \frac{\text{Btu}}{\text{gal}} \right)$	=	31
Total Input		15,907
<u>Output</u>		
$\left(25.245 \times 10^6 \frac{\text{gallons denatured EtOH}}{\text{year}} \right) \left(0.0845 \times 10^6 \frac{\text{Btu}}{\text{gal}} \right)$	=	2,133
$\left(388.1 \times 10^6 \frac{\text{kWh}}{\text{year}} \right) \left(3414 \frac{\text{Btu}}{\text{kWh}} \right)$	=	1,325
$\left(3630 \text{ tons CH}_4 \right) \left(47.8 \times 10^6 \frac{\text{Btu}}{\text{ton}} \right)$	=	174
Total Output		3,632
$\frac{3632 \times 10^9 \text{ Btu/hr}}{15907 \times 10^9 \text{ Btu/hr}} \times 100\% = 22.8\%$		

Process Economics

Investment Cost Estimates

The estimated plant facilities investment (PFI) costs and total capital costs for MSW processing Plants A and B (including steam and power generation) are summarized in Table 6. The total investment cost is approximately \$50,000/ton of average daily throughput capacity. This estimate may be optimistic, however; if transfer stations for the MSW and special site conditions are considered, the investment cost could be 25% to 50% higher.

Plant facilities investments for enzymatic hydrolysis and ethanol production are estimated to be about \$60.1 million for the batch process method and \$51.3 million for continuous ethanol fermentation (see Table 7). The largest investment is for enzyme production, which accounts for about 38% and 46% of the battery limits investment in the two cases.

The estimated total capital investments for the regulated and unregulated ventures are presented in Table 8.

Operating Costs and Revenue Requirements

Production of Cellulosic Substrate from MSW

Appendix B presents information concerning the general economic and design bases used for the analysis. The total estimated operating costs and revenue requirements for production of cellulosic substrate at the MSW processing plants are summarized in Table 9. These estimates assume that plants are operated as a private regulated venture, comparable to a regulated utility. Note that 30% of the revenue requirements is represented by the return on rate base and income tax. For a tipping fee of \$15/ton paid to the plant, the cost of the cellulosic substrate for hydrolysis would be ~ \$33.5/ton (at 25% moisture). If the

Table 6

ESTIMATED TOTAL CAPITAL INVESTMENT FOR PRODUCTION
OF CELLULOSIC SUBSTRATE FOR ENZYMATIC HYDROLYSIS FROM MSW

Basis: 5,454.5 metric t/d (6,000 t/d) design capacity
for MSW*, and power generation facilities for
private, regulated venture

	Millions of Dollars (Regulated Venture)
Plant Section Equipment	
Plant A (adjacent to EtOH production facility)	45.6
Process steam generation equipment for EtOH production facility	6.8
Boilers and power generation system	77.1
Plant B (Located approximately 10 miles or 16.1 kilo- meters from Plant A)	
Mechanical processing system	45.6
Boiler and power generation system	43.9
General service facilities for Plants A and B (mechanical processing sections)	<u>13.1</u>
Total plant facilities investment	232.7
Land cost (Plants A and B)	0.7
Interest during construction	17.7
Organization and startup expenses	11.6
Working capital requirements	<u>4.4</u>
Total capital investment	267.1
Depreciable investment	262.0
Debt capital	173.6
Equity capital	46.7

* Plant operates at 90% of design capacity, 294 days/year.

Table 7

ESTIMATED PLANT FACILITIES INVESTMENT FOR ETHANOL PRODUCTION
FACILITIES USING THE NATICK ENZYMATIC HYDROLYSIS PROCESS
WITH AN MSW-DERIVED CELLULOSIC SUBSTRATE

Bases: 94.63 million l/yr of 199° proof Ethanol
(25 million gal/yr)

	Million \$	
	<u>Batch Ethanol Fermentation</u>	<u>Continuous Ethanol Fermentation</u>
Battery Limits Investment		
Enzyme production	15.21	15.21
Substrate pretreatment	3.54	3.54
Hydrolysis	6.89	6.89
Ethanol fermentation	9.93	2.62
Ethanol recovery, including denaturing and yeast drying	<u>4.99</u>	<u>4.99</u>
Subtotal	40.56	33.25
Utilities* and Tankage Investment	7.53	7.53
General Service Facilities [†]	<u>12.02</u>	<u>10.56</u>
Plant facilities investment	<u>60.11</u>	<u>51.34</u>

* Not including steam generation facilities.

† Including waste treatment allowance.

Table 8

TOTAL CAPITAL INVESTMENTS FOR ETHANOL PRODUCTION FACILITIES
USING THE NATICK ENZYMATIC HYDROLYSIS PROCESS WITH AN MSW-
DERIVED CELLULOSIC SUBSTRATE

Basis: 94.63 million l/yr of 199° proof ethanol
(25 million gal/yr)

	Million \$			
	Regulated Venture		Nonregulated Venture	
	Batch*	Continuous*	Batch*	Continuous*
Plant facilities	60.11	51.34	60.11	51.34
Land	0.38	0.38	0.38	0.38
Interest during construction	4.85	3.91	0	0
Organization and startup expenses	3.01	2.57	3.01	2.57
Working capital requirement [†]	3.56	3.23	4.89	4.55
Initial chemicals	<u>0.02</u>	<u>0.02</u>	<u>0.02</u>	<u>0.02</u>
Total capital investment	71.66	61.45	68.41	58.79
Depreciable investment	67.70	57.82	60.11	51.33
Debt capital	46.58	39.94	0	0
Equity capital	25.08	21.50	68.41	58.79
Average equity capital	12.54	10.75		
Regulated utility rate base	71.64	61.42		

* Mode of operation of ethanol fermentation section.

[†] Processed MSW price for the regulated venture = \$30.38/metric ton (\$33.49/ton) and for the nonregulated venture = \$76.15/metric ton (\$83.96/ton).

Table 9

PRODUCTION OF CELLULOSIC SUBSTRATE FOR HYDROLYSIS
FROM MSW, ESTIMATED ANNUAL OPERATING COSTS AND REVENUE
REQUIREMENTS FOR A REGULATED PRIVATE VENTURE

Basis: 5,454,5 metric t/day (6,000 t/d) design capacity
MSW resource recovery facilities including
steam and power generation

	Millions of Dollars per Year	Dollars per Ton of Cellulosic Substrate
Materials and supplies		
Fuel and lubricating oils	0.10	0.16
Wet filter cake	6.38	10.02
Truck haul of substrate	0.40	0.63
Residue landfill	0.86	1.35
Maintenance materials	<u>4.65</u>	<u>7.31</u>
Total materials and supplies	12.39 (17%)	19.47
Labor		
Operating labor	2.46	3.86
Supervision	0.37	0.58
Maintenance labor	5.82	9.14
Administrative and support labor	1.73	2.72
Payroll burden	<u>3.62</u>	<u>5.68</u>
Total labor costs	14.00 (19%)	21.98
Purchased utilities		
Water	<u>0.95</u>	<u>1.49</u>
Total purchased utilities	0.95 (1%)	1.49
Fixed costs		
G&A expenses	4.65	7.30
Property taxes and insurance	5.82	9.14
Plant depreciation in 20 years	<u>13.10</u>	<u>20.58</u>
Total fixed costs	23.57 (32%)	37.02
Return on rate base*	15.10 (21%)	23.72
Income tax*	<u>7.43</u> (10%)	<u>-11.69</u>
Total revenue required*	73.44 (100%)	115.39
Source of required revenue		
Cellulose substrate	21.32 (29.03%)	33.49
Scrap ferrous metal	1.83 (2.49%)	2.87
Alum. and nonferrous metal	3.88 (5.28%)	6.10
Mixed colored glass cullet	0.52 (0.72%)	0.81
Electricity to ethanol plant	12.09 (16.46%)	19.00
Electricity to utility	7.76 (10.57%)	12.19
Process steam	2.23 (3.03%)	3.50
Tipping fee for MSW†	<u>23.81</u> (32.43%)	<u>37.41</u>
Total revenue*	73.44 (100%)	115.37
Revenue required (nonregulated venture)‡	(105.56)**	

*20-year-average value.

†\$16.5/metric ton or \$15/ton MSW.

‡DCF return: see Appendix B.

**(\$53.44) revenue for sale of cellulose substrate only.

MSW processing facilities are operated by a nonregulated private venture that expects a 15% discounted cash flow (DCF) return, then the plant revenue requirements would be ~ \$105.6 million/year (44% higher than for the regulated private venture) and the price of the cellulosic substrate would be over \$50/ton.

A more realistic financing option (not listed in Appendix B), would be to completely finance the MSW processing plants by sale of tax-free municipal bonds. Table 10 shows that the revenue requirements under such a plan would be approximately \$56 million/year if the bond interest rate is 7% and the plant is amortized over 20 years. For the same base case tipping fee of \$15/ton of MSW, the price of the cellulosic substrate would be \$5.76/ton.

Figure 4 shows the estimated cellulosic substrate price as a function of tipping fee for the three financing options considered (regulated and nonregulated private ventures, a municipal venture). For the base case tipping fee of \$15/ton of MSW and a regulated private venture, about one-third of the plant revenue would come from collection of the tipping fee. Sale of electric power to the ethanol production facility (at 3.5¢/kWh) and to the electric utility company (at 2¢/kWh) would account for ~ 27% of the plant revenue. The cellulosic substrate sales would account for about 29% of the plant revenue and steam sales for about 13% (see Table 8). Total revenue from sale of metals and glass would account for only 8 to 9% of total plant revenues. In the case of municipal bond financing, Table 10 indicates the relative importance of various revenue sources; the required revenue from sale of the cellulosic substrate is much lower in this case, representing only 6.5% of the total plant revenue.

SA-8760-4 R

FIGURE 4 PLANT GATE PRICE FOR CELLULOSIC SUBSTRATE FOR HYDROLYSIS
VERSUS TIPPING FEE FOR MUNICIPAL SOLID WASTE

Table 10

PRODUCTION OF CELLULOSIC SUBSTRATE FOR HYDROLYSIS FROM MSW,
ESTIMATED ANNUAL OPERATING COSTS AND REVENUE
REQUIREMENTS FOR A MUNICIPALLY OWNED AND OPERATED FACILITY

Basis: 5,454.5 metric t/d (6,000 t/d) design capacity
for MSW*, includes mechanical processing plant,
steam and power generation facilities

	Millions of Dollars per Year
Materials and supplies [†]	12.39
Labor [†]	14.00
Purchased utilities [†]	0.95
Fixed costs	
Insurance	2.90
Interest on Bonds [‡] (7%)	18.90
Amortization (20 years)	<u>6.59</u>
Total revenue required	55.73
Sources of Required Revenue	
Cellulose substrate	3.61
Scrap ferrous metal	1.83
Aluminum and nonferrous metals	3.88
Mixed colored glass cullet	0.52
Electricity to ethanol plant	12.09
Electricity to utility	7.76
Process steam to ethanol plant	2.23
Tipping fee	<u>23.81</u>
	55.73

* Plant operates at 90% of design capacity, 294 days/year.

[†] Same as figures shown on Table 9.

[‡] Assumes \$270 million municipal bond issue.

Production of Ethanol from Substrate

The analysis of economics for producing of 25 million gallons of 199° proof ethanol annually from the processed MSW is based on use of the Natick enzymatic hydrolysis process, as described in the preceding sections, the general assumptions stated in Appendix B, and the following additional assumptions:

- The wet cakes (by-products) produced in the enzyme production and hydrolysis are sold to the steam and electricity generating sections of the plant at about \$9.75/wet-ton, and steam and electricity are purchased from the same sections at about \$3.00/1,000-lb and 3.5¢/kWh, respectively.
- Gasoline used in the denaturing of the ethanol is priced at about 76¢/gal.
- No royalty fees are included.
- By-product "yeast" is credited at about \$300/t.
- The fuel gas generated in the waste treatment is credited as a by-product at \$1.00/1,000-scf.
- Wastewater effluent from the anaerobic filters is treated in the municipal treatment system for a fee of \$1/1000-gal.

The revenue required and operating costs for the base cases are presented in Table 11. For the base cases, it was assumed that the MSW and ethanol production facilities are both operated as private ventures. In one case the ventures are regulated, in the other case they are nonregulated. For these cases, the plant gate ethanol prices range from a low of \$1.88/gal (for a process using the continuous ethanol fermentation under regulated venture conditions) to a high of \$3.59/gal (for a process using the batch ethanol fermentation under nonregulated venture conditions). The total operating costs (variable and fixed) without the by-product credit of about 35¢/gal, range from about \$2.01/gal to about \$3.25/gal. The costs for the cellulosic substrate account for about 40% to 67% of the operating costs; electric power costs account for about 14% to 22% of operating costs.

The effects of changes in the cellulosic substrate cost on the ethanol selling price are shown in Figure 5.

Table 11

PRODUCTION OF ETHANOL FROM AN MSW-DERIVED CELLULOSIC
SUBSTRATE USING THE NATICK ENZYMATIC HYDROLYSIS PROCESS,
ESTIMATED ANNUAL OPERATING COSTS AND REVENUE REQUIREMENTS

	Cents/Gallon			
	Regulated*		Nonregulated*	
	Batch	Contin- uous	Batch	Contin- uous
Raw Materials				
Processed MSW	85.0	85.0	213.8	213.8
Lactose	13.4	13.4	13.4	13.4
Nutrients, chemicals	5.9	5.9	5.9	5.9
Gasoline	0.7	0.7	0.7	0.7
Maintenance materials	4.8	4.1	4.8	4.1
Total raw materials	109.8	109.1	238.6	237.9
Labor				
Operating labor	5.1	4.2	5.1	4.2
Supervision	0.8	0.6	0.8	0.6
Maintenance	6.0	5.1	6.0	5.1
Administration and support	2.4	2.1	2.4	2.1
Payroll burden	5.0	4.5	5.0	4.5
Total labor	19.3	16.5	19.3	16.5
Purchased Utilities				
Electric power	45.3	43.4	45.3	43.4
Water	1.0	1.0	1.0	1.0
Steam	8.9	8.9	8.9	8.9
Total purchased utilities	55.2	53.3	55.2	53.3
Waste Treatment	1.5	1.5	1.5	1.5
Fixed Costs				
General administration	4.8	4.1	4.8	4.1
Property taxes and insurance	6.0	5.1	6.0	5.1
Plant depreciation	13.5	11.6	0	0
Total fixed costs	24.3	20.8	10.8	9.20

Table 11 (Concluded)

	Cents/Gallon			
	Regulated*		Nonregulated*	
	Batch	Contin- uous	Batch	Contin- uous
Return on rate base and income tax	25.2	21.5	0	0
Capital charges for a 15% DCF return	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>
Total revenue required	235.3	222.7	394.0	378.0
Sources of Revenue				
Wet cake	42.1	42.1	24.1	24.1
Yeast cake	9.6	9.6	9.6	9.6
Fuel gas	1.3	1.3	1.3	1.3
Ethanol fuel	<u>200.3</u>	<u>187.7</u>	<u>359.0</u>	<u>343.0</u>
Total revenue	235.3	222.7	394.0	378.0

* Processed MSW prices for the regulated venture = \$33.49/ton and for the nonregulated venture = \$83.96/ton.

SA-8760-5

FIGURE 5 PLANT GATE ETHANOL PRICE VERSUS THE COST OF THE MSW-DERIVED CELLULOSIC SUBSTRATE FOR HYDROLYSIS
 Basis: 94.63 million liters per year of 199° proof ethanol (25 million gallons per year)

The three estimated values for the cellulosic substrate for hydrolysis shown on Figure 5 include:

<u>Point</u>	<u>MSW Processing Plants, Type of Venture</u>	<u>Cellulosic Substrate Cost* (\$/ton)</u>
1	Municipally owned and operated facility	~ 6
2	Private regulated venture	~ 33.5
3	Private nonregulated venture	~ 84

If the MSW processing plants are owned and operated by a municipality (financed with tax-free municipal bonds and no profits or taxes), the ethanol could possibly be sold for between ~ \$1.15 and ~ \$1.45/gal by private ventures, depending on the type of fermentation (batch or continuous operation) and the type of private venture (regulated type utility or nonregulated firm).

Cost Sensitivity Analysis

As discussed previously, the method of financial analysis has a great effect on the estimated cost of the cellulosic substrate (see Figure 4). Another important parameter is the tipping fee (see Figure 4). A fee of \$15/ton of MSW is currently charged in the Boston and New York City areas; however, a possible tipping fee of up to ~ \$20/ton is not an unrealistic estimate for many large cities.

As mentioned previously, the estimated capital investment for the base case plant could be low; many site-specific conditions could add to the costs for construction.

The effect of the cellulosic substrate cost for hydrolysis on the ethanol selling price is illustrated in Figure 5. The ethanol selling price will increase by ~ 25¢/gal for each \$10/ton increase in the substrate price.

The following data show how the estimated plant gate price for the cellulosic substrate is affected by the investment cost:

* At a tipping fee of \$15/ton of MSW.

Investment Cost	Municipally Owned and Operated Plant (\$/ton)	Regulated Private Venture (\$/ton)	Nonregulated Private Venture (\$/ton)
Base Case	6	34	84
1.25 x Base Case	22	57	120
1.5 x Base Case	39	81	156

The cellulosic substrate price could be reduced by increasing the sale price of electric power and steam to the ethanol production facility, but this would also increase the cost for ethanol production. Therefore, such a cost increase will not be discussed. Increasing the sale price of the electric power to the utility company (or, more likely, to a local industrial user) might be possible. A 50% increase in the sale price of the power (to 3¢/kWh) would lower the cellulosic substrate cost by ~ \$6/ton--in the case of a municipal-bond-financed plant with a \$15 tipping fee.

The effects on ethanol price of plant facilities investment, enzyme requirements, fermentable C₆ sugars yield, and by-product credit are illustrated in Table 12. The effect of fermentable C₆ sugars yield is based on the assumption that the enzyme-to-substrate ratio can be maintained at about 10 IU/gram. If, to increase the fermentable C₆ sugars yield, the enzyme requirements must also be increased, the effect would be less than illustrated.

The results of the analysis illustrate that the ethanol price is quite sensitive to changes in the substrate cost, the plant facilities investment, the sugar yield, enzyme requirements, the plant stream factor and by-product credits.

Availability of the Technology

Most of the process equipment considered for preparation of the cellulosic substrate from MSW is now being operated in commercial-scale facilities with different degrees of success. Routine maintenance

Table 12
SENSITIVITY OF PLANT GATE ETHANOL PRICE TO
VARIATIONS IN VARIOUS PARAMETERS FOR
MSW-DERIVED SUBSTRATE

	\$/Gallon			
	Regulated Venture		Nonregulated Venture	
	Batch [†]	Continuous [‡]	Batch [†]	Continuous [‡]
Base case [*]	2.00	1.88	3.59	3.43
Effect of plant facilities investment				
Increase by 20%	2.12	1.99	3.77	3.58
Increase by 50%	2.31	2.14	4.03	3.81
Effect of stream factor (base case = 0.9)				
365 days/year (stream factor = 1.0)	1.95	1.84	3.53	3.37
292 days/year (stream factor = 0.8)	2.07	1.94	3.69	3.51
Effect of enzyme (base case = 10 IU/gram) requirements				
8 IU/gram substrate	1.90	1.77	3.47	3.30
12 IU/gram substrate	2.11	1.98	3.72	3.55
Effect of fermentable C ₆ sugar yield (base case - 45% conversion to hexoses)				
At 55% conversion to hexoses [†]	1.71	1.54	3.04	2.81
Effect of by-product credits				
Increase all credits by about 20%	1.92	1.80	3.51	3.35
Decrease all credits by about 20%				

^{*} Processed MSW price for regulated venture - \$33.49/ton and for nonregulated venture = \$83.96/ton.

[†] Based on conversion of hydrolyzable material and an enzyme-to-substrate ratio of 10 IU/gram.

[‡] Mode of operation of ethanol fermentation section.

(1 shift per operating day assumed), multiple process trains (3 trains per plant), and installed overcapacity (at least 10%), are required to allow the systems to operate reliably. The Imax International equipment specified for the final separation to produce a substrate containing mainly paper fiber with little plastics, textiles or ash content, has not, to the best of our knowledge, been used in commercial-scale operations for this purpose. Therefore, it cannot be assumed to be commercially demonstrated technology.

It should be possible to burn the plastics-rich, organic fraction of the MSW and the wet cake from the hydrolysis facility. Because boiler tube corrosion is a problem in the combustion of plastic wastes, special designs and maintenance practices must be employed.

Two-roll milling of an MSW-derived cellulosic substrate has not been practiced in commercial-scale equipment or even tested over extended periods of continuous operation in pilot-plant-scale equipment. Contamination of the substrate with glass and metal fragments could cause operational problems, increase maintenance requirements, and decrease roller life.

Also, the effectiveness of roll milling of the cellulosic substrate has not been demonstrated on a material containing 25 wt% moisture. Tests to date have been conducted with dry material (< 10 wt% moisture). If the MSW should require drying, installation of drying equipment would add at least \$3 to \$4 million to the ethanol production plant investment cost (~ 5%). The steam requirements for drying would probably be approximately 75,000 lb/hr. Use of hot flue gas from the boilers might be possible for the drying.

The enzyme production and substrate hydrolysis have only been tested to date in small, pilot-scale equipment over relatively short periods of time. The technology is not yet ready for application in commercial-scale plants of the size considered in this analysis.

Batch fermentation of C₆ sugars to ethanol is well-established technology. Because of possible contamination of the sugar solution with inhibitory compounds, however, the fermentation process should be tested

in a pilot plant facility. On the other hand, the continuous fermentation process considered here is conceptual in nature. Continuous fermentation will require further process development work.

The design of the anaerobic filters for wastewater treatment is also conceptual in nature; process development work is required.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

PRODUCTION OF ETHANOL FROM WOOD

Process Description

Feedstock Characteristics

A hardwood with a typical composition as listed in Table 13 has been selected for the analysis. It is generally true that hardwoods have a lower lignin content than do softwoods and slightly higher cellulose and hemicellulose contents. The hemicellulose fraction of hardwoods may be composed of 80% pentosans whereas the hemicellulose in a softwood may be 55% hexosans and 45% pentosans. Hardwood was chosen as a basis for the analysis because of

- The higher cellulose content relative to softwood and the likelihood that softwoods will continue to be more valuable for fiber production.
- The promising results reported to date on short-rotation hardwood forestry.

Process Flowsheet and Design

A block flowsheet is shown on Figure 6. The wood will be delivered by truck to the plant site as minus 3" chips containing 50 wt% water. Two days of on-site storage capacity is provided for the wood using live-bottom storage silos. The wood chips are screened and the oversize ($> 3/4"$) are shredded. The shredded material ($< 3/4"$) is dried to < 25 wt% water using a direct contact, three-pass, horizontal, hot air dryer. The air for drying is heated indirectly by steam generated on-site using the waste cake from the hydrolysis section of the plant.

The dryers, shredders, and receiving bins are connected to a common fabric filter for particulate collection from vented gases. The collected dust is fired in the plant boiler.

FIGURE 6 BLOCK FLOW DIAGRAM WITH APPROXIMATE MASS FLOWS FOR MAJOR FEEDSTOCKS, PRODUCT AND BY-PRODUCTS FROM ENZYMATIC HYDROLYSIS AND FERMENTATION FACILITIES (Wood Feedstock)

Table 13

TYPICAL COMPOSITION OF HARDWOOD (Dry Basis)

<u>Component</u>	<u>Hardwood (%)</u>
Cellulose (all hexosans)	48
Hemicellulose	
Pentosans	20
Hexosans	5
(Total hexosans)	(53)
Lignin	20.5
Extractives	6
Ash	0.5
Moisture Content of Wood as Received = 50 wt%	
Higher Heating Value of Wood = 20,657 $\frac{\text{kJ}}{\text{dry kg}}$	
(or 8900 Btu/dry lb)	

The dried (≤ 25 wt% H_2O) wood chips ($< 3/4"$) are sent to the hydrolysis section. The enzyme production operation, the wood milling for pre-treatment, enzymatic hydrolysis, and fermentation operations are exactly as described in the MSW case study. The experimental results reported by Natick staff members indicate that C_6 sugar yields are essentially the same from wood as from the cellulosic substrate produced from MSW. The yield of C_5 sugars is considerably higher, however.

Because the C_5 sugar yield is much higher, a decision has been made to concentrate the stillage to produce a liquid cattle feed product. This by-product should generate much more revenue than would the production of methane.

The plant boiler generates steam to satisfy all of the on-site steam requirements, plus an average of 160,000 lb/hr of excess steam for sale across the plant fence line. The design does not include on-site electric power generation and capital costs that would be required for on-site power generation do not appear to be justified. An alternative to

consider in future evaluations is the use of steam drives (see comments on steam drives in the MSW case study).

Mass Flows and Operating Requirements

The approximate mass flows used for design purposes were presented previously (see Figure 6). The operating requirements for the plant are summarized in Table 14.

Thermal Efficiency

The overall thermal efficiency of the system is calculated based on the higher heating value of all energy products (denatured alcohol and excess steam sold over fence line), divided by the higher heating value of the inputs (wood, gasoline for denaturing the ethanol, and purchased electric power at 3414 Btu/kWh). The overall thermal efficiency, ~ 36%, was calculated as follows:

<u>Input</u>		<u>(10⁹ Btu/day)</u>
$\left(2893.4 \frac{\text{tons wood}}{\text{day}} \right) \left(8.9 \times 10^6 \frac{\text{Btu}}{\text{ton}} \right)$	=	25.751
$\left(757.6 \frac{\text{gal gasoline}}{\text{day}} \right) \left(0.125 \times 10^6 \frac{\text{Btu}}{\text{gal}} \right)$	=	0.095
$\left(54890 \frac{\text{kw} \times 24 \text{ hr}}{\text{day}} \right) \left(3414 \text{ Btu/kWh} \right)$	=	<u>4.497</u>
Total input		30.343
<u>Output</u>		
$\left(76,500 \frac{\text{gal denatured EtOH}}{\text{day}} \right) \left(0.0845 \times 10^6 \frac{\text{Btu}}{\text{gal}} \right)$	=	6.464
$\left(3.84 \times 10^6 \frac{\text{lbs steam}}{\text{day}} \right) \left(\frac{1200 \text{ Btu}}{\text{lb}} \right)$	=	<u>4.608</u>
Total output		11.072
$\frac{11.072 \times 10^9 \text{ Btu/day}}{30.343 \times 10^9 \text{ Btu/day}} \times 100 = 36\%$		

Table 14

SUMMARY OF OPERATING REQUIREMENTS
(Wood Feedstock)

	<u>Operating Requirements</u>
Labor	
Wood receiving, size reduction, drying, and steam plant	8 men/shift
Enzymatic hydrolysis	8 men/shift
Ethanol fermentation (batch) and recovery	7 men/shift
Ethanol fermentation (continuous) and recovery	4 men/shift
Power	
Wood receiving, size reduction, drying, and steam plant	2,500 kW
Enzymatic hydrolysis (mainly for mills)	49,900 kW
Batch fermentation	3,490 kW
Continuous fermentation	1,700 kW
Average steam	
Dryers	63,636 kg/hr (140,000 lbs/hr)
Enzymatic hydrolysis	6,273 kg/hr (13,800 lbs/hr)
Ethanol fermentation and recovery	36,364 kg/hr (80,000 lbs/hr)
Concentration of stillage	42,727 kg/hr (94,000 lbs/hr)
Miscellaneous plant use	5,455 kg/hr (12,000 lbs/hr)
Other	
Lactose and nutrients	1.26 dry metric tons/hr
Gasoline (for denaturing)	119.5 liters/hr (31.6 gal/hr)
Miscellaneous fuel oils	189 liters/day (50 gal/day)

Because the electrical power consumption is so high and excess steam is generated,* any future analysis work should consider on-site power generation, or possibly steam drives, for the large two-roll mills.

Process Economics

Investment Cost Estimates

The estimated plant facilities investment costs and total capital costs for production of ethanol from wood are summarized in Tables 15 and 16. The plant facilities investments are estimated to be about \$93.1 and \$84.4 million for processes using the batch and the continuous ethanol fermentation respectively (see Table 15). The largest investment is for enzyme production, which accounts for about 31% and 37% of the battery limits investment.

The estimated total capital investments for the regulated and nonregulated ventures are presented in Table 16, and the revenue required and operating costs for the base cases are presented in Table 17.

Operating Costs and Revenue Requirements

The cost estimates for annual production of 25 million gallons of a 199° proof ethanol from wood, using the "Natick" enzymatic hydrolysis process, are based on the process described in the preceding sections and the general assumptions stated in Appendix B, as well as the following assumptions:

- The wet cakes (by-products) produced in the enzyme production and hydrolysis are used as fuel for in-plant steam generation; steam generated in excess of in-plant requirements is exported at a credit of \$3.00/1,000-lb.

* 160,000 lb/hr of excess steam is generated if the moisture content of the wood is reduced from 50 wt% to 25 wt%. If the moisture content must be reduced to ≤ 10 wt%, $\sim 75,000$ lbs of additional steam would be required.

Table 15

ESTIMATED PLANT FACILITIES INVESTMENTS FOR ETHANOL PRODUCTION
FROM WOOD USING THE NATICK ENZYMATIC HYDROLYSIS PROCESS

Basis: 94.63 million ℓ /yr of 199° proof
Ethanol (25 million gal/yr)

	Million \$	
	<u>Ethanol Fermentation</u>	
	<u>Batch</u>	<u>Continuous</u>
Battery limits investment		
Wood processing	4.83	4.83
Enzyme production	15.21	15.21
Substrate pretreatment	4.35	4.35
Hydrolysis	6.89	6.89
Ethanol fermentation	9.93	2.62
Ethanol recovery, including denaturing, yeast drying and C5 sugar solution recovery	<u>7.59</u>	<u>7.59</u>
Subtotal	48.80	41.49
Utilities and tankage investment	27.53	27.53
General service facilities	<u>16.80</u>	<u>15.33</u>
Plant facilities investment	93.13	84.35

Table 16

ESTIMATED TOTAL CAPITAL INVESTMENTS FOR ETHANOL PRODUCTION
FROM WOOD USING THE WATICK ENZYMATIC HYDROLYSIS PROCESS

Bases: 94.63 million l/yr of 199° proof
Ethanol (25 million gal/year)

	Million \$			
	Batch*		Continuous*	
	Regulated Venture	Nonregulated Venture	Regulated Venture	Nonregulated Venture
Plant facilities	93.13	84.35	84.35	93.13
Land	0.63	0.63	0.63	0.63
Interest during construction	7.10	0	6.43	0
Organization and startup expenses	4.66	4.22	4.22	4.66
Working capital requirement	4.15	3.88	3.88	4.15
Initial chemicals	<u>0.04</u>	<u>0.04</u>	<u>0.04</u>	<u>0.04</u>
Total capital investment	109.71	93.12	99.55	102.61
Depreciable investment	104.89	93.13	95.00	84.35
Debt capital	71.30	0	64.70	0
Equity capital	38.39	102.60	34.84	93.11
Average equity capital	19.20	--	17.42	--
Regulated utility rate base	109.66	--	99.55	--

* Mode of operation of ethanol fermentation section.

Table 17

PRODUCTION OF ETHANOL FROM WOOD USING THE NATICK
ENZYMATIC HYDROLYSIS PROCESS, ESTIMATED ANNUAL
OPERATING COSTS AND REVENUE REQUIREMENTS

	Cents/Gallon			
	Batch*		Continuous*	
	Regulated Venture	Non-Regulated Venture	Regulated Venture	Non-Regulated Venture
Raw Materials				
Wood		42.5		42.5
Lactose		13.4		13.4
Nutrients, chemicals		5.9		5.9
Gasoline		0.7		0.7
Oil and fuels		0.1		0.1
Maintenance materials		<u>7.4</u>		<u>6.7</u>
Total raw materials		70.0		69.3
Labor				
Operating labor		7.4		6.6
Supervision		1.1		1.0
Maintenance labor		9.3		8.4
Administrative and support		3.6		3.2
Payroll burden		<u>7.5</u>		<u>6.7</u>
Total labor		28.9		25.9
Purchased utilities				
Electric power		63.6		61.6
Water		<u>1.0</u>		<u>1.0</u>
Total purchased utilities		64.6		62.6
Fixed costs				
General administration		7.4		6.7
Property taxes and insurance		9.3		8.4
Plant depreciation	<u>21.0</u>	<u>0</u>	<u>19.0</u>	<u>0</u>
Total fixed costs	37.7	16.7	34.1	15.1
Return on rate base and income tax	37.9	0	34.5	0
Charges for a 15% DCF return and income taxes	<u>0</u>	<u>103.0</u>	<u>0</u>	<u>93.4</u>
Total revenue required	239.1	283.2	226.4	266.3
Sources of Revenue				
Yeast		12.7		12.7
Steam		15.2		15.2
Wood molasses		25.4		25.4
Ethanol	<u>185.8</u>	<u>229.9</u>	<u>173.1</u>	<u>213.0</u>
	239.1	283.2	226.4	266.3

* Mode of operation of ethanol fermentation section.

- All electricity is purchased at a cost of 3.5¢/kWh.
- Gasoline used in the denaturing of the ethanol is priced at 67¢/gal.
- No royalty fees are included.
- Molasses product (at 55 wt% sugar) is produced from the stillage and sold for \$70/liquid-ton.

The estimated plant gate ethanol prices range from \$1.73/gal for a process using the continuous ethanol fermentation under regulated venture conditions to \$2.30/gal for a process using the batch ethanol fermentation under nonregulated venture conditions. By-product sales account for the equivalent of 53.3¢/gal in revenue. The costs for wood and electric power account for about 21% to 25% and 32% to 36% of the operating costs, respectively.

Cost Sensitivity Analysis

The effect of the wood cost on ethanol selling price is illustrated in Figure 7. For example, if the price for wood is raised to about \$16/ton from the base case value of \$11.13/ton, the revenue required would be increased by 9 to 10%, as shown below:

<u>Revenue Required, \$/gal</u>		<u>Venture/Ethanol Fermentation</u>
<u>(Base Case)</u>	<u>(High Feedstock Cost)</u>	
1.73	1.91	Regulated/continuous
1.86	2.05	Regulated/batch
2.13	2.32	Nonregulated/continuous
2.30	2.50	Nonregulated/batch

The effects of plant facilities investment, enzyme requirements, fermentable C₆ sugars yield, and by-product credit are illustrated in Table 18. The effect of fermentable C₆ sugars yield is based on the assumption that the enzyme-to-substrate ratio can be maintained at about 10 IU/gram. If the enzyme requirement must also be increased to increase the fermentable C₆ sugars yield, the effect would be less than illustrated.

SA-8760-6

FIGURE 7 PLANT GATE ETHANOL PRICE VERSUS THE COST OF WOOD CHIPS

Table 18

SENSITIVITY OF PLANT GATE ETHANOL PRICE TO VARIATIONS
IN VARIOUS PARAMETERS FOR THE WOOD FEEDSTOCK CASES

	(\$/Gallon)			
	Regulated Venture		Nonregulated Venture	
	Batch*	Continuous*	Batch*	Continuous*
Base case	1.86	1.73	2.30	2.13
Effect of plant facilities investment				
Increase by 20%	2.05	1.90	2.57	2.38
Increase by 50%	2.34	2.16	2.99	2.75
Effect of stream factor (base case = 0.9)				
365 days/yr (stream factor = 1.0)	1.79	1.67	2.20	2.04
292 days/yr (stream factor 0.8)	1.96	1.82	2.45	2.27
Effect of enzyme (base case = 10 IU/gm) requirement				
8 IU/gram substrate	1.74	1.62	2.16	1.99
12 IU/gram substrate	1.95	1.82	2.43	2.24
Effect of fermentable C ₆ sugar yield (base case = 45% conversion to hexoses)				
At 55% conversion to hexoses [†]	1.53	1.37	1.94	1.71
Effect of by-product credit				
Increase all credit by about 20%	1.75	1.62	2.19	2.02
Decrease all credit by about 20%	1.97	1.84	2.41	2.24

* Mode of operation of ethanol fermentation section.

[†] Based on conversion of hydrolyzable material and an enzyme-to-substrate ratio of 10 IU/gram.

Because electric power requirements for the milling are very high (~ 64¢/gal of product), any changes in electric power costs will have a significant effect on the ethanol price. Use of steam drives for the mills or alternative pretreatment methods should be considered.

Availability of the Technology

The mechanical handling, drying, and milling equipment could be installed now and be expected to perform reliably. The extent of drying necessary before milling, however, is not known. Tests to date have been conducted with dry material (≤ 10 wt% moisture). Drying to 25 wt% moisture (from 50 wt% as received) was assumed to be adequate. Drying to ≤ 10 wt% moisture might not require additional dryer capacity, but would require considerably more steam.

The previous discussion of technology availability for enzyme production, hydrolysis, and continuous fermentation that appears in the MSW case study also applies to wood feedstock cases.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SUMMARY AND DISCUSSION OF RESULTS

The preceding analysis of possible costs for ethanol produced from cellulosic substrates clearly illustrates that depending on the design and economic assumptions made, it is possible to arrive at a very wide range of estimated product prices. No one number should be cited as "the likely product price." Citing a range of costs is much more meaningful.

To put the results of this analysis in perspective, it may be instructive to compare them with the results from an SRI report prepared for DOE under Contract EY-76-C-03-115/PA141, "Preparation of a Cost Data Bank for DOE/Biomass Energy Systems Branch." The estimated plant gate ethanol prices developed to date as part of this other project are listed first in Table 19 (corn and wood feedstocks). The economic and design bases are the same as those used for the analysis of the Natick process. The ethanol output is also the same. In the other study, the uncertainties in the capital investment costs and feedstock costs were estimated. (Other cost uncertainties related to costs for maintenance, purchased utilities, labor rates, and fixed charges were also considered, but will not be discussed here.) The calculated maximum uncertainties for the total capital investment are shown for the first two cases. Note that, even for a commercial technology such as corn conversion to ethanol, many uncertainties exist in non-site-specific estimates and where firm equipment quotes are not received.

The ranges of feedstock costs considered are also listed in Table 19 for the first two cases. The maximum effects of the possible investment and feedstock variations on estimated plant gate ethanol prices are shown for both regulated and nonregulated ventures. Although the maximum potential variation in the price of ethanol from corn is

Table 19

SUMMARY OF ECONOMIC DATA FOR SELECTED ETHANOL PRODUCTION OPTIONS^x

Feedstock	Estimated Base Case Total Capital Investment	Process	Status of Development	Feedstock Costs	Estimated Base Case Plant Gate Ethanol Prices (\$/gallon)	
					Regulated	Nonregulated
Corn	\$49.5 x 10 ⁶	Conventional (whole grain processing) + batch fermentation	Commercial technology	\$2.70/bushel (\$2.30-3.00/bushel)	(\$1.35 (-19¢/gal) +24¢/gal) [*]	1.55 (-18¢/gal) +39¢/gal) [*]
Wood	\$104.9 x 10 ⁶	Tsao/Purdue process (Concentrated H ₂ SO ₄ and MeOH) + batch fermentation	Laboratory scale and small pilot plant scale de- velopment work in progress	\$11.13/wet ton (\$8.90-15.13/wet ton)	1.23 (-39¢/gal) +74¢/gal) [*]	1.66 (-44¢/gal) +98¢/gal) [*]
Wood	\$109.7 x 10 ⁶	Natick enzymatic hydrolysis + batch fermentation	Small pilot plant scale development work	\$11.13/wet ton	\$1.86	\$2.30
MSW- derived cellulosic substrate	\$267.1 x 10 ⁶	MSW processing to produce cellulosic sub- strate for hydrolysis	Commercial tech- nology except for final separation device to remove plastics, textiles and other unwanted materials.	\$6/ton [†] (municipally owned) MSW processing plant	1.40	1.69
				\$22/ton ^{††} (municipally owned) MSW processing plant	1.73	2.09
	71.6 x 10 ⁶	Natick enzymatic hydrolysis + batch fermentation	Small pilot scale development work	\$33.5/ton [†] (regulated private venture)	2.00	
	\$338.7 x 10 ⁶			\$84.0/ton [†] (nonregulated private venture)	—	3.59

* Potential price variations resulting from calculated investment and feedstock price uncertainties or changes.

† Assumes \$15/ton tipping fee for as received MSW.

†† Corresponds to a 25% increase in plant facilities investment cost for MSW processing section.

^x Basis: Production of 25 million gal/year of 199° proof ethanol.

not expected to be more than +25% or -14%, the variation for a wood feedstock using new unproven technology could be +60% or -32%.* The uncertainty in the much higher capital cost estimate for the second case is a major reason for the greater possible price variation.

The results of the analysis of ethanol production using the Natick process are also summarized in Table 19. The most attractive base case ethanol price listed is for the situation where the MSW processing facility is owned and operated by a municipality. In this case the ethanol prices are comparable to those for the first two cases listed in Table 19 (corn and wood). If the investment cost estimated for the MSW processing facility is low by 25% (not at all unlikely), then the cellulosic substrate cost would more than triple and the ethanol prices for both a private regulated venture and private unregulated venture would increase by ~ 25%.

Operation of an MSW processing and ethanol fermentation plant by a private nonregulated venture is far less attractive than the two cases listed where the MSW-derived substrate preparation plant is owned and operated by a municipality. Based on the estimated ethanol prices listed in Table 19, construction and operation of both an MSW processing and an ethanol production facility by a private nonregulated venture is unlikely.

The estimated investment costs for the two wood conversion cases are very close. One of the major reasons for differences in the estimated ethanol prices is that the plant using the Tsao/Purdue process is estimated to require 38% less wood to produce the same quantity of ethanol. Again, the possible uncertainty ranges for the estimated ethanol prices for the Tsao/Purdue process are quite great; however, they are no greater than can be expected for the option using the Natick process. For example, if the enzyme requirement could be lowered from 10 to 8 IU/g of substrate and the sugar yield increased by about 20%, the estimated ethanol price would be within 20% of the base case estimate for the Tsao/Purdue process.

* Resulting from errors in investment cost estimates or feedstock cost changes.

In the Natick process, the use of two-roll milling for pretreatment is very energy intensive and represents a major operating cost for electricity (43¢ to 64¢/gallon of product) for the cases considered. Alternative pretreatment schemes or steam driven mills should be considered in future work.

CONCLUSIONS

Status of the Technology

We conclude that the Natick process is not currently at a stage of development that would allow construction of a commercial facility without a high degree of technical and economic risk. Based on the results of the economic analysis, it does not appear that the Natick process, at this time, could significantly reduce the costs for producing ethanol relative to other conversion routes. Future improvements in various aspects of the process might lead to the production of ethanol from cellulosic substrates at prices competitive with conversion of starch or sugar substrates, or conversion of cellulosic substrates using other processes now being developed. Conclusions concerning the specific cases considered follow.

MSW Feedstock Cases

For the cases where the cellulosic substrate for hydrolysis and ethanol production is produced from MSW, it does not appear that a private nonregulated venture could economically justify the construction and operation of the entire system. The outlook for a private regulated venture (such as a utility company) is more promising. By far, the most economically attractive option is for a municipality to construct and operate the MSW processing operation and to sell the cellulosic substrate to a privately owned and operated ethanol production facility. The costs for ethanol from such operations could conceivably be competitive with other future sources of ethanol produced from biomass.

Wood Feedstock Cases

Production of ethanol from wood using the Natick enzymatic hydrolysis technology is unlikely to be as economically attractive as the lowest

cost MSW feedstock cases. The estimated ethanol prices are also higher than those estimated for another advanced conversion process now being developed using wood as the feedstock. The uncertainties in both estimates are so great, however, that it would be unwise to choose between the processes solely on the basis of the results of these preliminary economic analyses.

Appendix A

PROCESS DESCRIPTION AND DESIGN FOR ETHANOL FERMENTATION AND RECOVERY FACILITIES

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Appendix A

PROCESS DESCRIPTION AND DESIGN FOR ETHANOL FERMENTATION AND RECOVERY FACILITIES

Fermentation Section Design Bases

The block flow diagrams for the batch fermentation and the continuous fermentation plants are shown in Figures A-1 and A-2. The design assumptions concerning the fermentation section for the two types of processes are summarized in Table A-1. In both designs, the beer from the fermentation section will be centrifuged and a portion of the cell mass will be recycled. The remainder of the cell mass (at a solids concentration of approximately 15 wt%) will be dried and sold for use as a high-protein additive to livestock rations.

The centrifuged beer will be pumped to the ethanol recovery area of the plant, which is described in the following section.

Ethanol Recovery Area

The ethanol concentration in the dilute beer is approximately 6.5 vol% or 5.2 wt% ethanol. The distillation system to be used for the base case plant is based on the design presented in the report by Moon et al. of Raphael Katzen Associates (1978). The design presented in the Katzen report is for a beer containing 7.1 wt% ethanol and 6.97 wt% total solids produced from fermentation of a corn mash. The steam requirements presented in the Katzen report have been adjusted to take into account the lower concentration of ethanol in the beer. The steam requirements have been estimated to increase by 20% for this case relative to the case considered in the Katzen report. This estimate is based on a correlation of energy requirements (per gallon of 92 wt% ethanol produced from various ethanol-water solutions) developed at the University of Pennsylvania and reported in Reference 2. The distillation system contains three towers:

FIGURE A-1 SIMPLIFIED BLOCK FLOW DIAGRAM AND MASS FLOW FOR ETHANOL PRODUCTION WITH CONTINUOUS FERMENTATION

FIGURE A-2 SIMPLIFIED BLOCK FLOW DIAGRAM AND MASS FLOW FOR ETHANOL PRODUCTION WITH BATCH FERMENTATION

Table A-1

FERMENTATION SECTIONS
DESIGN SUMMARY

	<u>Batch Fermentation</u>	<u>Continuous Fermentation</u>
<u>Yeast Type</u>	Strains of <u>Saccromyces cerevisiae</u>	
<u>Yeast Source</u>	Cultivated aerobically from laboratory culture through a series of step-up culture tanks and fermenters	
<u>Yeast Recycle</u>	Yes	Yes
<u>Fermenter Operating Conditions</u>		
pH range	4 to 5	4 to 5
Temperature	86°F(30°C)	86°F(30°C)
Pressure	Atmospheric	Atmospheric
Other conditions	nonaseptic, anaerobic	nonaseptic, anaerobic*
C ₆ sugar concentration in feed solution to fermenters	10.7 wt%	10.7 wt%
Batch Operation		
Retention time	41 hours	--
Cycle time	64 hours	
Continuous Operation		
Dilution rate [‡]	--	0.25 hr ⁻¹

*Small amount of aeration provided.

†If sugar concentration is more dilute, evaporative concentration equipment will be provided.

‡Dilution rate is the reciprocal of hydraulic retention time and is a common term used in the fermentation industry.

- A combination pressure-rectifier/stripper operating at 50 psig pressure produces a 95 vol% ethanol overhead product and a fusel-oil side-stream. Heat is supplied to the base of the column by condensing steam to 150 psig in a reboiler. The heat content of the overhead vapor from the column is used to supply the heat for the reboiler on the dehydration column, to supply heat for the reboiler on the hydrocarbon stripper, and to partially preheat the dilute beer feed. The top few trays of the column operate in a total reflux condition. A small purge stream is removed from the condensate return stream to remove small quantities of high vapor pressure constituents such as certain low molecular weight aldehydes. This stream is burned in the plant boiler. The liquid product (95 vol% ethanol) is removed about 5 trays from the top and is passed to the midsection of the dehydration tower. The bottoms stream contains < 0.02 wt% ethanol.
- A dehydration tower operates at about atmospheric pressure and produces a 99.5 vol% ethanol product from the bottom of the tower. The overhead product is a ternary minimum boiling azeotrope consisting of hydrocarbon, alcohol, and water. A portion of the overhead vapor is used for preheating the dilute beer feed to the pressure-rectifier/stripper and the remainder is condensed with cooling water. The overhead stream is decanted and the hydrocarbon-rich layer is returned directly to the top tray of the dehydration column. The water layer containing some water and some hydrocarbon is pumped to the top tray of the hydrocarbon stripper. The heat supply for the column is the overhead vapor from the pressure-rectifier/stripper.
- The hydrocarbon stripper operates at atmospheric pressure and also uses the overhead vapor from the pressure-rectifier/stripper as a heat source. The bottoms from the stripper is essentially an aqueous stream free of hydrocarbon and alcohol. The overhead stream contains hydrocarbon, water and alcohol. The overhead stream is condensed in a dilute beer preheater and then returned to the dehydration tower via the previously mentioned decanter.

The bottoms streams from the pressure-rectifier/stripper and the hydrocarbon stripper are pumped to the wastewater treatment systems.

The dilute beer is preheated prior to introduction into the pressure-rectifier/stripper in seven preheaters operating in series. The preheater sources of heat are as follows:

<u>Preheater</u>	<u>Other Functions or Heat Source</u>
#1	Condenser for a portion of overhead stream from the dehydration tower and condenser for hydrocarbon stripper
#2	Condenser for a portion of overhead stream from the pressure-rectifier/stripper
#3 & #4	Steam from flashing the bottoms stream from the pressure-rectifier/stripper
#5	15 psig steam
#6 & #7	Steam from flashing the bottoms stream from the pressure-rectifier/stripper

Ethanol Storage and Denaturing

Tanks are provided on site for storing product 30 days. The ethanol will be denatured by blending it with gasoline at the time of shipment. The blending formula will be one gallon of gasoline per 100 gallons of ethanol as specified under Formula No. 28-A by the Department of the Treasury, Bureau of Alcohol, Tobacco, and Firearms.

Process Mass Flows and Operating Requirements

An estimated mass balance for the major process flow streams is shown in Figure A-3. The plant operating requirements are summarized in Table A-2.

Plant Facilities Investment Costs

The appropriate plant for fermentation of a C₆ sugar solution will be selected for the various sugar production options to be considered. The estimated investment costs for the different plants are summarized in Table A-3.

The land requirements for all of the designs considered are estimated to be roughly 15 acres.

FIGURE A-3 APPROXIMATE MASS FLOWS FOR MAJOR FEEDSTOCK, PRODUCTS AND BY-PRODUCTS

*Base case yeast production will be conservatively assumed to be 25 t/day.

Table A-2

SUMMARY OF OPERATING REQUIREMENTS

	Batch Fermentation		Continuous Fermentation
	4 wt%	10.7 wt%	10.7 wt%
C ₆ Sugar Concentration			
C ₆ Sugar (ton/d)	542.5	542.5	542.5
Gasoline (gal/d)	758	758	758
Misc. Chemical (¢/gal 199° proof EtOH)	0.2	0.2	0.2
Operating Labor (men/shift)	7	7	4
Electric Power (kW)	3,570	3,490	1,700
Process Water	Neg.	Neg.	Neg.
Steam (lb/hr)	173,000	80,000	80,000

Table A-3

ESTIMATED PLANT FACILITIES INVESTMENT
COSTS FOR FERMENTATION* AND ETHANOL
RECOVERY SECTIONS IN MILLIONS OF DOLLARS

Basis: 25 million gal/yr 199° proof ethanol

Plant Section (Sugar Cane)	Batch		Continuous
	4 wt%	10.7 wt%	10.7 wt%
Sugar solution concentration	5.09	0	0
Ethanol fermentation	9.93	9.93	2.62
Ethanol recovery (includes denaturing) and yeast drying	4.99	4.99	4.99
Utilities† and tankage	3.29	3.26	3.26
General service facilities‡	--	--	--
	23.27	18.18	10.87

*Fermenters designed to use a sugar solution as a feedstock.

†Does not include boiler house for steam production. One boiler plant to be installed in design of total facility sugar production and fermentation operations.

‡General service facilities to be included with sugar production plant and fermentation plant estimate.

Optional CO₂ Recovery Operation

The plant facilities investments shown in Table A-3 do not include any facilities for production of a liquid CO₂ product. The fermentation operation will generate ≥ 239 tons of CO₂. About 225 tons CO₂/day can be recovered in liquid form, using a process such as the Airco Carbon Dioxide Process. The liquid CO₂ product is stored at about 220 psig and -15°F. The investment for the liquefaction and product storage facilities (5 days storage capacity) would be approximately $\$3 \times 10^6$. The CO₂ recovery facility would require ~ 1300 kW of electric power.

REFERENCES

1. G. D. Moon, Jr. et al., "Grain Motor Fuel Alcohol Technical and Economic Study," report prepared by Raphael Katzen Associates for the U.S. Department of Energy, DOE Contract No. EJ-78-C-01-6639 (December 31, 1978).
2. Fuels from Biomass Fermentation Newsletter, edited by H. R. Bungay and T. J. Walsh, Rensselaer Polytechnic Institute, Troy, NY (February 1978).
3. Personal communication with Mr. Edward Fradkin of Scientific Design Company, Inc., New York, NY (July 1979).

Appendix B
GENERAL ECONOMIC AND DESIGN BASES

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Appendix B

GENERAL ECONOMIC AND DESIGN BASES

Three general areas are covered in the discussion of the economic and design basis of biomass conversion plants.

- Capital investment--including a definition of the boundaries of the capital investment for a conversion plant, plant capacities; discussions of nonplant investments such as interest during construction, land, royalties, working capital, start-up costs; and discussion of depreciable investment and plant operating schedules.
- Operating and maintenance costs--including feedstock costs, purchased materials (e.g., water, catalysts, maintenance materials), labor, fixed costs (e.g., property taxes and insurance), and by-product credits.
- Financial analysis--including taxes, services of investment capital, interest rates, rates of return on equity, depreciation, project life, and revenue requirements.

Capital Investment

Investment Factors--Conversion Plant

The plant facilities investment (PFI) is the total cost to construct the plant and prepare it for start-up. It consists of all process facilities, necessary utilities, and general plant facilities, including equipment and all direct and indirect costs of installation. The PFI does not include an across-the-board contingency factor. However, judgment has been used in developing costs for specific sections of each process, depending on the level of commercial experience that has been developed. Sensitivities of product cost were made for wide variations from the base case PFI. Paid-up royalties are included in the PFI as appropriate.

Plant facilities investments were developed by use of SRI cost files and by consulting with equipment vendors and engineering firms that specialize in construction of specific equipment or plant sections.

The total capital investment includes the plant facilities investment, cost of land,* working capital,* and start-up costs* for the general conversion plant considered here. When considering debt-financed ventures (as typified by regulated utility plants), interest during construction* is included in the total capital investment.

Certain investments and operating costs are estimated by applying percentage factors against either investments or operating costs that have been previously estimated in detail. For example, investments required for start-up costs, and plant maintenance are estimated as percentages of the plant facilities investment. Similarly, supervision, administrative labor, and payroll burden are estimated as percentages of the operating labor costs. This method of estimating certain investments and operating costs follows current engineering practice for preparing budget estimates for alternative projects.

All monetary figures for investments and operating costs are given in mid-1979 constant U.S. dollars. The philosophy of "mature plant" operation, as opposed to a pioneering venture, is followed in the general evaluation approach. Product transportation facilities are not included in the plant facilities investment, and product prices are on a "plant gate" basis.

Conversion Plant Utilities Investment

Facilities are provided for generating all steam required for process needs by heat recovery or by burning plant fuel.

The plant utilities investment includes the following facilities where required:

- Raw water filtering and softening facilities.
- Cooling water system (includes either air cooling or wet cooling towers, distribution system, and blowdown treatment).
- Boiler feedwater demineralizers and deaerators.
- Water distribution.
- Wastewater collection and treatment.

* Discussed later in this section.

- Emission control equipment.
- Plant fuel system.
- Steam generation, distribution system, condensate lines, and boiler blowdown treatment facilities, if not separately identified.
- Instrument air and inert gas systems.
- Ash disposal.

The plant general facilities investment comprises the following buildings, shops, and installations:

- Office buildings
- Laboratory
- Maintenance shops
- Supplies warehouse
- Control laboratory
- Cafeteria, dispensary, and change house
- Plant roads, parking areas, walks, and storm sewers
- Plant communications system
- Plant fences, guard houses, and lighting system
- Fire protection facilities.

The utilities and general facilities costs do not include provision for site-specific offsites such as water pipelines, power generation, access roads, railroads, bridges, or tunnels. Some of these items may be necessary to the completion of a project. Since it is assumed that in most cases, electric power and makeup fresh water are purchased and delivered to the plant, the utilities investment does not include investment for water supply development and delivery.

Conversion Plant Emissions

The control of plant emissions is based on standards that the EPA has established or proposed for similar industrial operations.

Interest During Construction

Regulated industry plants are constructed with funds borrowed at 10% interest, which is compounded during the construction period and is capitalized with the plant investment.

Nonregulated industry plants are constructed with equity funds assumed to yield a 15% DCF rate of return covering the construction period and for the remainder of project life.

Land Investment

Land required for the plant site is assumed to be valued at \$5,000 per acre (\$12,354 per hectare) in rural U.S. locations and \$25,000 (\$61,880 per hectare) in urban locations. Land cost includes rough grading and site preparation.

Working Capital

Working capital is provided for payroll and other cash operating expenses plus funds for feedstock purchase, until receipt of accounts receivable. It includes the following items:

- Three months' total labor expense
- Two months' other cash operating expenses.

Organization and Start-Up Costs

These costs include equipment modification and repair during start-up, operator training, property taxes and insurance during construction, and materials consumed during start-up. These costs are estimated to be 5% of the plant facilities investment. Regulated industry start-up costs are capitalized, while nonregulated industry start-up costs are expensed.

Depreciable Investment

Regulated industry plant depreciable investment is the sum of plant facilities investment, interest during construction, paid-up royalties, and start-up expenses, typical of a regulated utility.

Nonregulated industry plant depreciable investment includes plant facilities investment and paid-up royalties, representative of an industrial venture.

Plant On-Stream Factor

After the start-up period is completed, the conversion plants are generally assumed to operate on-stream about 90% of the time, approximately 330 days per year.

Construction Period

The estimated construction period is 2 years.

Conversion Plant Construction, Start-Up, and Operating Schedule

The example shown in Table B-1 gives the assumed time schedule and percentage distribution of positive and negative cash flows for construction funds, land purchase, working capital, operating costs, and revenue received during the project life. A 2-year plant construction schedule is shown.

Table B-1

EXAMPLE OF 2-YEAR PLANT CONSTRUCTION SCHEDULE

<u>Start of Year</u>	<u>Depreciable Investment</u>	<u>Land</u>	<u>Working Capital</u>	<u>Cash Operating Costs</u>	<u>Revenue *</u>	<u>Paid-Up Royalties</u>
1	-30%	100%				
2	-70%					-100%
3 [†]			-100%	-70%	+ 70%	
4				-90%	- 90%	
5				-100%	+100%	
⋮				↓	↓	
Final year of project				-100%	+100%	

* Percentage of maximum.

† Start-up.

Operating and Maintenance Costs

Feedstock Costs

The following feedstock costs or credits delivered to the conversion plant are assumed for the base case economic evaluation. Because feedstock costs or credits can be highly variable, depending on location and market conditions; the effect on product price of feedstock cost or credit variations will be illustrated.

<u>Feedstock</u>	<u>Base Case Value</u> <u>(\$/ton as received)</u>	<u>Range</u> <u>(\$/ton as received)</u>
Municipal solid waste	(15)*	(10) to (25)
Wood	\$11.13 [†]	8.90 to 15.13

* Tipping fee paid to facility operator; MSW with a higher heating value of 4470 Btu/lb as received.

[†] Wood at 50 wt% moisture with a higher heating value of 4450 Btu/lb of wood as received.

Catalysts and Chemicals

The annual consumption and costs of chemicals and catalysts are estimated for each process based on current U.S. market prices.

Maintenance Materials and Supplies

Maintenance materials and supplies are estimated as 2% of the plant facilities investment.

Labor Factors

The following assumptions were made for conversion plant operating labor:

Plant operating labor (\$/hr)	8.5
Plant supervision (% of plant operating labor)	15
Maintenance labor (% of plant facilities investment)	2.5
Administrative labor (% of operating, supervision, and maintenance labor)	20
Payroll burden (% of all labor)	35

Administrative and support labor is assumed to include plant manager, process engineers, laboratory technicians, clerks, secretaries, telephone operations janitors, guards, and firemen. Payroll burden is assumed to cover costs of health insurance, disability insurance, vacations, sick leave, and retirement payments.

Fixed Costs

Annual local property taxes and insurance are estimated to be 2.5% of the plant facilities investment.

General administrative and overhead expenses are assumed to be 2% of the plant facilities investment. These include head office expenses for accounting, purchasing, legal services, office supplies, communication, travel fees, and contracted services.

By-Product Credits

Revenue from the sale of by-products is based on the following values.

<u>By-Product</u>	<u>Dollar Credit</u>
Ferrous metal	\$ 25/ton *
Aluminum	\$380/ton
Glass (mixed colored)	\$ 4/ton
Glass (produced by froth flotation)	\$ 25/ton
Liquid carbon dioxide	\$ 10/ton
Yeast cake ($\leq$ 5 wt% moisture)	\$400/ton (wood case) \$300/ton (MSW case)

Purchased Utilities

Electric power is purchased at 3.5 ¢/kWh and water is purchased at 60 ¢/per thousand gallons delivered to the plant.

* Contains ~ 3 wt% organics

Financial Analysis

Income Taxes

Federal and state corporate taxes are assumed to total 51% applied to taxable income, reflecting a federal corporate tax rate of 46% plus a 5% state income tax rate.

Investment Tax Credit

The present U.S. industrial investment tax credit of 10% is taken in the financial analysis of the base cases.

Sources of Investment Capital--Regulated Ventures

Regulated industries are assumed to partially finance the total capital investment of proposed biomass conversion facilities with debt capital. A typical ratio of debt-to-equity capital of 65/35 was used in this analysis. Table B-2 shows the base financial parameters used for this work.

Table B-2

FINANCIAL PARAMETERS STUDIED

Conversion Plant Organizational Structure	Base Percent Debt Capital (%)	Base Percent Equity Capital (%)	Base Debt Capital Interest Rate (%)	Base Return on Equity Capital (%)
Regulated	65	35	9	15
Unregulated	0	100	0	15

Source of Investment Capital--Unregulated Ventures

The base case financial analysis assumes that all funds for the total capital investment are provided from equity capital and yield a 15% DCF rate of return both during the plant construction period and over the life of the project. Since these projects are capital intensive, 100% equity financing results in high capital charges.

Depreciation and Project Life

The depreciation tax life is assumed equal to the project life for the regulated biomass conversion plant base cases. The following depreciation schedules are used.

<u>Conversion Plant Organizational Structure</u>	<u>Depreciation Tax Life (years)</u>	<u>Depreciation Schedule</u>
Regulated	20	Straight-line*
Unregulated	15	SOYD†

* Straight-line depreciation schedule was used for regulated plants, since that is normal practice for regulated utilities.

† Sum-of-years' digits accelerated depreciation schedule was used because it is a method frequently used for industrial investments.

The unregulated project life is 20 years.

Revenue Required--Regulated Industry

The accounting methods permitted and required of regulated U.S. utilities vary somewhat with the regulatory agency. The method applied in SRI studies has been used by the U.S. Federal Power Commission.* Organization and start-up costs, interest during construction, and paid-up royalties are capitalized as part of the depreciable investment. Straight-line depreciation over the life of the project is subtracted from the depreciable investment each year. The rate base in any year is the sum of the undepreciated plant investment, the cost of land, and the working capital. The return on rate base is a weighted average of the return and the simple interest rate on debt as follows:

$$P = d(i) + (1-d)r$$

* Federal Power Commission, Final Report, The Supply-Technical Advisory Task Force--Synthetic Gas--Coal, Appendix I (April 1973).

where:

P = return on rate base

d = debt fraction

i = interest on debt

1-d = equity fraction

r = return on equity.

In the base case, using the following values: d = 0.65, i = 0.09, and r = 0.15, the return on rate base (P) equals 11.1%. The total revenue required is the sum of return on rate base, income tax, and operating cost.

The by-product credit, if any, also is calculated separately, and the net product revenue is obtained by subtracting it from the total revenue required.

As noted, the return on rate base is derived as a dependent variable. Even though in rate cases much more complicated calculations are used, the principal effect of such calculations is to provide another approach to determining the return on rate base. Thus, sensitivity analysis of return on rate base shows the net effect of a number of factors.

Revenue Required—Unregulated Industry

Discounted cash flow (DCF) analysis is used to determine the revenue required to yield a desired rate of return on equity investment over the life of the project. A detailed discussion of DCF analysis is not attempted in this report. Very briefly, the net cash flow for any year is the sum of positive and negative cash flows consisting of revenue received, operating costs, income tax, equity investment, and payments for debt principal and interest. The annual net cash flow is discounted each year by multiplying it by the appropriate discount factor defined by the following equation:

$$d = \frac{1}{(1 + i)^n}$$

where:

d = discount factor

i = DCF rate of return on equity investment

n = year of project life to which cash flow applies.

The revenue required to yield the desired rate of return on equity investment is determined by iterative calculation such that the sum of all discounted positive and negative annual cash flows over the life of the project will be zero.