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SECOND-YEAR PROJECT ANALYSIS OF THE ARIZONA STATE UNIVERSITY PROCESS TO CONVERT CELLULOSIC WASTES INTO LIGHT FUEL OIL. FINAL REPORT

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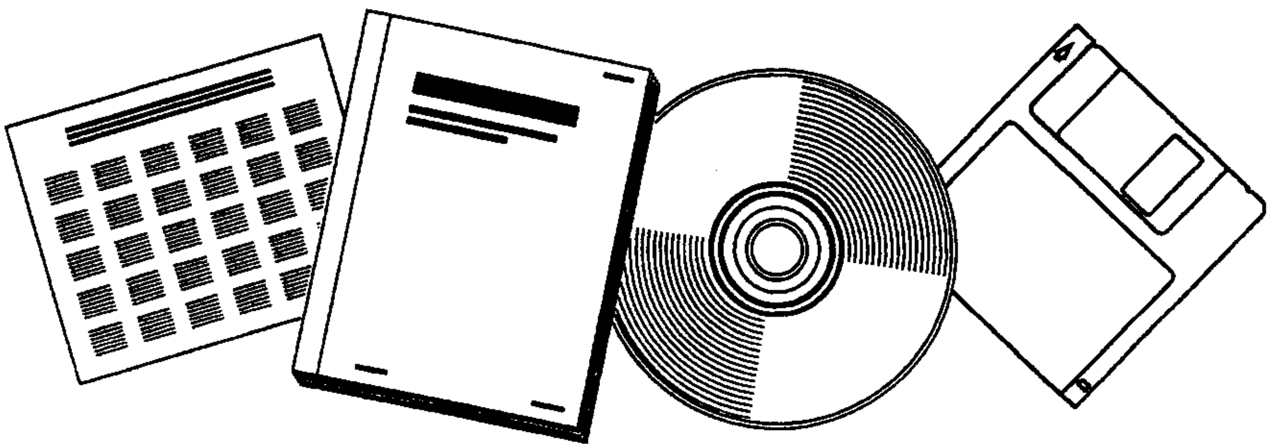

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SECOND-YEAR PROJECT ANALYSIS

OF THE

ARIZONA STATE UNIVERSITY
PROCESS TO CONVERT CELLULOSIC
WASTES INTO LIGHT FUEL OIL

FINAL REPORT

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DISCLAIMER

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NOTICE

SUMMARY

An indirect liquefaction process is being developed by Arizona State University (ASU) for the conversion of cellulosic wastes into light fuel oil. In this process the cellulosic waste feedstock is first gasified, by catalytic flash pyrolysis, then liquefied in a modified Fischer-Tropsch catalytic reactor. The liquid-fuel product is similar to petroleum refinery-produced diesel oil and No. 2 fuel oil. Depending upon the liquid fuel conversion yield and feedstock moisture content, a high-quality by-product gas is available for sale or supplementary gaseous fuel is needed to sustain the process.

The existing research-scale process development unit has an approximate feedstock capacity of 25 pounds per hour. Arizona State University proposes to construct a pilot scale unit with a feedstock capacity of 10 tons per day. The smallest commercial scale for conversion plants of this type is about 500 tons per day.

Product yield in the research-scale process development unit is currently about 10 gallons per ton of feedstock. The immediate research goal is to demonstrate a product yield of 40 gallons per ton, principally through improvement in the choice of liquefaction-reactor catalyst. The optimum product yield is reported to be approximately 100 gallons per ton. A previous economic analysis of the projected commercial-scale process assumed a yield of 80 gallons per ton of zero-moisture feedstock at a plant factor of 90 percent.

Successful development of this process could lead to economical conversion of large quantities of available cellulosic waste material into diesel oil or similar light commercial fuels. The main technical question is whether or not a sufficiently high product yield can be obtained to justify advancement of the project to the pilot-plant stage.

This study examines the projected process costs at the commercial scale over the range of expected variation and uncertainty in product yield, plant factor, feedstock capacity, feedstock moisture content, and future fuel prices. The quantities of cellulosic waste feedstocks economically available over these parameter ranges are estimated. The study results allow straightforward interpretation of the national energy conservation significance of technical progress as the R&D project continues.

The principal findings and conclusions of this study are as follows:

- *As expected, the present product yield of 10 gallons per ton feedstock must be improved by a factor of at least 5 and possibly 6 for successful commercial introduction of the ASU process.*

- *Other technical uncertainties which could limit the national petroleum saving potential of the process include the establishment of the product's substantial equivalence with a commercial fuel oil. There is much work to be done in this area if the required product yield improvement is obtained.*

- *There remain technology and logistics issues concerning the supply and handling of waste cellulosic feedstocks. The technology to suitably collect and prepare agricultural residues and waste wood feedstocks, for example, does not yet exist. Technical progress in these areas as well as the growing general experience with refuse-derived fuel (RDF) should be closely monitored and balanced against the projected feedstock costs used in this analysis. The pilot facility should test feedstocks pre-processed to differing extents, and the pilot study program should at least include feedstocks available in nationally significant quantities.*

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I. INTRODUCTION

The Alternative Materials Utilization Branch, Office of Industrial Programs, U.S. Department of Energy (DOE) supports research, development, and demonstration projects involving innovative processes or technologies designed to reduce the rate of use of scarce fuels. Conducted on a cost-shared basis with industrial partners, the relatively few projects in the demonstration stage represent significant public investments in the acceleration of technical innovation to save energy. A larger number of projects are in the development stage, typically addressing problems of component design and system integration in pilot plant facilities. These projects are somewhat higher risk endeavors than the demonstration projects, but involve correspondingly smaller public investments. The largest number of projects, each with a modest budget, are in the research stage of the RD&D process. These projects are characteristically laboratory investigations carrying considerable risk of eventual failure.

One of the functions of the Alternative Materials Utilization Branch is to make critical decisions regarding the advancement of projects under its administration through these RD&D stages. The rate of investment of public funds increases significantly as successive stages are entered. The problem of the Federal RD&D program managers is one of organizing a diversity of general economic and project-specific uncertainties to obtain the maximum decision-making utility from the technical results generated by the RD&D projects themselves.

Recognizing this need, the Alternative Materials Utilization Branch contracted with Argonne National Laboratory in September, 1980 to procure a series of "Second Year Project Analyses," each addressed to an existing RD&D project nearing a critical decision point regarding its advancement to a new stage of research, development, or demonstration activity. The primary purpose of these "Second Year Project Analyses" (SYPA's) is to provide DOE with independent information with which to interpret the technical results of RD&D projects. This information is vital to program management decisions regarding mid-course corrections in the progress of these endeavors and to the development of qualified, valid national energy savings projections.

This document is an account of work performed by Energetics, Incorporated between September 27, 1980 and February 23, 1981 under Subcontract No. 31-109-38-5869 issued by Argonne National Laboratory. The "Second Year Project Analysis" study series originated with an unsolicited proposal submitted July, 1979 by Energetics, Incorporated to the Alternative Materials Utilization Branch. This work is performed as part of Argonne National Laboratory's ongoing effort to provide systems analysis support to the Alternative Materials Utilization Branch.

This study is addressed to the currently active research project entitled "Cellulosic Waste Conversion to Liquid Fuels," being conducted by Arizona State University. After several years of promising research funded by DOE and others*, the Arizona State University (ASU) process is nearing readiness for advancement to the pilot plant development stage.

Thus far, the ASU process research has been performed with a 25 pound feedstock per hour laboratory test rig. ASU's proposed pilot plant would have a feed capacity of ten tons per day. The generally accepted minimum capacity for a commercial plant of this type is 500 tons (feedstock) per day.

The ASU process is categorized as indirect liquefaction in that incoming feedstock is first gasified, by catalytic flash pyrolysis, then liquefied in a modified Fischer-Tropsch catalytic reactor. The liquid fuel product is a light heating oil similar to petroleum refinery-produced diesel oil and No. 2 fuel oil. A water-propanol stream is also produced. Depending upon plant performance and feedstock parameters, a high quality byproduct gas is available for sale or supplementary gaseous fuel is needed to sustain the process.

One of the most sophisticated, advanced processes under development for the conversion of waste cellulose to fuel, the ASU process appears to offer inherent cost advantages in lower process temperatures and pressures, and perhaps improved product uniformity and control, over several other thermochemical processes also under development. The cost advantages over fermentation and destructive distillation-based processes and acid or enzyme hydrolysis processes for converting cellulosic wastes to ethanol and methanol are shorter processing times and fewer environmental problems. While no process is known to exist which can economically produce petroleum-saving liquid fuels from cellulosic wastes on a commerical basis, there is considerable R&D interest in developing such technologies. Due to the early stage of development of these technologies and the fact that the ASU process appears to offer a least-cost alternative to other advanced fuel oil synthesizing processes,** this study makes no attempt to compete the projected commercial ASU process against others, as is possible, for example, using a market share simulation model such as ISTUM (Industrial Sector Technology Use Model).

The ASU process has been laboratory tested on a wide range of cellulosic feedstocks, including those with central bearing on the national petroleum-saving potential of the process (refuse-derived fuel, agricultural residues, and wood residues). In general, the process has proven flexible with regard to feedstock and appears capable of producing tailored light fuel oils fully substitutable with commercial diesel oil or No. 2 heating oil made from petroleum. The central issues, then, appear to be the process cost at the commercial scale and the consequent quantities of cellulosic wastes which will be economically available for conversion.

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* See Appendix A for a summary description of this project.

** See Appendix B for a direct comparison of the ASU process with other thermochemical processes.

To address these issues, the study is focused on the following elements:

- <u>Cellulosic Waste Availability and Cost</u>

  The quantity of cellulosic feedstock potentially available from municipal and industrial solid waste, agricultural residues, and wood residues is very large, on the order of hundreds of millions of dry equivalent tons each year. Commercially successful capture of a significant portion of this waste resource base by the ASU process would return the public investment in its development many times over. But these wastes have widely varying costs associated with their acquisition, collection, transport, preprocessing (size reduction, cleaning, etc.), and storage. The basic information needed to determine how much feedstock will be available at what cost, over time, is available in the published results of a major alcohol fuels feedstock availability study performed by DOE.

- <u>ASU Process Feedstock Cost Ceiling Analysis</u>

  Capital and operating costs provided by Argonne National Laboratory were previously used by Mittelhauser Corporation in an economic analysis of the ASU process. This analysis essentially computed the product price requirement for two assumed commercial plants (500 TPD and 1000 TPD), using the leveled cost method and treating feedstock cost as an input parameter. The sensitivity of the calculation to changes in economic parameters such as capital cost estimate, tax credit, depreciation method, ROI, and feedstock cost was tested. No review of the 80 gallon per ton yield parameter, 90 percent plant factor, or other process cost elements used in this economic analysis was attempted. In the present study, the leveled cost approach used by Mittelhauser Corporation is reversed, treating product price as an input and computing the feedstock cost compatible with a 15 percent after-tax ROI. The plant economic analysis is otherwise consistent with the Mittelhauser report, except that capital and operating costs are adjusted to examine differing feedstock moisture contents, plant factors, operation start dates, product yields, plant capacity, and projected fuel prices across the ranges of uncertainty associated with each. Preliminary plant mass flow estimates published by Kuester are used to develop a crude plant energy balance, permitting the determination of the by-product gas or supplementary gas requirement associated with any feedstock moisture and product yield combination. The resulting delivered feedstock cost "ceilings" are mapped out in considerable detail to cover the wide range of uncertainty in commercial scale plant performance and future fuel prices.

- **Potential Petroleum Energy Savings and Cost Impacts of The ASU Process**

  Nominal, Pessimistic, and Optimistic ASU process commercial scale plant characterizations are specified, as are Low, Middle, and High 1985 fuel price projections. By combining the feedstock price ceiling associated with pairwise combinations of these plants and fuel price projections with delivered feedstock supply curves, maximum potential impacts are determined for each combination. This maximum economic impact potential is then reduced further by the application of an arbitrarily specified market penetration curve to represent the diffusion of the new technology. By identifying the minimum plant performance characterization at each fuel price projection consistent with large available feedstock quantities and nationally significant petroleum savings, conclusions are made regarding appropriate performance goals for the RD&D project. The sensitivity of the results to an increment in delivered feedstock costs (a shift in the feedstock supply curve) is examined.

Subsequent chapters of this report describe the availability and cost of cellulosic wastes, the ASU process feedstock cost ceiling analysis, and the potential impacts of the process's successful commercialization. Appendix A describes the ASU/DOE research project and Appendix B includes a cost comparison of the ASU process (as projected in a commercial plant) against other innovative, directly competing conversion processes. This comparison uses the method and general assumptions published previously by SRI International. Additional information on sources used in this study may be found in the References.

II. ASSESSMENT OF CELLULOSIC FEEDSTOCK AVAILABILITY

The national petroleum-savings potential attributed to the ASU process is limited principally by the amount of cellulosic waste economically available as feedstock. While there is a great variety of such under-utilized cellulosic material generated in logging, industry, agriculture, commercial and domestic activities, a recent major study of the entire biomass resource base for alcohol fuels identified three major categories of cellulosic wastes: the cellulosic fraction of municipal solid waste, agricultural residue (principally corn stover and wheat straw), and wood residue (Reference 1). Together, these three waste streams present a total potential of about 778 million dry tons equivalent per year (1980). The projected maximum quantities available for each of these waste streams over time and by region are shown in Tables II-1 and II-2. The regional breakdown used in this data is indicated in Figure II.1.

About 70 percent of the cellulosic fraction of all municipal solid waste generated is considered sufficiently concentrated geographically for use as a process feedstock for plants of at least 500 - 1000 TPD capacity. The cellulosic fraction of municipal solid waste is assumed in this study to be delivered to the plant at a 20 percent moisture content after separation, cleaning, sizing, and densifying operations associated with densified RDF (refuse-derived fuel). An average ten-mile one way haul distance from the RDF preparation plant to the fuel oil conversion plant is assumed.

Agricultural residues are dominated in quantity by corn stover (typically 45 percent moisture) and wheat straw (typically 15 percent moisture content). An average moisture content of 35 percent is assigned to agricultural residues in this analysis. The resource base estimation considers that 35 percent of agricultural residues will always be returned to the soil, and that another 20 percent will be used as feed, used as fuel, or too dispersed for commercial collection.

Agricultural residues may not be available year round. The only attempt to include this issue in the present analysis is through parametric testing of the plant factor assigned to commercial ASU process plants. The apparent flexibility of the ASU process in accepting different feedstocks is a positive attribute, especially as compared with distillation-based alcohol fuel conversion technology.

Agricultural residues are assumed to be collected, cleaned, and sized. The technology to perform this function does not currently exist. Thus the costs taken from the Alcohol Fuels Policy Review (Reference 1) to represent these activities assume that such technology will be developed. A thirty mile average haul distance is assigned to agricultural residue feedstock.

TABLE II-1 ASU PROCESS FEEDSTOCK RESOURCE BASE

	Million Dry Tons Per Year			
	1980	1985	1990	2000
Municipal Solid Waste[1]	86	92	99	116
Agricultural Residues[2]	193	220	240	278
Wood[3]	499	464	429	549
TOTAL	778	776	768	943

[1] Clean cellulosic fraction, assumed for costing purposes to be similar to RDF (refuse-derived fuel)

[2] Comprised principally of corn stover and wheat

[3] Assume wood from silvicultural farms starting in 1995

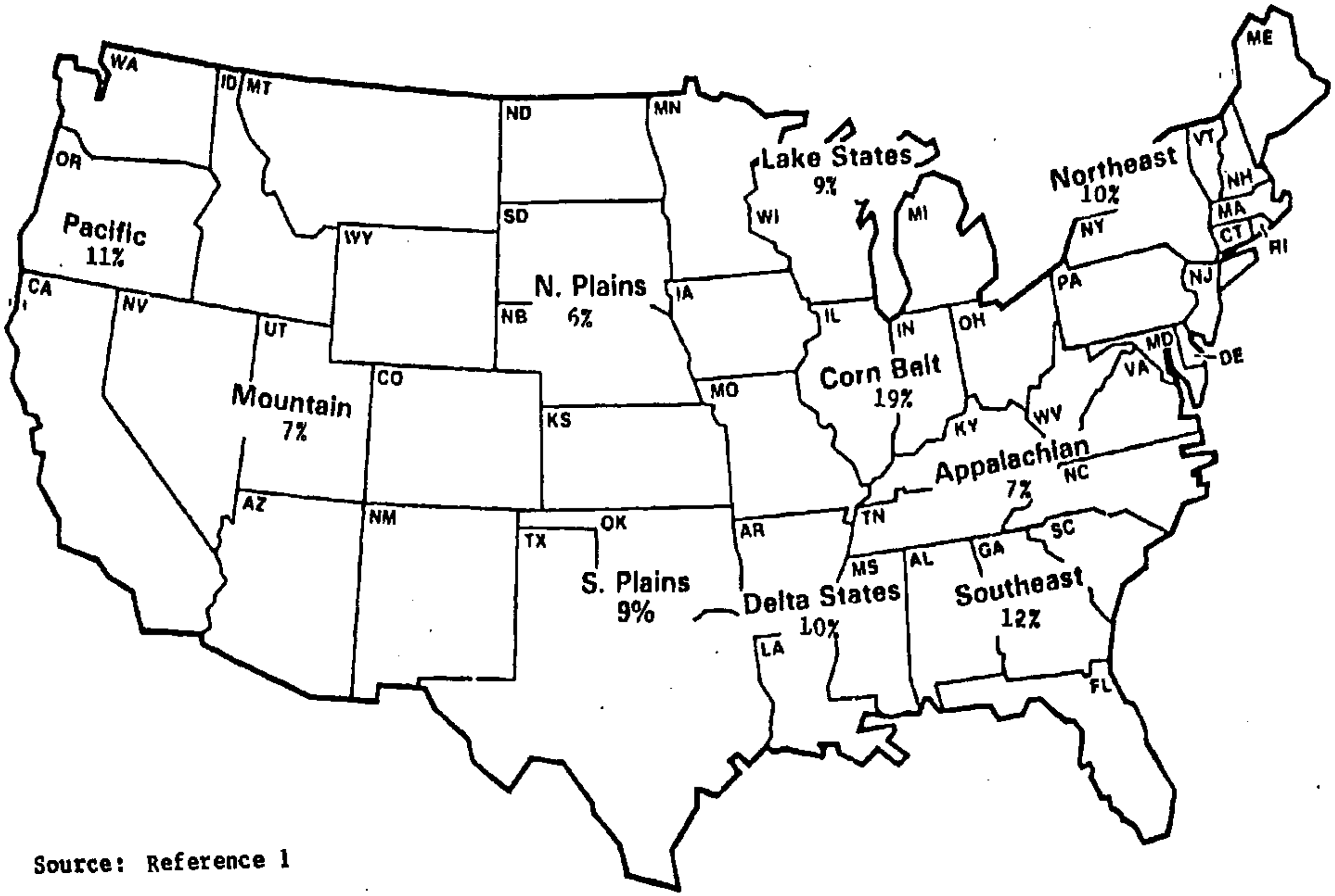
Source: Reference 1

TABLE II-2 PROJECTED U.S. CELLULOSIC FEEDSTOCK AVAILABLE FOR CONVERSION TO LIQUID FUEL -- BY REGIONS FOR THE YEAR 2000

Percent on a Dry Ton Basis

	MSW	Agricultural Residues	Wood	Total
Northeast	29	1	10	10
Southeast	14	2	17	12
Appalachian	--	--	12	7
Lake States	6	10	9	9
Corn Belt	17	42	8	19
Delta States	5	8	12	10
N. Plains	--	18	1	6
S. Plains	8	8	9	9
Mountain	4	5	9	7
Pacific	17	6	13	11
TOTAL	100	100	100	100

Source: Reference 1



Source: Reference 1

Figure II.1 Projected Percentage of U.S. Biomass Resources Available for Alcohol Production for the Year 2000

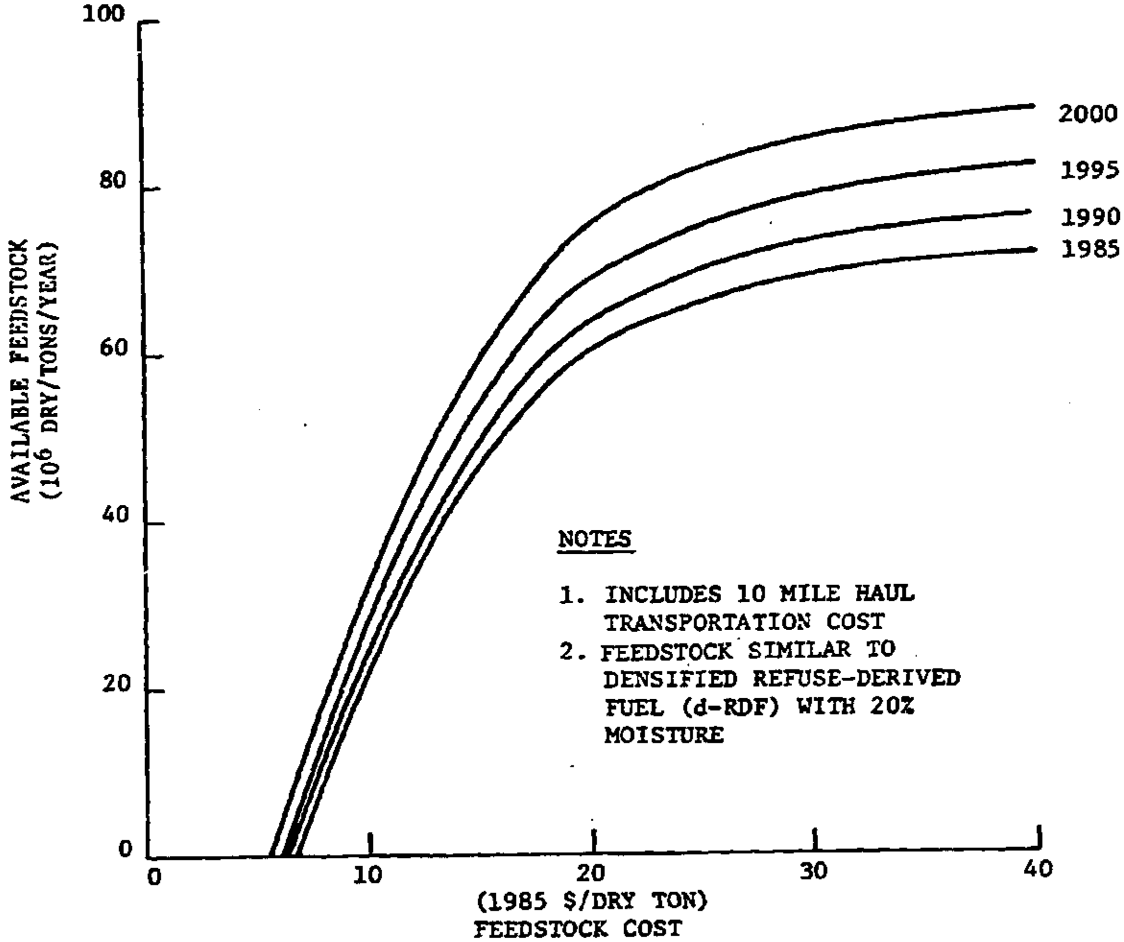
As a check on the assumed haul distance, consider that there are some 143,000,000 acres planted in corn and wheat in the U.S. It is estimated that the quantity of corn stover and wheat straw available at a cost of $20/dry ton in 1985 is about 60,000,000 tons/year, or 0.42 tons per acre-day. A 500 TPD conversion plant operating 260 days per year, then, would use the available residues at $20/ton from 309,833 acres, or about 484 square miles of planted fields. Assuming that in intensively grain farmed regions 20 percent of the land is planted in corn and wheat, this 500 TPD plant could be served by a surrounding area of 2420 square miles, which can be represented as a square with sides 49 miles long. Locating the plant at the center, the average over-the-road haul distance would apparently be on the order of 20-25 miles.

Wood potentially used as feedstock includes available mill and forest residues, surplus growth, annual mortality, and non-commercial timber. Silvicultural wood production is assumed to start in 1995, and to comprise nearly 50 percent of the available wood by the year 2000. These quantities exclude wood expected to be needed by the forest products industry. Costs for delivered wood feedstock include acquistion, collection, and transportation over an average 40 mile haul distance. Wood feedstock is assigned an average 50 percent moisture content. Again, delivered feedstock costs assume development of new technology for forest residue removal.

Figures II.2, II.3, and II.4 present supply curves adapted from Reference 1 for RDF, agricultural residues, and wood, respectively. The adjustments made to these curves consist of adding transportation costs taken from Reference 30 and converting costs to 1985 dollars at an assumed 8.0 percent inflator.

There is obviously considerable uncertainty in these supply curves, involving regional and feedstock aggregations as well as assumptions regarding technology development. Generally, the Alcohol Fuels Policy Review (Reference 1) associates greatest uncertainty with the agricultural residue curves, and progressively less uncertainty with the wood and RDF curves.

The cost range reported in Reference 1 for the cellulosic fraction of RDF and adjusted for use in this study appears corroborated by other sources on RDF preparation (References 4, 5, 6, and 8). A $6 per ton increase in the cost of delivered RDF is examined for its effect on the study results in Chapters III and IV.



Source: References 1 and 30

Figure II.2. Supply Curve — Clean Cellulosic Fraction of Municipal Solid Waste, Delivered