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August 1976

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FUEL AND ENERGY PRODUCTION BY BIOCONVERSION OF WASTE MATERIALS
State-Of-The-Art

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FUEL AND ENERGY PRODUCTION BY BIOCONVERSION OF WASTE MATERIALS

State-of-the-Art

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This state-of-the-art summary discusses biological conversion of solid waste, both municipal and agricultural, to fuels. Bioconversion holds promise of reducing the amount of solid waste which enters the environment and helping conserve valuable fuel resources. Such a summary provides the basis for designing research strategies and developing specific research programs in the field.

Francis T. Mayo, Director
Municipal Environmental
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ABSTRACT

This report is a state-of-the-art summary of biological processes for converting waste cellulosic materials (agricultural, municipal and lumbering wastes) to fuels. It indicates the locations and quantities of suitable wastes and discusses the status of the current processing schemes. The processes discussed are:

- acid hydrolysis followed by fermentation
- enzyme hydrolysis followed by fermentation
- anaerobic digestion of manure and municipal solid waste
- biophotolysis

Cost data for these processes are given and, where possible, compared. The range of cost was $1.39 to approximately $5.00 per million BTU of net energy output.

It was concluded that energy production by these methods on a national scale can, at best, produce the equivalent of only about 3 million barrels of oil per day by 1980. These may, however, be an economical and environmentally acceptable means of waste management which should be explored further.

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PREFACE

"The World's consumption of fuel has become so enormous as to show that our present supplies cannot possibly last for many generations more. Coal and oil are strictly limited in quantity and can never be replaced when once removed from the earth. As an alternative, alcohol is beautifully clean and efficient, and can be produced from vegetable matter of almost any kind. The waste products of our farms are all available, and even the garbage of our cities."

– Alexander Graham Bell, 1922.

EXECUTIVE SUMMARY

Current methods of disposal of organic solid wastes, principally land-fill or incineration, are becoming economically and environmentally unacceptable. By 1980, an estimated 1,061 million dry tons of organic solid wastes will be generated each year by municipalities, industry and agriculture. Recent trends in the management of these waste streams have emphasized energy resource recovery by a number of processes including bioconversion.

Bioconversion is the biological stabilization of organic wastes through the action of a living organism. Anaerobic digestion of cellulosic residues produces methane and carbon dioxide through the activities of at least three sets of bacteria. Alternatively, organic wastes can be biodegraded to glucose by the fungus, *Trichoderma viride,* and fermented to ethanol using yeast cultures. Bioconversion processes can be used to make single cell protein (SCP) from wastes, however this report concentrates on energy production by the two methods mentioned only.

Anaerobic digestion of manures has already been demonstrated as feasible for 350 head of dairy cattle on a farm in Michigan and is entering the commercial exploitation stage. Three firms have signed contracts to build plants processing tens of thousands of tons of cattle dung per year to produce methane for the energy requirements of the feedlots supplying the waste and/or to feed directly into local gas pipelines. The process looks economically favorable, producing methane at a gross cost of from \$1.39 to \$3.19 per 10^6 BTU's of net energy output. The Southeastern and Southwestern regions of the United States would be ideal areas to apply this technology for a number of reasons, including availability of wastes, potential market for methane and climatic conditions minimizing the need for external energy to maintain the digestion process.

Anaerobic digestion of municipal solid wastes (MSW) has not yet been demonstrated on a large scale, but negotiations are underway between Waste Management, Inc. of Illinois and the Energy Research and Development Administration (ERDA) to build a pilot plant digester in Florida. The gross cost of digestion of MSW is less attractive than combustion processes currently being utilized as the gross cost of producing pipeline quality methane, excluding any credits, is in the range of \$3 to \$5 per 10^6 BTU's of net energy output. An increase in the price of natural gas and expected shortfalls in its supply along the Eastcoast where the concentration of MSW is greatest, would make the Atlantic seaboard the target area for utilization of this technology.

Cellulosic wastes can be more efficiently hydrolyzed to glucose by the fungus, *Trichoderma viride,* than by sulfuric acid. Recent increases in the cost of producing ethanol from ethylene, due to the current energy crisis, have made the production of ethanol by fermentation very competitive. Improvements in the technology of fermentation, particularly the computer-monitoring of the

reaction, have made the design of large-scale fermentation plants feasible. The production of ethanol from organic wastes via glucose would substitute for fossil fuels currently used to derive a wide range of industrial chemicals.

It is not proposed that energy production from cellulosic wastes will solve the energy crisis, as the amount of energy produced would be equivalent to only 3 million barrels of oil per day assuming complete utilization of all of the solid wastes projected to be potentially available in 1980. However, the bioconversion of cellulosic wastes to produce energy is an economically and environmentally acceptable means of solid waste management that should be further explored and exploited.

Introduction

The purpose of this study is to provide the U.S. Environmental Protection Agency's Solid and Hazardous Waste Research Program with an overview of the status of bioconversion in this country so that an informed decision can be made relative to the feasibility of the U.S. Environmental Protection Agency undertaking a major bioconversion research program. The need for such a study arises from consideration of two seemingly unrelated problems: the magnitude of the current energy crisis and the increasing problems of solid waste disposal.

In the United States, the total energy input for 1970 was estimated at 68.8×10^{15} BTU's. Energy needs are expected to double in the next 15 years.[1] Current resources of fossilized fuels, with the exception of natural gas, are abundant but are not unlimited. This knowledge, together with the political energy crisis, has stimulated the search for alternative sources of fuel.

One possible source of energy is the reuse of the organic wastes that are at present causing an environmental problem. These wastes include municipal refuse – both garbage and sewage – agricultural crops and food wastes, animal manure from feedlots, forestry waste products, and organic industrial wastes. It is estimated that by 1980, 200 million dry tons per year of organic wastes will be readily available for energy conversion of a possible 1,061 million dry tons of waste generated,[2] (see table 1). The oil potential from these available wastes in 1980 is approximately 255.5 million barrels per year, which is equivalent to 70% of the crude oil imported directly from the Middle East in September 1973, or 2.2% of all energy consumed in the United States in 1970.

TABLE 1. ESTIMATES OF ORGANIC WASTES AVAILABLE IN THE U.S.[1] (millions of dry tons/year)

Source	Potentially Available		Readily Available		Types of Pollutants in Source
	1971	*1980*	*1971*	*1980*	
Manure	200	266	26	38	Toxicants, etc.
Urban refuse	129	222	71	104	Aluminum; Traces of Heavy Metals; Toxicants, Hydrocarbons, etc.
Uncovered logging and wood manufacturing residues	55	59	5	8	Insignificant
Agriculture crops and food wastes[2]	390	390	22	33	Pesticides, etc.
Industrial wastes[3]	44	50	5	8	Aluminum; Traces of Heavy Metals; Toxicants, Hydrocarbons, etc.
Municipal sewage solids	12	14	1	2	Toxicants, Hydrocarbons, etc.
Miscellaneous organic wastes	50	60	5	7	Toxicants, Hydrocarbons, etc.
TOTAL	880	1,061	136	200	
Equivalent Net Oil Potential,[4] million barrels/day	3.0	3.6	0	0.7	
Total Annual Cost of Foreign Imports Saved at $11/BBL	$12 Bil./Yr.	$15 Bil./Yr.	$1.5 Bil./Yr.	$2.2 Bil./Yr.	

Source: *EPA Wastes as Fuel Research, Development and Demonstration Program Plan,* USEPA, April, 1975.

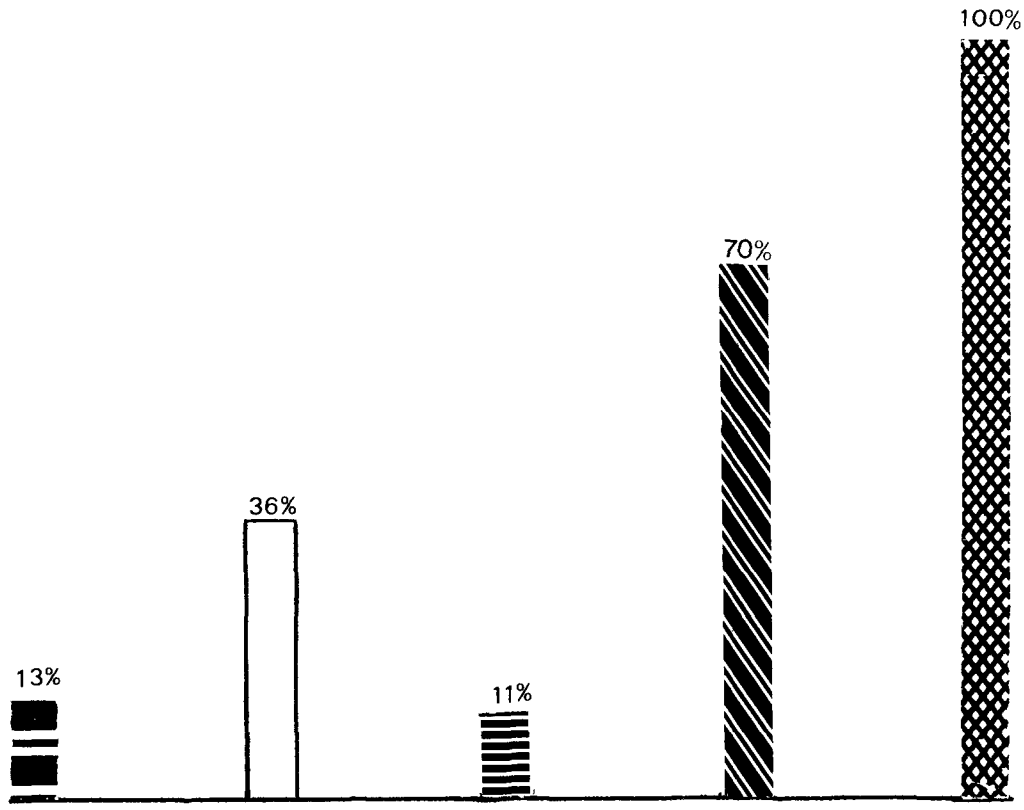
[1] L.L. Anderson, *Energy Potential from Organic Wastes: A Review of the Quantities and Sources,* U.S. Bureau of Mines Information Circular 8549, 1972.

[2] Assuming 70 percent dry organic solids in major agricultural crop waste solids.

[3] Based on 110 million tons of industrial wastes per year in 1971, of which about 40% were organics.

[4] Quantities of oil are based on conversion of wastes to oil by reacting carbon monoxide and water. Net oil produced gas based on 1.25 barrels per ton of dry organic waste.

FIGURE 1. PROJECTED AMOUNT OF ENERGY READILY AVAILABLE FROM MAJOR WASTE STREAMS IN 1980*



MANURE
MUNICIPAL SOLID WASTE
CROP RESIDUES
ALL SOLID WASTE
CRUDE OIL IMPORTED FROM THE MIDDLE EAST, SEPT. 1973

Based on oil imports of 1 million B/DOE
Quantities oil calculated using 1.25 barrels/ton of dry organic waste
* As a percentage of crude oil imported from the Middle East, Sept. 1973

Source of raw data: Table 1.

SECTION A. SOURCES, QUANTITIES, AND DISTRIBUTION OF THE MAJOR WASTE STREAMS

Agricultural Wastes

Crop Wastes

The generation of field wastes by major agricultural crops is high (an estimated 390 million tons in 1970)[3] but is generally spread over such vast areas as to make collection and utilization of these wastes an uneconomic proposition. Currently, the wastes are either burned in situ to kill topsoil micro-organisms, or left to prevent erosion, and to return humus and nutrients to the soil. Enforcement of pollution control regulations is limiting the former means of disposal.

Some residues are found in centralized locations, notably bagasse from sugar mills, corn cobs and stalks, milling wastes from wheat, rice, and other grains. The following maps (figures 2-7) are an attempt to locate these available crop wastes by state. While there is no conclusive proof that crop waste quantity is directly related to crop yield, the assumption is made that the greatest concentration of a particular waste is found in the states with the largest crop harvest.

The prunings from orchards and vineyards constitute problem wastes which may be incinerated or landfilled; incineration contributes toward air pollution, and landfilling may propagate plant diseases and insect pests.

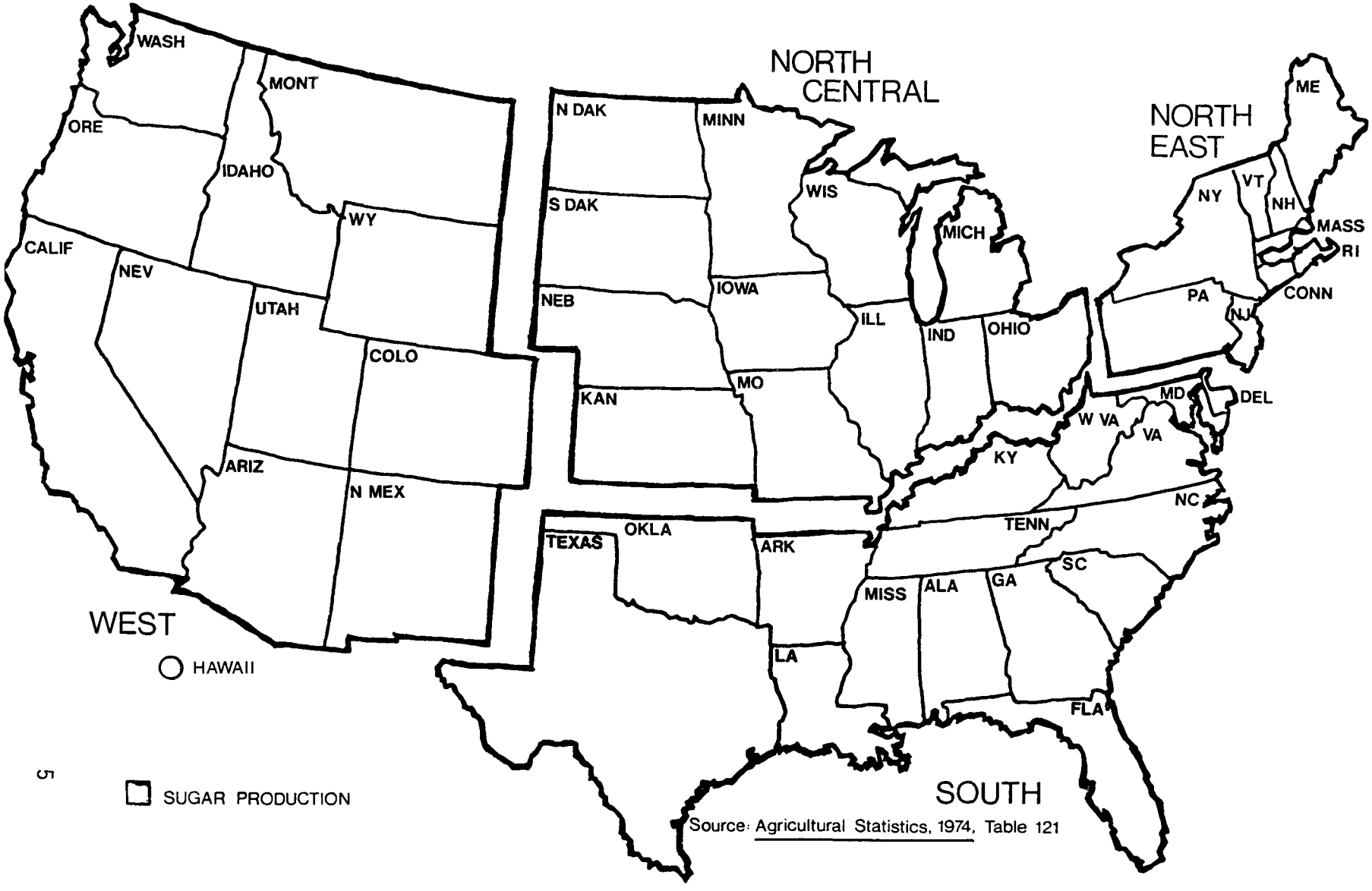
An extensive state-by-state inventory of all agricultural wastes will be concluded shortly at Stanford Research Institute. One report has already been issued;[4] the complete findings will be the most complete and accurate record of the nature, magnitude, and distribution of agricultural wastes across the entire United States.

TABLE 2. FIELD RESIDUES FOR A NUMBER OF SELECTED CROPS

Crop	*Billion/Pounds (Blb) of Residues (wet)*
Barley	36.7
Corn	376.0
Oats	58.5
Rice	13.4
Wheat	108.0
Sugar Cane	17.2
Total	**609.8**

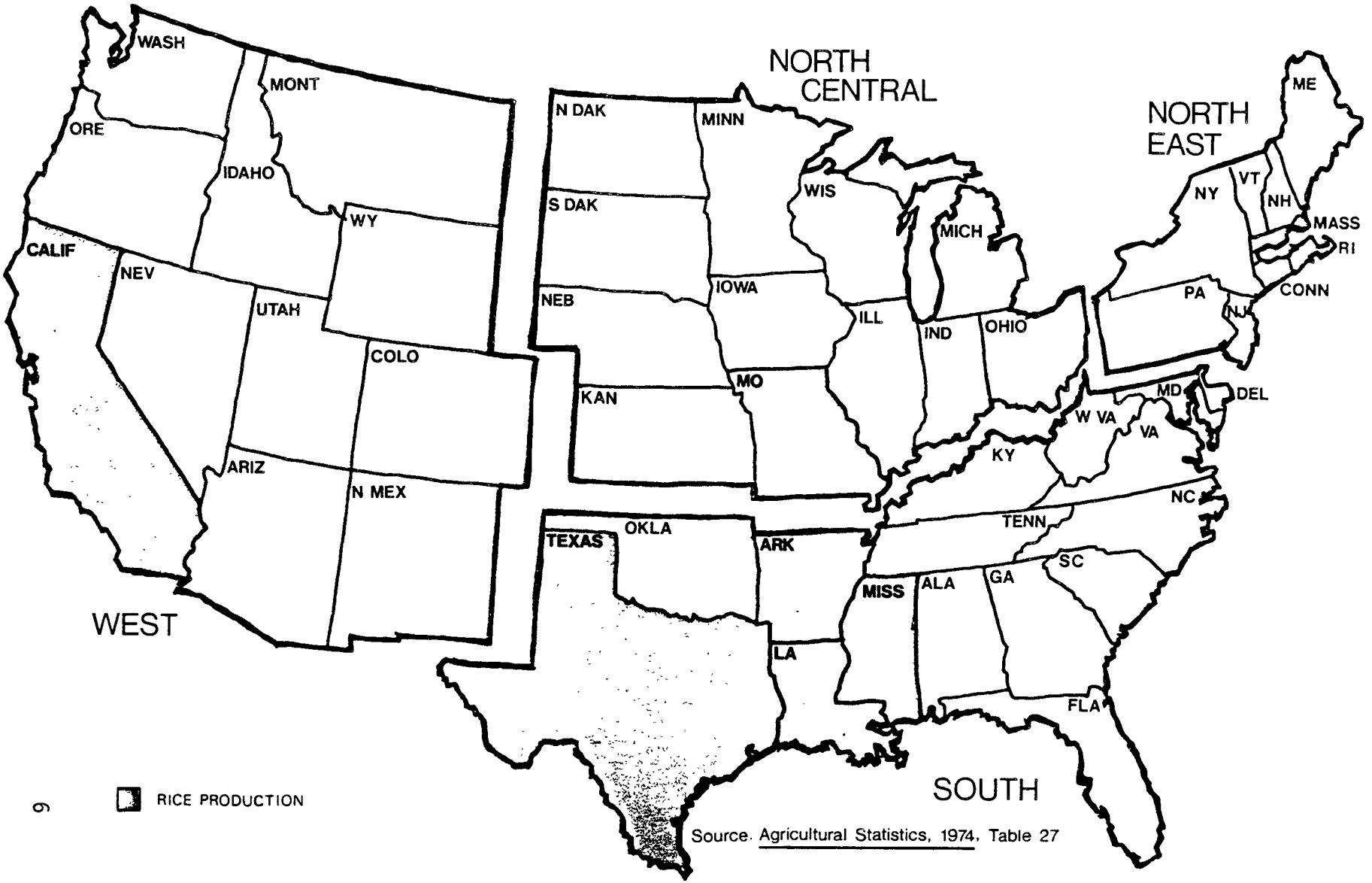
Source: *Problems and Opportunities in Management of Combustible Solid Waste,* IRT, D.C., October 1972, p. 27.

FIGURE 2. SUGAR CANE PRODUCTION IN THE UNITED STATES, 1973



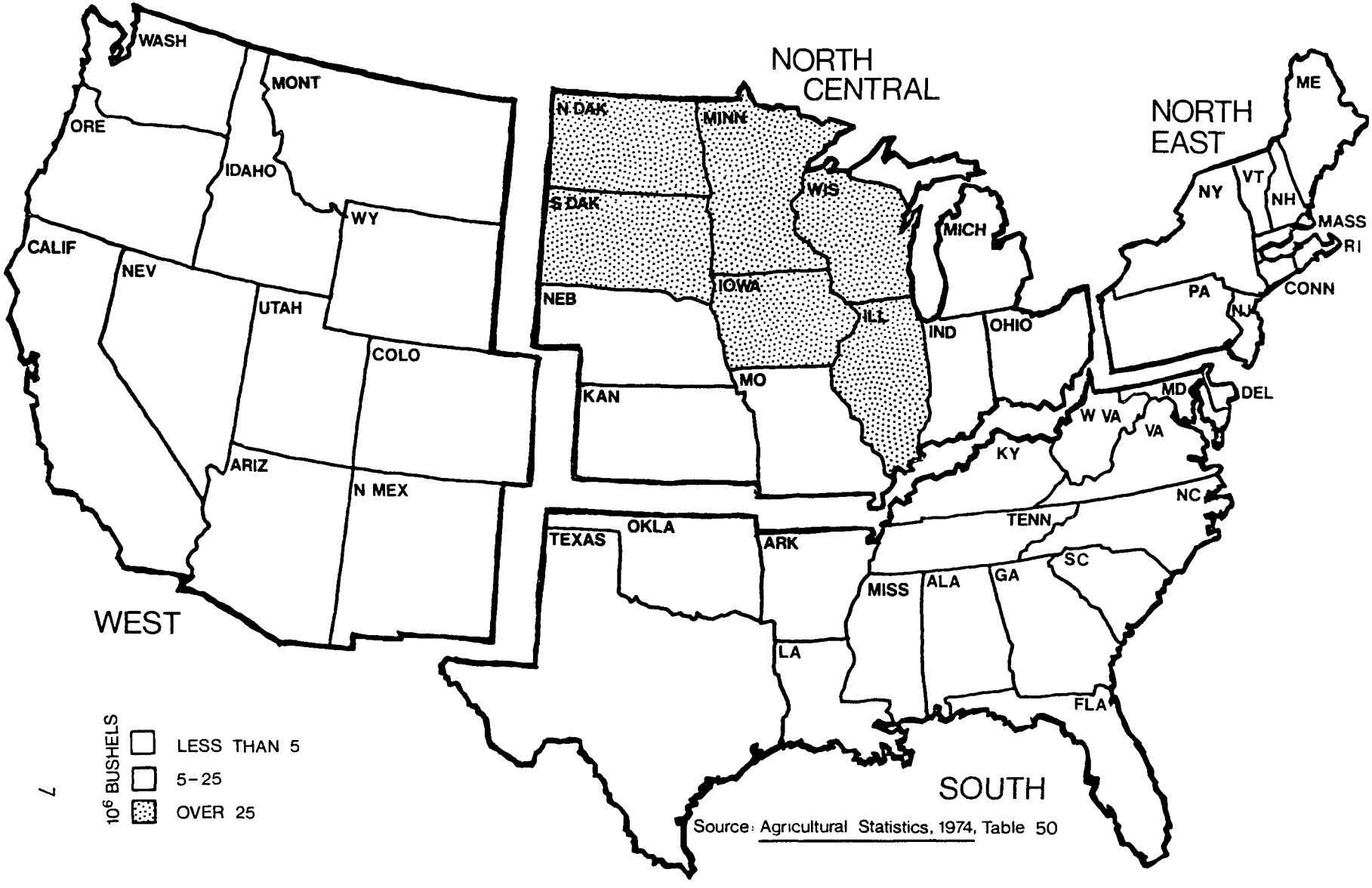
Source: Agricultural Statistics, 1974, Table 121

FIGURE 3 RICE PRODUCTION IN THE UNITED STATES, 1973



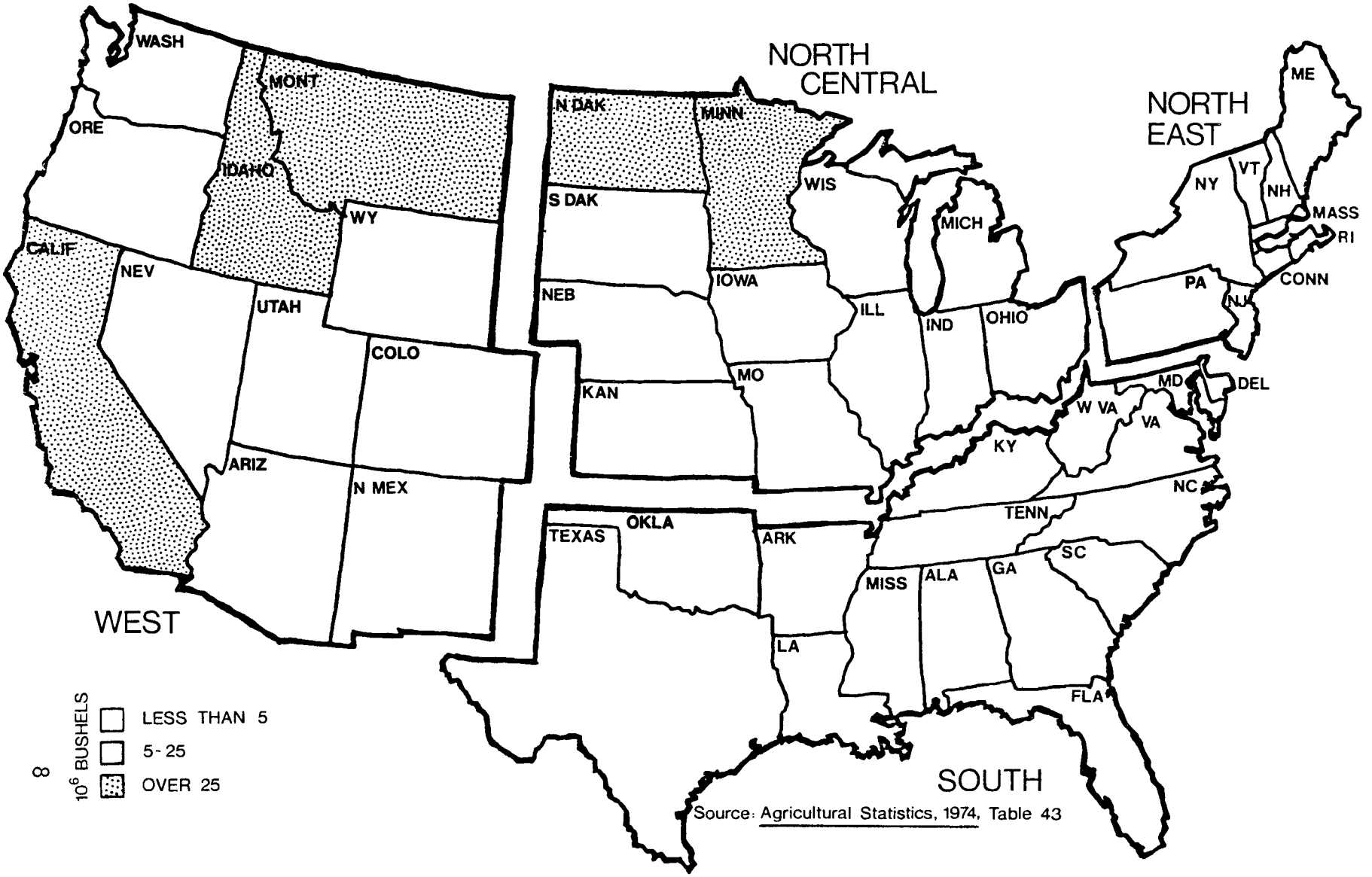
Source. Agricultural Statistics, 1974, Table 27

FIGURE 4. OATS PRODUCTION IN THE UNITED STATES, 1972



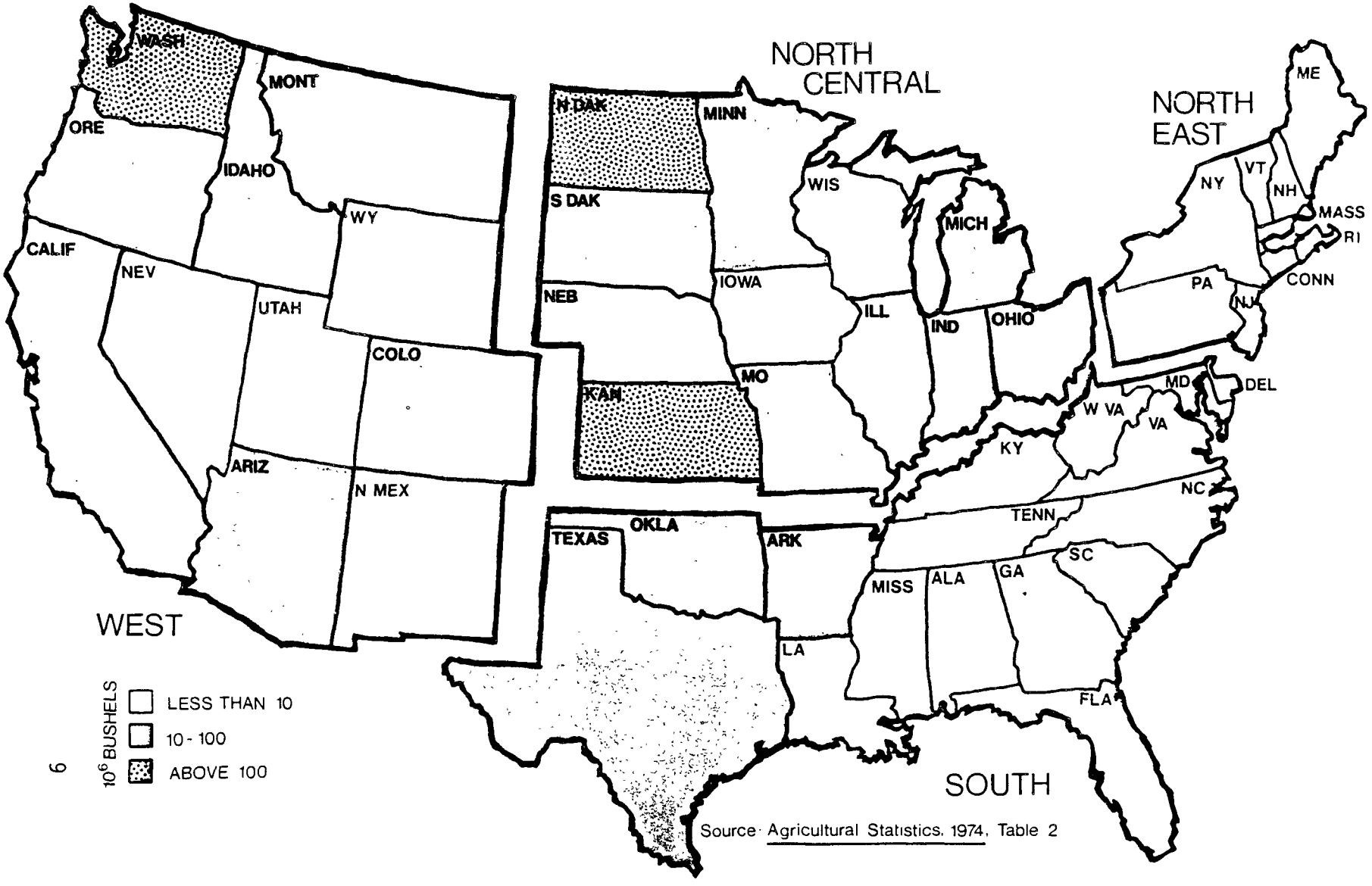
Source: Agricultural Statistics, 1974, Table 50

FIGURE 5. BARLEY PRODUCTION IN THE UNITED STATES, 1972



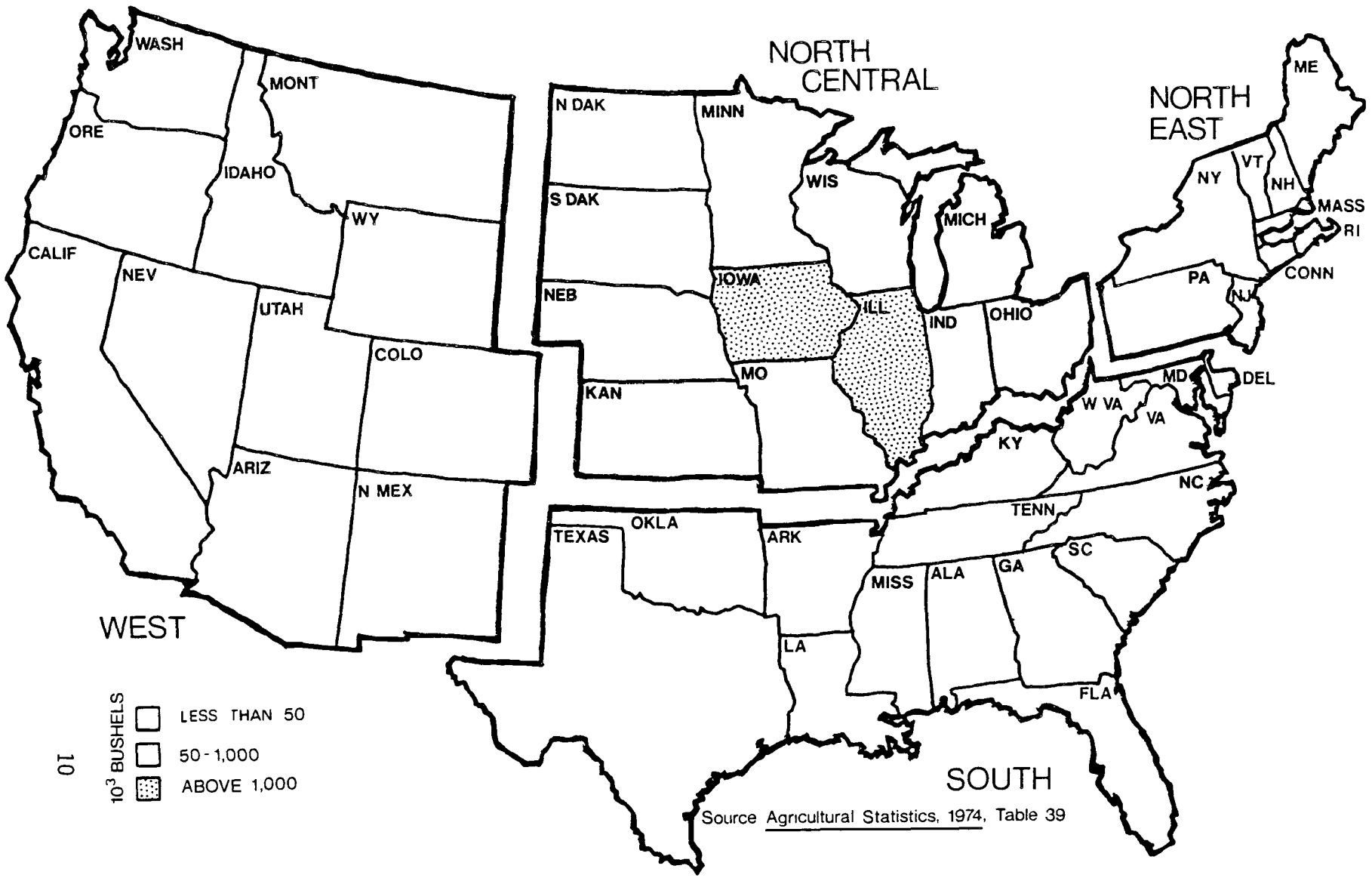
Source: Agricultural Statistics, 1974, Table 43

FIGURE 6 WHEAT PRODUCTION IN THE UNITED STATES, 1972



Source: Agricultural Statistics, 1974, Table 2

FIGURE 7 CORN PRODUCTION IN THE UNITED STATES, 1972



10

Source Agricultural Statistics, 1974, Table 39

Animal Wastes

Animal wastes were once valued as a fertilizer, but with the ready availability of the more convenient commercial fertilizers, and the concentration of large quantities of animals in feedlots, manures have become a disposal problem. Manures may be safely applied to land at a rate of 10 tons of waste per acre per year,[5] but land disposal of the thousands of tons of waste generated by cattle, swine, and poultry feedlots is obviously an impossibility. Animal wastes eroded from feedlots have been identified as the cause of fish kills and stream eutrophication. The Water Pollution Control Act Amendments of 1972 which applied to feedlots with a pollution equivalent of 1,000 head of cattle or more were judged to be illegal in court, March 1975, due to the size limitation requirement. Pollution control legislation will apply to all operations soon. The current costs of waste collection, storage, and disposal are high enough to make the possibility of offsetting costs through energy and/or protein production look very attractive.

By 1980, an estimated 266 million tons of manure will be generated per year. Not all of this is readily available for energy conversion. Estimates of the collectability of manures from different types of livestock have been made by the United States Department of Agriculture (USDA), Agricultural Research Service.[6] These estimates are based on the practicality of collecting and processing the wastes either on the farm, or a centrally located processing station (see table 3). Figures 8 and 9 are an attempt to indicate the locations of the greatest quantities of available cattle and poultry wastes, based on these collectability figures.

TABLE 3. ESTIMATED COLLECTABILITY OF EXCRETA FROM LIVESTOCK

	Class of Livestock	% Collectable
BEEF CATTLE	Beef Cows	0
	Cow Placements	0
	Other > 227 kilograms	90
	< 227 kilograms	30
DAIRY COWS	Dairy Cows	50
	Replacement Heifers	20
SWINE	Breeding	10
	Market Hogs	80
SHEEP	Stock Sheep	0
	Sheep & Lambs on feed	90
POULTRY	Laying Hens & Pullets	100
	Pullets & Other Chickens	100
	Broilers	100
	Turkey (growing)	50
	Turkey (breeder)	50

Source: Yeck, Robert G., *Recovery of Nutrients From Animal Wastes – an Overview of Existing Options & Potentials for Use in Feed,* Univ. of Illinois, April 21-24, 1975, p. 10.

TABLE 4. GAS PRODUCTION FROM ANIMAL WASTES

Kind of Animal	Gas* Productions (scf/day)	Energy** Value (BTU's/day)
1,000 lb. milk cow	40.00	20,000
1,000 lb. steer	30.00	15,000
100 lb. pig	3.00	1,500
5 lb. hen	0.30	150

Source: *Producing Methane Gas From Animal Wastes,* USDA Agricultural Research Service, August 1974, p. 3.

*an approximation based on multiplying waste production rates by a gas production of about 6 cu. ft./lb. of dry matter.

**for a gas of 50% methane, 500 BTU's/scf. of gas.

The percentage collectability is based on the practicality of collecting and processing wastes on the farm or a centrally located processing station. The 90% collectability figure for beef cattle weighing over 227 kilograms, refers to manure from cattle in feedlots, being fattened before slaughter.

FIGURE 8. DISTRIBUTION OF CATTLE WITH READILY AVAILABLE MANURE IN THE UNITED STATES, 1973

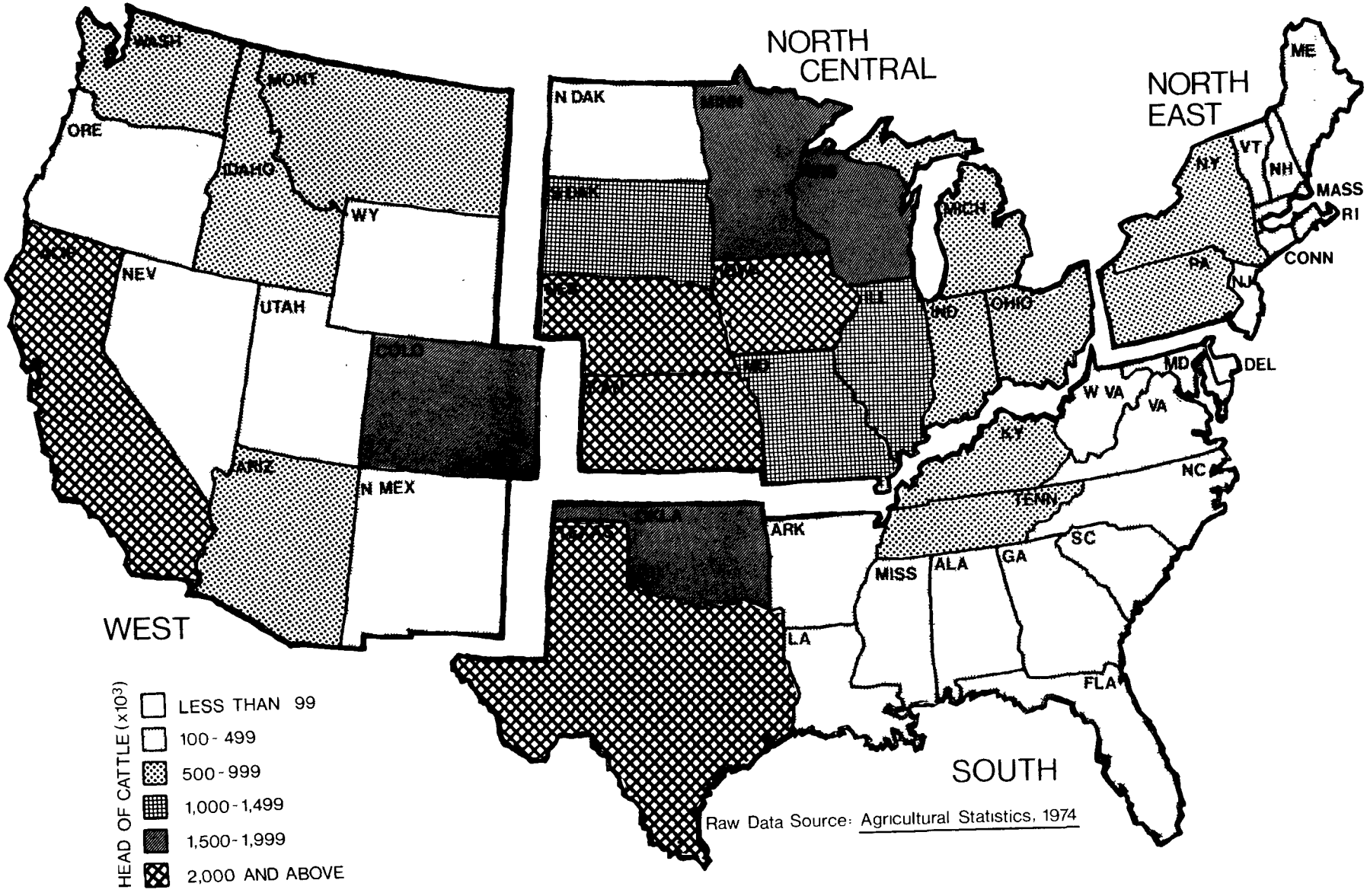


FIGURE 9. DISTRIBUTION OF POULTRY WITH READILY AVAILABLE MANURE IN THE UNITED STATES, 1972

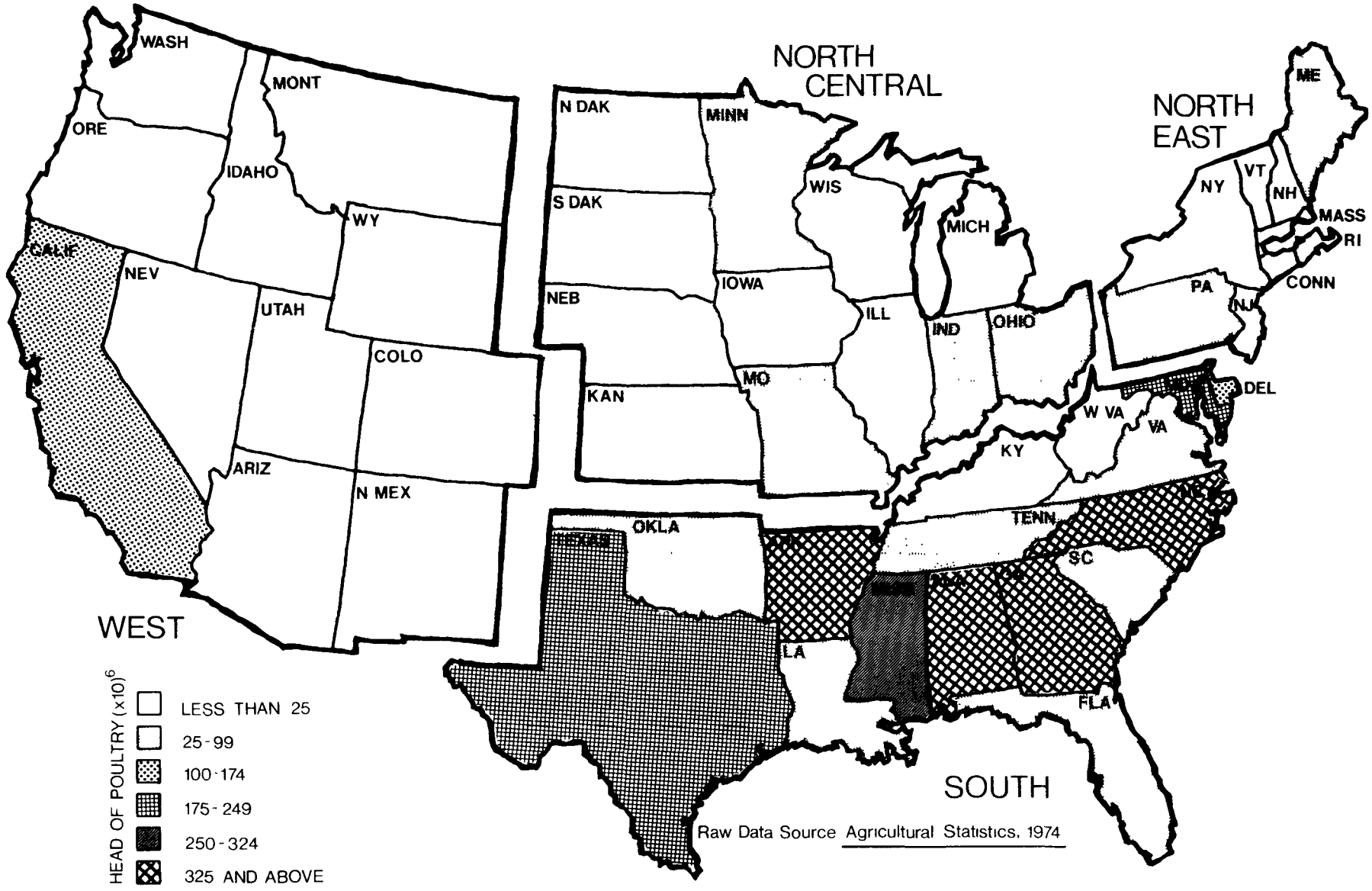


TABLE 5. LISTS OF MAJOR ANIMAL PRODUCTION STATES

Major Beef States (Feedlot Basis)*

1. Texas
2. Nebraska
3. Iowa
4. Kansas
5. Colorado
6. California
7. Illinois
8. Arizona
9. Minnesota

Note: The above nine states were responsible for over 80% of the total beef confinement in feedlots in 1973.

Major Swine States (Total Hog Basis)*

1. Illinois
2. Indiana
3. Iowa
4. Kansas
5. Minnesota
6. Missouri
7. Nebraska
8. Ohio
9. North Carolina
10. Georgia
11. Wisconsin
12. South Dakota

Note: The above 12 states are responsible for over 80% of all swine numbers in the U.S. in 1973.

Major Dairy States*

1. Wisconsin
2. California
3. Iowa
4. Minnesota
5. New York
6. Ohio
7. Pennsylvania
8. Texas
9. Michigan
10. Illinois
11. Mississippi
12. Kentucky
13. Florida
14. Indiana
15. Tennessee
16. Washington
17. Nebraska
18. South Dakota
19. Virginia

Note: The above 19 states combine 79% of all dairy cows and heifers that calved in 1973.

Source: Inman, Robert E., *An Evaluation of the Use of Agricultural Residues as an Energy Feedstock, Report* NSF/RANN/SE/GI-438597/PR/72/4, February 1, 1975, pp. 15, 16, 18.

Forestry Wastes

Logging residues produced in 1970 amounted to almost 1.6 billion cubic feet; 58% of the total were softwoods and 42% were hardwoods. While the residues are widely scattered over thousands of logging locations throughout the country, the greatest concentrations are found in Washington, Oregon, and Northern California. Of the total softwood residues of the entire United States, 36% are found in the forests of Western Washington and Oregon where slash-fuel weights range from 37 to 27 tons per acre.[7]

The volume of softwood residues generated in the South is much lower than in the West due to the presence of an expanding pulpwood industry utilizing most of the bole, and because the standing timber volume per acre is less than that in the West. Logging slash does not accumulate because the climatic and biotic factors in the area favor speedy decomposition. Hardwood residues are more numerous (over 400 million cubic feet) but are widely scattered.[8]

The accumulation of logging slash may be ecologically beneficial in a number of ways, but timber experts agree that physical removal of the slash would be acceptable if it could be accomplished with the minimum disturbance of soil or riparian habitats. Removal of logging slash discourages the growth of insect and rodent populations and is usually helpful in preparing the ground for seeding and planting. The appearance of timber harvest residues is considered by many people to be esthetically unpleasant and evidence of bad timber management. In the past, environmental groups have made it necessary to alter harvesting practices despite economic loss. The collection and utilization of these residues to produce energy would presumably be very acceptable to these powerful groups, but only if accomplished with the minimum of environmental disturbance.

TABLE 6. VOLUME OF LOGGING RESIDUES CREATED IN 1970 ON ALL FOREST LANDS

AREA	Volume Created in 1970		% of Totals by Specific Subgroup	
	Softwoods (million scf)	*Hardwoods (million scf)*	*Softwoods*	*Hardwoods*
North	62	222	7	33
South	263	421	28	63
Rocky Mountains	103	–	11	–
California	92	13	10	2
Pacific Northwest	404	16	44	2
(Douglas Fir sub-region)	(330)	(16)	(35)	(2)
(Ponderosa Pine sub-region)	(34)	–	(4)	–
(Alaska)	(39)	–	(4)	–
Total	924	672	100	100

Source: *Report of the Close Timber Utilization Committee,* USDA, Forest Service, June 28, 1972, p. 31.

Municipal Solid Wastes

EPA estimates that about 125 million tons of municipal wastes were generated from residential and commercial sources in the United States in 1971, (3.32 lbs per person per day).[9] By 1980, the U.S. National Average is expected to be around 3.91 lbs per person per day; and the Urban Area Average to be about 4.33 lbs per person per day.[10] The energy equivalent potentially recoverable from the Standard Metropolitan Statistical Area (SMSA), waste stream is projected to be about 1,085 trillion BTU's per year, the equivalent of over 512,000 barrels per day of oil equivalent (B/DOE) or 187 million barrels per year of oil equivalent (B/YOE), (see table 7). Note that this quantity is substantially higher than the estimate given in table 1, but represents a more recent evaluation of the amounts.

TABLE 7. ENERGY POTENTIALLY RECOVERABLE FROM MUNICIPAL SOLID WASTE, 1980

	BTU's (trillion)	Barrels/day oil equivalent (thousand)	B/YOE (million)
Theoretical	1,440	680	248
Available	1,085	512	187
Projected Implementation	85	40	15
Potential Candidates	558	263	96

Source: Lowe, Robert, *Energy Conservation Through Improved Solid Waste Management,* USEPA Report SW 125, 1974, p. 12.

TABLE 8. DETAILED STATUS OF RECOVERY SYSTEM IMPLEMENTATION, JANUARY 1975

Systems In Operation	Systems Selected*	Communities Committed**	Other Communities Listed in Report
Braintree, Ma	Under Construction:	Wilmington, De	Denver, Co
Charleston, WV		Dade County, Fa	Washington, DC
Franklin, Oh	Saugus, Ma	Minneapolis, Mn	Montgomery County, Md
Nashville, Tn	Chicago, Il	Milwaukee, Wi	Knoxville, Tn
St. Louis, Mo	Baltimore, Md	Akron, Oh	New York, NY
East Bridgewater, Ma	New Orleans, La	Housatonic Valley, Ct	Madison, Wi
	Bridgeport, Ct	Cleveland, Oh	Honolulu, Ha
	Ames, Ia	Palmer Township, Pa	Onondaga County, NY
		Memphis, Tn	TVA: Knoxville
	Construction Not Started:	Mt. Vernon, NY	Memphis
		Westchester County, NY	Asheville
		Albany, NY	Paducah
	Lowell, Ma	Lane County, Or	Muscle Shoals
	San Diego, Ca	Lawrence, Ma (See Commonwealth of Massachusetts)	Nashville
	New Britain, Ct		Houston, Tx
	St. Louis, Mo (expansion)		Montgomery County, Oh
	Monroe County, NY		Hackensack Meadowlands, Nj
	Hempstead, NY		Lexington, Ky
			Seattle, Wa

Source: Hopper, Richard E., *A Nationwide Survey of Resource Recovery Activities,* USEPA, SW-142, January 1975.

*Systems Selected – Winner of an RFP of construction contract awarded.

**Communities Committed – RFP issued, design study underway, or construction funding made available.

TABLE 9. POTENTIAL CANDIDATE AREAS (SMSA's) FOR ENERGY RECOVERY IN 1974
(With Potential Energy Recoverable Projected to 1980)

	Standard Metropolitan Statistical Areas	Population 1970 (thousands)
1.	New York, New York	11,572
2.	Chicago, Illinois	6,979
3.	Philadelphia, Pennsylvania	4,818
4.	Detroit, Michigan	4,200
5.	Washington, D.C. – Md. – Va.	2,861
6.	Boston, Massachusetts	2,754
7.	Pittsburgh, Pennsylvania	2,401
8.	St. Louis, Missouri	2,363
9.	Baltimore, Maryland	2,071
10.	Cleveland, Ohio	2,064
11.	Newark, New Jersey	1,857
12.	Minneapolis – St. Paul, Minnesota	1,814
13.	Milwaukee, Wisconsin	1,404
14.	Atlanta, Georgia	1,390
15.	Cincinnati, Ohio	1,385
16.	Patterson, New Jersey	1,359
17.	San Diego, California	1,358
18.	Buffalo, New York	1,349
19.	Miami, Florida	1,268
20.	Denver, Colorado	1,228
21.	Portland, Oregon	1,009
22.	Columbus, Ohio	916
23.	Providence, Rhode Island	911
24.	Rochester, New York	883
25.	San Antonio, Texas	864
26.	Louisville, Kentucky	827
27.	Memphis, Tennessee	770
28.	Albany, New York	722
29.	Toledo, Ohio	693
30.	Akron, Ohio	679
31.	Hartford, Connecticut	664
32.	Gary, Indiana	633
33.	Jersey City, New Jersey	609

TABLE 9 -- Continued

	Standard Metropolitan Statistical Areas	Population 1970 (thousands)
34.	Nashville, Tennessee	541
35.	Jacksonville, Florida	529
36.	Wilmington, Delaware	499
37.	Knoxville, Tennessee	400
38.	Bridgeport, Connecticut	389
39.	New Haven, Connecticut	356
40.	Peoria, Illinois	342
41.	Little Rock, Arkansas	323
42.	Chattanooga, Tennessee	305
43.	Madison, Wisconsin	290
44.	Rockford, Illinois	272
45.	Lawrence, Massachusetts	232
46.	Charleston, West Virginia	230
47.	Eugene, Oregon	213
48.	Brockton, Massachusetts	190
	Total Population, 1970	71,786
	Total Population, 1980	78,462
	Waste Generation, 1980 – Annual	62.0 Million Tons
	Daily	170 Thousand Tons
	Number of Equivalent 1,000 TPD Plants	170
	Energy Recoverable	558 Trillion BTU's Per Year
		263,000 Barrels Per Day of Oil Equivalent
		96 Million Barrels Per Year of Oil Equivalent

Source: Lowe, Robert, *Energy Conservation Through Improved Solid Waste Management,* USEPA SW-125, 1974, p. 18.

Note: Recoverable energy is a function of waste generation, which is a function of population.

In 1980, it is projected that almost 30 cities and counties around the country will be operating the equivalent of about thirty-six 1,000 tons per day (TPD) plants, recovering an estimated 85 trillion BTU's per year, (40,000 B/DOE, or 15 million B/YOE).[11] These communities have already taken steps toward implementing such an energy recovery system. Such steps include actual construction, solicitation of proposals, legislation to implement, or an active planning effort. Of these identified cities, 21 are considering or implementing the technology of using solid waste as fuel, 3 are interested in pyrolysis, and 4 in water wall incineration.

A number of additional communities have been selected from the SMSA's as having local conditions in 1974 which favor implementation of an energy recovery system by 1980.[12] These conditions are:

1. economics – high disposal and alternative fuel costs

2. market – available technology to implement the scheme

3. public interest – a high enough level of public interest will encourage energy recovery even though the economic conditions are unfavorable.

The public interest factor was identified as being strong(S), adequate(A), nominal(N), or opposing(O) resource recovery. Of over SMSA's screened, no active opposition was recorded and over 55% of the cities considered expressed strong or adequate interest. In the following areas, public interest in energy recovery was significantly more important than other factors in the decision to designate a SMSA as a potential candidate:

1. Denver, Colorado
2. Bridgeport, Connecticut
3. Peoria, Illinois
4. Chattanooga, Tennessee
5. Lawrence/Haverhill, Massachusetts
6. Portland, Oregon
7. New Haven, Connecticut
8. Madison, Wisconsin
9. Rockford, Illinois
10. Eugene, Oregon

Survey by International City Management

International City Management Association, Washington, D.C., conducted a survey of 2,000 cities in the United States with populations exceeding 10,000 to determine which of the cities had plans to develop a capital intensive resource recovery system in the next five years.[13] They found that of the 1,025 cities replying to the question, 166 or 16% had such plans and 859 or 84% did

not. Including those cities which did not reply, this gives a figure of over 300 cities entertaining plans for capital intensive resource recovery systems in the next five years.

There is a growing interest in the use of municipal solid wastes to generate energy, but it is likely that as the focus of interest is at present on non-bioconversion technologies, that these processes will be further implemented as more cities develop energy recovery systems. Bioconversion of MSW to produce methane would be particularly attractive along the East coast, which relies most heavily on imported fuels, and expects short falls in supply of natural gas this winter reaching as high as 15%. The Southeastern portion of the United States is probably more favorable than the Northeastern section as the higher temperatures, particularly in winter, would decrease the energy requirements of the digester. The digesters planned by Waste Management Inc. at Pompano Beach, Florida are to be added to the front-end resource recovery system already built. Other small cities with resource recovery systems might consider similar additions. The Southwest of the United States also seems an attractive area for digestion: the temperatures are high and, as anaerobic digestion does not require large quantities of water, the aridity is no deterrent.

It is clear from the results of the International City Management Survey that smaller communities do not have the same commitment to a capital intensive resource recovery system as the larger cities with the more acute waste disposal problem. It is possible that small towns in rural areas would react favorably to agricultural waste digestion units with a small capital outlay as sugar, corn logging and poultry wastes are plentiful in the Southeast.

POPULATION BREAKDOWN OF RESULTS

Population	No. of Replies	No. of Positive Replies	Percent of Positive	Number of Negative	Percent of Negative
Over 500,000	16	12	75	4	25
250,000 – 499,999	19	11	58	88	42
100,000 – 249,999	62	21	34	41	66
50,000 – 99,999	143	33	23	110	77
25,000 – 49,999	255	38	15	217	85
10,000 – 24,999	530	51	10	479	90

GEOGRAPHIC DISTRIBUTION OF INTEREST

Geographic Area	No. of Replies	No. of Positive Replies	Percent of Positive	Number of Negative	Percent of Negative
NE	219	50	23	169	77
N. Central	326	40	12	286	88
S	251	36	14	215	86
W	229	40	17	189	83

Source: International City Management, *1975 Municipal Year Book*, Washington, D.C.

Industrial Wastes

Wood Related. – Wood related wastes are generated at sawmills, and in the pulp and paper industries. Much of the sawmill wastes are used as a fuel, for the manufacture of pulp and paper, or for production of particle board and plywood. Primary wood manufactures in Oregon and Washington report up to 80-94% reuse of wood and bark residues. Even so, the total wood manufacturing and construction amounted to 29.42 B lb.[14] Projections into 1990 show certain areas in Washington, Oregon, North Carolina, Virginia, Massachusetts, and New York to have especially large concentrations of these wastes.

Pulp, paper and allied industries are employing a number of different chemical recovery cycles expected to bring about a 50%[15] reduction in wastes generated by 1990.

Other Industries. – Paper plant trash is generated in all manufacturing processes. Cellulosic wastes are produced by a number of industries, primarily the food, textile and clothing, paper and printing, and leather industries.

Much of the food wastes can be used as an animal feed. The food processing and canning industries are producing approximately 100,000,000 lbs. of waste per day with a potential yield of 10^9 cu.ft. of methane.[16] Both beet sugar and tomato cannery wastes have yielded about 8 cu.ft. of total gas/lb. of BOD.[17] The Western and Southern regions of the United States produce a large percentage of these food wastes.

Residues from textile and clothing manufacture are concentrated in the Middle and South Atlantic States, particularly in North and South Carolina and Georgia.

SECTION B. BIOCONVERSION PROCESSES TO TREAT CELLULOSIC WASTES (EXCLUDING PROTEIN PRODUCTION)

Waste Management with Reclamation of Energy

In the past the emphasis of waste management has been on disposal rather than reclamation, however, newer methods of management have emphasized the reclamation of waste materials both for inorganic and organic content. Energy may be obtained from organic refuse by a number of processes including:

1. Direct combustion to produce steam for heating or electricity
2. Cofiring with coal to produce electricity as at the St. Louis plant
3. Pyrolysis or destructive distillation to produce fuel oil, gas, and a carbon char or other products
4. Catalytic reduction to produce fuel oil
5. Bioconversion

Bioconversion is the biological stabilization of organic wastes through the action of a living organism—a fungus, yeast, alga, bacterium, or a fly. Given time, nature will accomplish the biodegradation of wastes. Landfills anaerobically digest the cellulose content of the fill to produce methane. The NuFuel Company has commenced methane recovery from the Los Angeles County Palos Verdes landfill and is negotiating for other landfill testing rights in California, Arizona, Illinois, New Jersey, New York and Pennsylvania. The Los Angeles Power and Water Department together with the city's Bureau of Sanitation are presently driving a 200 kw. electric generator by combustion of methane drawn from the city's Sheldon-Arleta landfill. The recovery of gas has its greatest potential from canyon fills in very dry climates, and cannot be considered to have great potential as an energy recovery system—particularly in the Northeast where the need is greatest, but the climate is damp and the landfills shallow. Methane recovery from a fill peaks after a few years and gradually declines.

The University of Florida is conducting preliminary experiments on the recovery of methane from anaerobic lagoons. The University of Minnesota is considering the possibility of covering an outside lagoon to determine if gases from the lagoon can be tapped as an energy source.[18] Anaerobic lagooning of hog wastes has been explored by Muehling at the University of Illinois in 1969. In 1970, Claybaugh suggested the use of a plastic bubble over a lagoon to collect methane for use on the farm.

Methane from landfills or lagoons is in a sense an after-thought to the process. Of much greater interest are technologies developed specifically to maximize energy production, notably anaerobic digestion to produce methane and hydrolysis and fermentation to alcohol. In addition to manufacture of methane and ethanol from cellulosic wastes, it is possible to produce protein for human and animal consumption by a number of different fermentation processes. Perhaps at some future date, the processes to produce food or energy will be in competition with each other for the reactant wastes.

Acid Hydrolysis of Cellulose and Fermentation to Ethanol

The bench-scale production of sugar by acid hydrolysis of municipal solid wastes has been investigated by the Thayer School of Engineering. The process can be accomplished in a continuous flow reactor to produce about 52-54% yield of sugar.[22] The reaction is carried out isothermally at 230° C using 1% weight of sulfuric acid and a reaction time of 20 seconds.[23] The yield was found to be a function of time of reaction, temperature, concentration of the acid and solid-to-liquid ratio in the slurry. As the hydrolysis conditions also favor the decomposition of the sugar, the maximum yield expected is 53% conversion of cellulose to sugar.

A hot slurry of wastes is mixed with sulphuric acid prior to entering the reactor, a 5 foot long steel tube. The temperature and pressure in the reactor are carefully monitored, and the products of hydrolysis are cooled in a quencher and collected at 25-30° C in a product accumulator. If the slurry is kept at 230° C for less than 15 minutes prior to entering the reactor, there is little thermal degradation of cellulose.[24] Difficulties experienced on the small scale could be eliminated on a larger scale; there is a definite need to study the kinetics of the reaction in a large-scale flow reactor.

For large plants, Converse et. al. assume the pretreatment of the wastes by possibly the FIBRECLAIM or HYDRASPOSAL process of the Black Clawson Company.[25] The HYDRASPOSAL process though more costly, was found to allow greater sugar yields per ton of initial raw refuse. The cost of the sugar produced was found to be dependent on the paper content of the MSW. Costs varied from under 2¢ to 4¢ per lb., (from 40% paper to 60%).[26]

Fermentation of the products of hydrolysis with the organism, *Saccharomyces cerevisiae,* in a 800 ml. fermenter gave yields of from 85-93% of ethanol after approximately 20 hours (rate achieved from molasses is about 80%).[27] The rate of fermentation increased with higher concentrations of sugar (from 4g/100mls. to 12g/100mls) but not the yields.

Cost analysis of the process shows that ethanol can be produced at a lower cost than the current market price.[28] The ethanol produced could be used as the starting point in the synthesis of a number of organic chemicals presently derived from fossil fuels, thus resulting in an energy savings. It should be noted that the Exxon Corporation's synthetic ethanol plant in New Jersey[29] recently closed because the equipment was old, and the ethanol could no longer be marketed at a competitive price. The Tennessee Eastman Company has ceased marketing synthetic ethanol, and absorb the alcohol they manufacture internally, as there is an increased demand as an intermediary for their own products.

Until recently, there has been little use of continuous fermentation on a large scale, due to difficulties in maintaining a sterile system, lack of knowledge of microbial behavior and chances for harmful mutation within the enzyme system. Knowledge advances in both the biochemistry and engineering of the system have made the design of large scale continuous fermentation plants feasible.[30] Computer coupled fermentation systems will provide immediate and continuous systems analysis permitting the regulation of environmental conditions within the fermenter, including oxygen transfer rate, homogeniety of nutrients, sterility and stability of the system.[31]

The firm of Microbic Operations[32] reports a zero failure rate in their system of fermenters; they apparently achieve an optimum inoculum for a 10,000 liter reactor by step up fermenters of 30 mls,100 mls. and 1,000 mls.

Georgia-Pacific Corporation chemical plant at Bellingham, Washington, has reported that it is converting spent pulp to high grade alcohol.

Enzymatic Hydrolysis of Cellulose

The world authorities in the field of enzymatic hydrolysis are the researchers of the Army's Natick Laboratories. However, other investigators are extending their inquiries, notably Dr. Wilke at Berkeley and the USDA Forest Products Research Laboratory in Madison, Wisconsin.

Researchers at Natick have developed a mutant strain of the fungus, *Trichoderma viride,*[33] which can manufacture enzymes to break down both the crystalline (C_1) and the amorphous form of cellulose (C_x). (see figures 10-13). The cellulases, of enzymes produced by the fungus to convert cellulose to glucose, will bring up to 90%[34] conversion of the cellulose fraction of waste materials in about 24 hours (6 hours for a feedlot substrate), depending on the nature of the substrate. The product—glucose—has many possible uses (see figure 14). Natick researchers estimate that the cost would be about 2¢/lb.[35] with credits for disposal costs and recycling of metals. Researchers at the University of California quote estimates of around 26¢/kg,[36] with ethanol fermented from the glucose at 8¢ per liter—about one-half of the current market price.

Enzymatic hydrolysis involves initial preparation of the enzymes by growth of *Trichoderma viride* on a starving diet of cellulosic wastes (0.75%) at 25-28°C and a pH carefully controlled to prevent hyperacidity.[37] The fungus produces enzymes to break down the cellulose molecule to sugar, which it then consumes. Once the broth has grown and the enzymes are in solution, the broth is filtered. The filtrate containing the cellulase complex is fed into the hydrolysis reactor where at 50°C and atmospheric pressure, the enzymes break down a cellulose rich slurry (pH 4.8) into sugar. After up to 24 hours, the syrup is harvested and some of the slurry is recycled. The economic bottleneck of the process is in the initial pretreatment of the wastes to break up the crystalline structure of the cellulose.

Researchers at Natick are investigating a variety of methods to prepare the cellulose for the enzymes. These methods include: chemical and/or physical means (ball-milling), ionizing radiation, ultrasonics and development of other enzymes. The feasibility study currently underway at the USDA Forest Products Laboratory includes an examination of this pre-hydrolysis step, in order to produce non-crystalline cellulose with better surface presentation for subsequent hydrolysis.[38] Dr. Erikson, in Finland, is concentrating on the removal of the lignin fraction which apparently shields the crystalline cellulose from attack by the C_1 enzyme.

The pre-pilot stage at present operating at Natick at a capacity of 1,000 lbs/month and interfaced with a computer for rapid data analysis and process estimation, will increase capacity

FIGURE 10. STRUCTURAL FORMULA OF CELLULOSE

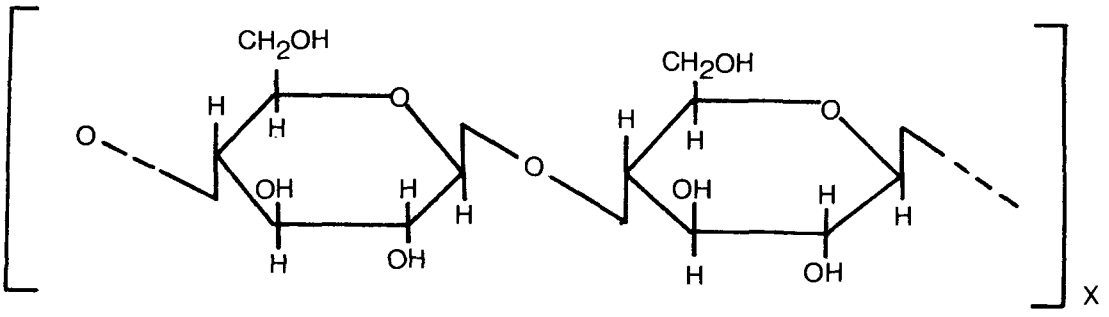


FIGURE 11. CELLULOSIC MICROFIBRIL[19]
(After Cowling and Brown)

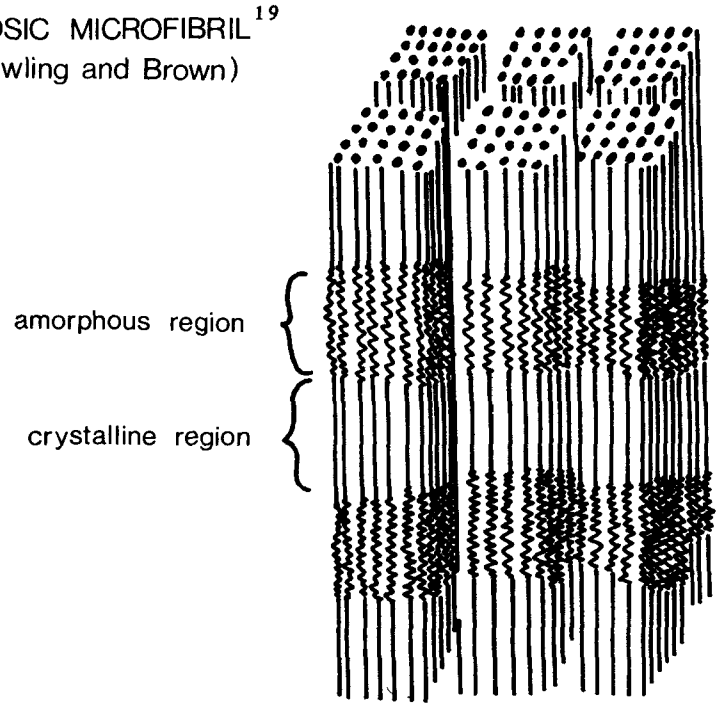


FIGURE 12. ENZYMATIC HYDROLYSIS OF CELLULOSE [20]

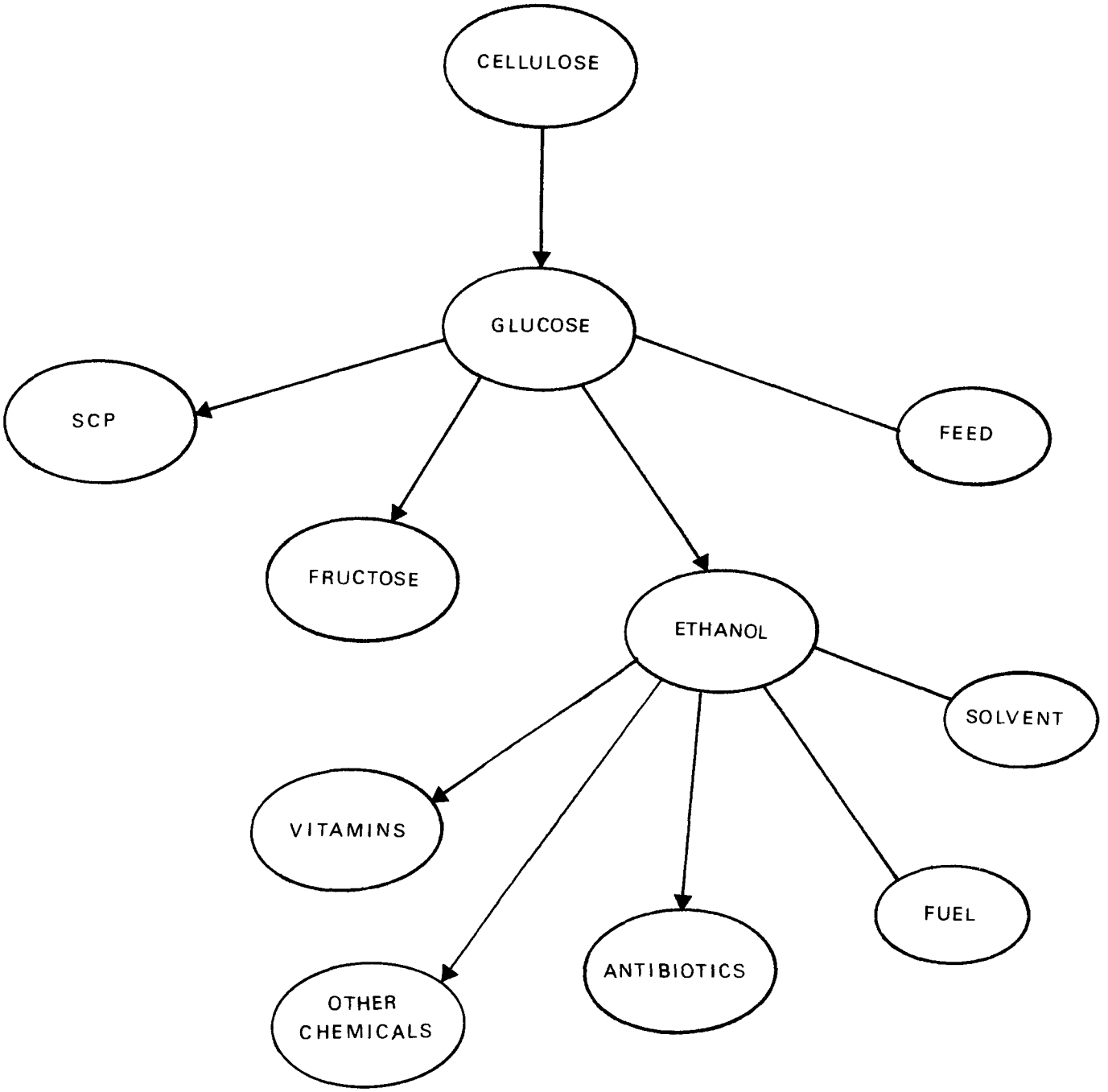
Native Cellulose $\xrightarrow{C_1}$ Linear Cellulose Chains $\xrightarrow{C_x}$ Cellobiose$^{\oplus}$ ⟶ Glucose

FIGURE 13. ANAEROBIC STABILIZATION OF COMPLEX ORGANICS [21]

Complex Organics ⟶ Organic Acids ⟶ Methane and Carbon Dioxide

$^{\oplus}$ CELLOBIOSE - A WATER-SOLUBLE DISACCHARIDE

FIGURE 14. PRODUCTS FROM HYDROLYSIS OF CELLULOSE



steadily to 4,000 lbs/month. Data collected will permit a scale-up to a larger unit. Current calculations indicate that as the scale goes higher, the kinetics of the reaction improve.

Enzymatic hydrolysis has a number of advantages over acid conversion of cellulose:

1. Expensive corrosion resistant equipment is unnecessary
2. Process conditions such as temperature do not have to be so closely monitored
3. The conversion can approach 90% compared to the 50% level recorded for acid hydrolysis
4. The process is not energy intensive

Another factor that makes this a potentially very attractive process is the complete utilization of the materials involved. In addition to using the sugar, the solid wastes from the fermenter, principally lignin, could be used as a fuel, and the fungus itself as an animal food if they could be harvested separately. It will be possible to buy the enzyme and conduct the hydrolysis at small local sites.[39] The research team in California reports that if the paper wastes generated per year were converted to ethanol, this country could produce 49 billion liters of alcohol per year, with energy equivalent to 10% of the annual gasoline production.[40] Even if the ethanol is not used as an automotive fuel, it is a valuable chemical feedstock. As the process is technically feasible, it is not unlikely that the large scale production of glucose from cellulose will be a reality by 1980.

Anaerobic Digestion

Introduction

The first recorded attempt to build a digester to produce methane from organic wastes was in India in 1900.[41] Since then, anaerobic digestion of human wastes has been extensively utilized, and the methane gas produced has been used for practical purposes in India, Taiwan, Africa and Europe. By 1963, over 70% of waste water treatment plants in the United States used anaerobic digestion to stabilize the organic fraction of liquid wastes. The process has been well used, but has a reputation for unreliability. The sensitivity of operation can be upset by design inadequacies in the plant, unskillful operation or heavy metal contamination in the feed. For some years, there was a decline in interest in the process, and incineration was thought to be the solution to sludge disposal.

The current burst of interest in biogasification research began in India in the 1940's, and led to the formation of the Gobar Gas Research Station and emphasis on village level production of methane by such men as Ram Bux Singh.[42] In the United States, economic and cultural factors emphasized the disposal of wastes rather than their use. The sludge and gas from digestion have been regarded as waste disposal problems. However, in some cases the gas has been used to power generators and pumps in the treatment plants. The Los Angeles Hyperion Sewage Treatment Plant generates enough methane from primary sludge treatment to power its 24-2,000 hp. diesel engines.

The following section summarizes current research interest in anaerobic digestion of municipal solid waste and animal manures in the United States. The process is essentially the same for either feedstock and involves biodegradation of the cellulose fraction of the wastes by at least three sets of bacteria, cellulolytic, acetogenic, and methanogenic bacteria. Initially the cellulose is converted to short chain volatile acids. The methane forming bacteria then convert the products of acidogenesis to a mixture of methane and carbon dioxide. (see figure 13). The compositions of both waste streams have been shown amenable to anaerobic digestion.

Anaerobic Digestion of Manures

It is well established that manures can be effectively digested anaerobically to produce methane gas. Important environmental and operational parameters are now being delineated to maximize the production/cost efficiency of the process as applied to cattle, swine and poultry wastes. Calculations made by Dr. W. Jewell at Cornell University indicate that anaerobic digestion is the most feasible method for converting cow manure to energy on a New York Dairy farm.[43]

The number of animals required to economically support methane generation from animal wastes has also been determined by Dr. Jewell and co-workers.[44]

TABLE 10. NUMBER OF ANIMALS REQUIRED TO ECONOMICALLY SUPPORT METHANE GENERATION TREATMENT OF ANIMAL WASTES**

ANIMAL	Number of Animals	
	Energy Only	*Energy and Nitrogen*
Beef	570	155
Dairy	380	80
Poultry	57,000	5,200
Swine	2,800	585

Source: Jewell, W. J.; Morris, G. R.; Price, D. R.; Gunkel, W. W.; Williams, D. W. and R. C. Loehr, *Methane Generation from Agricultural Wastes: Review of Concept and Future Applications,* presented by the ASAE, West Virginia University, August 18-21, 1974, p. 5.

TABLE 11. RELATIVE FEASIBILITY OF UTILIZING VARIOUS ENERGY RECOVERY PROCESSES TO CONVERT DAIRY COW MANURE TO USABLE ENERGY

Processes Capable of Capturing Energy	*Index of Feasibility Energy Recovery
1. Biological Aerobic Fermentation (ambient temperature)	5.5
2. Biological Anaerobic Fermentation (at a raised temperature)	14.7
3. Thermophilic Aerobic Digestion	
Dry Method	7.6
Slurry Method	6.8
4. Destructive Distillation	
Hydrocarbonization	3.6
Pyrolysis	3.5
5. Incineration	0.7

Source: Jewell, W. J., *Energy from Agricultural Waste – Methane Generation,* Cornell University, Agricultural Experiment Station, New York; p. 5.

Note: A high index indicates that the method is easier to implement and that a larger amount of energy will be available than with lower indices. Factors considered in arriving at the index were availability of technology, availability of full scale equipment, skilled operation, required operation time commitment, complexity of process and operation by agriculturally trained personnel.

They find that if the residues left after digestion are to be economically exploited as a fertilizer or feed for ruminants, in addition to the marketing of the methane produce, the number of animals to break-even becomes surprisingly small (see table 10). Other researchers support the conclusion that the economic potential of anaerobic digestion of manures lies in the selling of the residues. The limiting environmental and operational parameters differ, depending upon the source of the manure and diets of the animals providing the wastes. Much research is underway to identify the problem areas, and to resolve the technical difficulties. One point of interest is the effect of fermentation design on efficiency and cost.

Alternative Fermentation Designs

Completely Mixed (Mesophilic) Digestion. – The process currently applied to municipal sewage sludges. The waste is immediately and uniformly digested from periods of 15-30 days and temperatures of 30-40°C. The effluent is withdrawn at a rate equal to the inflow rate to maintain a constant volume. Mesophilic digestion has produced yields of from 1.3 scf methane/lb. of dry matter to 3 scf methane/lb.[45] Optimization of conditions produces yields double this value for cattle manure. Hog wastes have produced from 7.7 to 16.8 scf of total gas per lb. of volatile solids destroyed, with 60% methane.[46]

Completely Mixed (Thermophilic) Digestion. – Operates above 50°C with additional energy expenditure. Investigators at the Northern Regional Research Center, USDA, under the direction of Dr. Rhodes, have developed this process to produce yields of about 4 scf methane/lb. of dry matter (cattle).[47] Several important challenges imposed on their fermenters have significantly added to understanding of the process:

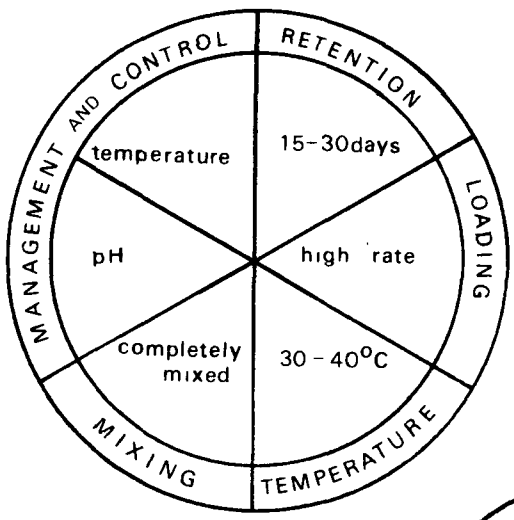
1. They have operated a stable digester with loading rates as high as 16 g. volatile solids/liter/day (commonly quoted, c.f. 1.6-3.2 g/liter/day)[48]
2. Recirculation of the effluent gas has quickly improved the health of failing fermenters.
3. Pretreatment of the feed material with sodium hydroxide (up to 8% solution) with neutralization prior to digestion increases the solubilization of the lignin fraction of the wastes. There are indications that solubilization is a major rate limiting factor.

Partially Mixed (Liquid Displacement). – The capital and operational costs are lower than the completely mixed process but the biodegradation and gas production are also less.

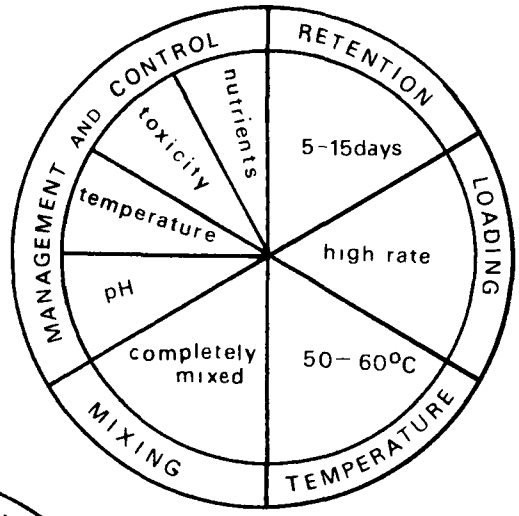
The Batch Load Digester. – Employs two completed mixed reactors, one of which ferments while the other is fed, resulting in an increase in efficiency. Like the completely mixed process, it is necessary to premix and dilute the manure with an increase in capital and operational costs. However, there is also an improvement in biodegradation and gas production.

The Plug Flow Longitudinal Reactor. – As planned for use by the Montford Feedlots involves no intermixing of the contents of the digester. Costs are lower but so is gas production and end-stablization rate.

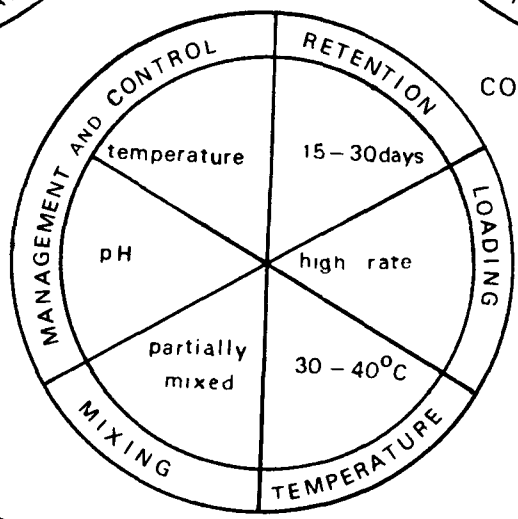
FIGURE 15. ALTERNATIVE ANAEROBIC FERMENTATION DESIGNS



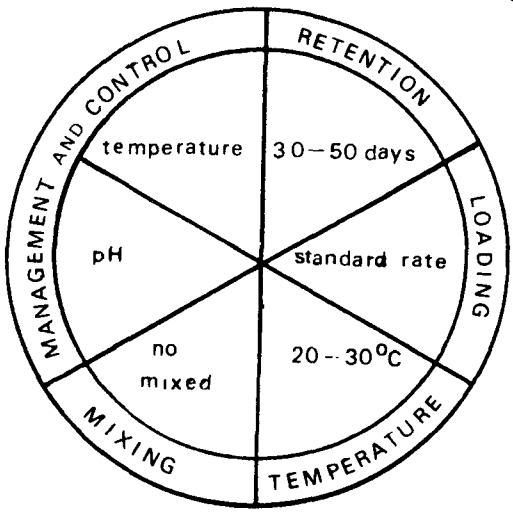
COMPLETELY MIXED(MESOPHILIC)



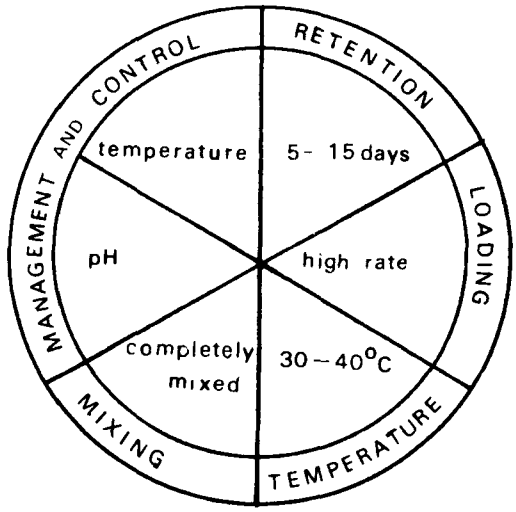
COMPLETELY MIXED (THERMOPHILIC)



PARTIALLY MIXED



PLUG — FLOW



BATCH

Source of original information: MORRIS, Gary R. et al., ALTERNATIVE ANIMAL WASTES ANAEROBIC FERMENTATION DESIGNS AND THEIR COSTS, Cornell University, 1974

Several commercial animal/gas production units are under construction:

(a) *Calorific Recovery Anaerobic Process Inc. of Oklahoma City* has signed a contract with Natural Gas Pipeline Company of America, Chicago, to provide gas generated from cow dung at a plant to be built in the Oklahoma Panhandle.

(b) *ERA Inc., Lubbock, Texas* signed a contract in June 1975, to provide Natural Gas Pipeline Co. with 650 million cu.ft. of methane per year from 80,000 tons of cow dung at a base price of $1.30 per thousand cu.ft.[49] ERA has plans for building approximately 40 large manure-to-gas plants in feedlots around the country, if the Texas plant proves feasible. The Texas plant will cost an estimated $2.6 million. The cost of the mathane is higher than current domestic natural gas prices, but below other forms of synthetic and natural gas currently being developed. Deregulation of domestic natural gas prices will make a significant difference for all forms of anaerobic digestion. The digesters will employ completely mixed mesophilic digestion to produce about 60% methane. The company also sees application of their process to municipal solid wastes, wood slash, etc. Patents are pending.

(c) *Skelley B. Don & Associates of Denver* will build a $4 million plant to gasify manure for the Montford Feedlots. The plant is slated to have a capacity of 120 million cu.ft./month of methane, 70 million of which will go to Montford to meet its gas needs.[50] The remainder of the gas will be sold to Colorado Interstate Gas, and fed directly into their pipeline less than a mile from the site. The carbon dioxide produced in the process will be used for the manufacture of dry ice. Montford will take back the digested sludge at 50% moisture for use as a fertilizer. The plant which will be completed by 1976 is based on the Plug Flow design of digester.

(d) *Jerry Malstrom of Ludington, Michigan* has built the largest digester of manures now in operation. The digester, at present operating below capacity (350 head of cattle), produces between 20,000-22,000 cu.ft. of gas daily from around 220-250 head of cattle. The digester, which is fully automated, is loaded once a week and provides electricity for use on the farm. Mr. Malstrom sees the break-even point as 100 head of dairy cattle. His firm is now designing a 2 1/2 million turkey digester.[51]

(e) *The University of Wisconsin* is associated with a commercial digester which ferments the wastes of 100-150 horses. The biogas is burned directly for space heat, but electrical generating capacity will be added at a later date.[52] The University also has plans for two fowl-manure digestion units.

(f) *Tennessee State* is just completing construction[53] of two steel 2,000 gallon digesters to ferment the wastes from 60 head of cattle at a packing plant. The gas which will initially be burned off, will eventually power an electric generator. Laboratory findings have emphasized studies of the nutritional value of the sludge and the possibility of ground contamination after land disposal of the sludge.

Anaerobic Digestion of Municipal Solid Wastes

After several years of laboratory-scale investigations, Dr. Wise, Dr. Kispert and co-workers at Dynatech have completed an economic analysis of a pilot plant facility to process one ton per day of municipal solid wastes. The plant has not yet been constructed. The conceptual design involves

four major sub-systems: a feed preparation and storage sub-system, mixing tank and mesophilic digester, scrubbing and dewatering sub-systems.[54]

After being dumped, the refuse passes through a hammermill shredder to reduce particle size and facilitate removal of the inorganic fraction and into a magnetic separator to remove ferrous metals. A revolving screen picks out the other metals and glass, and an air classifier completes separation of the light organic fraction to be fed to a mixing tank. A 12% slurry is fed into the circular concrete digester with lime for pH control, and sewage sludge with nitrogen and phosphate chemicals for nutrients. Floating covers on the tank maintain a constant internal pressure. The gas produced is sweetened by MEA contact and the remaining liquid dewatered by vacuum filtration. The cake produced can be incinerated to provide heat for the digester, a portion of the filtrate is recycled to the front end of the digester and the excess is sent to a sewage treatment plant.[55]

Thirty-nine percent of the energy consumed in the process is used in the scrubbing and drying stages and 21% of the cost. For a 1,000 TPD facility, this process could yield 3.7×10^6 cu.ft./day of pipeline quality methane, the energy obtained amounting to about 2 2/3 the energy consumed. Such a plant, corresponding to a population of approximately 1/2 million, could provide 9% of the gas consumed locally; or if exploited in all SMSA's, this size and above, 1 1/2% of the entire gas consumed in this country last year.[56]

The largest digester presently in operation is the 400 liter tank designed by Dr. John Pfeffer at Urbana, Illinois. This digester is Batch operated at between 55-60°C with retention for ten days to produce about 6 1/2 cu.ft. of gas/lb. of volatile solids added.[57] Lime, sewage sludge and nitrogen and phosphorus chemicals are added. A major problem of the process is in handling the slurry from the digester. Addition of ferrous sulphate and polymers to the residues, followed by loading on a centrifuge, produces a relatively clean liquid. Dr. Pfeffer has conducted calorimeter tests with the dry cake to investigate the feasibility of incinerating the solid residues. The heat content of the cake approaches 10,000 BTU's/lb. volatile solids, which for a 1,000 TPD plant amounts to 90-100 million BTU's/hr. as steam. To improve the economics of the system, the cake residue must be dry enough for incineration. The centrifuges probably will have to be sized on the basis of solids loading rather than liquid loading. The high concentration of solids in the slurry will overload the solids handling capacity of the machine if it is sized on the basis of liquid flow rate.

One major attempt to improve the biodegradability of cellulose (currently 50-55% conversion)[58] is underway at Stanford University, where Dr. McCarty is concentrating on the efficacy of prior heat treatment of the wastes from 25-250°C and pH values from 1-13.[59] Conditions of extreme acidity and alkalinity improved the solubilization and biodegradability of the previously digested refuse provided by Dr. Pfeffer. Current research has evaluated temperatures up to 133°C; the biodegradability of the predigested refuse nearly doubled after treatment at 133°C for 3 hours at pH 1. This is a 12%[60] increase in overall biodegradability of undigested refuse. High pH treatment might be preferred as the alkali added would be useful for pH control during digestion.

The Institute of Gas Technology, Chicago, is also working with anaerobic digestion. Their

investigators believe that the gas yield and production rate increase exponentially as particle size decreases from 1 in. to less than 1 mm.[61] They prefer the mesophilic variation, siting an improvement in gas yield and quality at the lower temperatures. They have also proposed a method where digestion takes place in two stages in order to promote the individual growth requirements of the different sets of bacteria.[62] Research involving two-phase digestion is also underway at the University of Pennsylvania.

It is obvious that some work is still to be completed before the commercial possibilities of this process can be fully exploited. It is necessary to perform a proof-of-concept experiment to establish the performance of a large digester. Operational and environmental parameters establishing a much greater conversion factor must be sought, including large-scale comparison of the mesophilic and thermophilic temperatures. A less expensive scrubbing process and residue handling system would make for a more healthy economic picture.

Waste Management Inc., Oakbrook, Illinois, with subcontractors, Jacobs Engineering, have signed a preliminary contract with ERDA to initiate the full design and construction plans for two digesters, to be added to the front end assembly of their existing resource recovery facility located in Pompano Beach, Florida. The digesters will process 50-100 TPD of municipal solid waste, and be operational within two years.

Two firms who believe they have solved some of the stated problems are Penn-State Engineering and Rec-Tech of Pennsylvania. They have approached pipeline companies in the area with a proposal to build a prototype digester to process a minimum of 250 TPD of municipal solid waste. The firms, hopefully, intend to produce 95% pure methane through modification of the mesophilic process, employing high loading rates of a 12% slurry, and a closed loop system to recirculate the initial effluents several times. The uniqueness of the process, which will permit marketing of the methane at $2-2 1/2 per thousand cubic feet, is in the repeated circulation of the effluents, and in removal of carbon dioxide.[63] Patents are pending on this process.

TABLE 12. ADVANTAGES AND DISADVANTAGES OF ANAEROBIC DIGESTION OF CELLULOSIC WASTES

Process	Advantages	Disadvantages
Anaerobic Digestion	1. methane production	1. explosive gas
	2. sludge has undiminished value as a fertilizer	2. high capital costs
A. Manures	3. sludge has potential as a feed	3. costs of producing pipeline quality methane
	4. not necessary to dry wastes	4. still large volume of sludge to dispose of if proved unmarketable
	5. odor free sludge	5. temperature sensitive to operate
	6. sludge does not attract flies and is biologically stable	6. energy requirements
	7. prepares sludge for final disposal	
	8. adaptable to rural areas (farms)	
B. Municipal Solid Waste	1. ready market for methane	1. capital costs high
	2. offsetting waste disposal costs by marketing of reclaimed materials	2. large scale digestion not yet demonstrated
	3. possible incineration of cake residue to defray costs	3. only 50% conversion of solids to gas
	4. partial stabilization of the organic fraction accomplished before disposal	4. still necessary to treat and dispose of the sludge
		5. sensitive to operate
		6. large volume of material still to be disposed of
		7. necessary to remove CO_2

TABLE 13. ADVANTAGES AND DISADVANTAGES OF HYDROLYSIS AND FERMENTATION OF CELLULOSIC WASTES

Process	Advantages	Disadvantages
Enzyme Hydrolysis and Fermentation	1. up to 90% conversion of cellulose 2. glucose is easy to store 3. careful operation not needed 4. not an energy intensive process 5. ethanol has a possible use as a fuel 6. alternate route to chemicals now made from fossil fuels, therefore conserving resources 7. complete utilization of wastes, lignin in sludge has possible use as fuel 8. yields of scale-up predictably reliable 9. products can be cheaply produced	1. initial pretreatment of refuse still to be optimized 2. large scale demonstration still required 3. limit to possible markets for products(?)
Acid Hydrolysis and Fermentation	1. glucose is easy to store 2. ethanol has possible use as a fuel 3. alternate route to chemicals now made from fossil fuels 4. costs of sugar and ethanol highly competitive	1. corrosion resistant equipment needed 2. careful regulation of temperature and pH required 3. only 50% conversion 4. treatment of sludge 5. energy requirements 6. large scale demonstration still to be proven 7. limit to possible markets for products(?)

Biophotolysis

The symbiotic relationship between light-converting protein complexes and hydrogen liberating enzymes will produce hydrogen from water by enzymatic reduction.[64] If long lasting films of these coupled proteins could be made, they could provide catalytic surfaces for the solar production of hydrogen from water at temperatures up to 50°C. Calculations made by L. W. Jones in 1971 indicate that a land area equivalent to 5×10^4 km.^{2} could provide hydrogen of energy equivalent to the gasoline used in the United States.[65]

Purple photosynthetic bacteria which are found in sewage and industrial wastes produce hydrogen during growth.

$$\text{organic substrate} \longrightarrow \text{new cells} + H_2 + CO_2$$

The presence of oxygen is incompatible with formation of hydrogen, but the gas could be mopped up by blue-green algae with a high rate of oxygen respiration.[66] Current research is concentrating on developments of stable biological systems which would bring about the photosynthetic decomposition of water.

Charles Scott[67] of the Molecular Anatomy Program at Oakridge has suggested that an attempt be made to use the biological system to process hydrogen from wastes employing a cyclic system requiring a certain energy trade-off.

Biophotolysis is moving through the theoretical stages into the preliminary laboratory investigations of the various biological systems to electrolytically decompose water.

Environmental Impact

As mentioned previously, there is a limit to the quantity of manure that can be safely landspread; runoffs from feedlots have been implicated with water contamination and stream eutrophication. Incineration of manures and agricultural field wastes is becoming ever more limited as air pollution controls are enforced. After anaerobic digestion, the residues are odorless and biologically stable. If the residues do find a market as a fertilizer or feedstock, there is no land disposal problem; if the residues prove unmarketable, they can be land disposed of with less difficulty than untreated wastes.

Anaerobic digestion of municipal solid wastes also produces residues that are biologically stable; the liquid effluent can be treated with polymers to produce a practically clear liquid with a particulate content of 16-17 mg. of suspended solids per liter.[68] The solid residues might possibly find a use as an incinerator cake, but if not, can be safely landfilled. Settling of landfills, a common problem with untreated refuse, is minimized with biodegraded wastes.

Fermentation of sugars from acid hydrolysis of refuse produces an effluent with BOD of 6,000 ppm.,[69] requiring treatment before disposal. Residues of enzyme hydrolysis will require no

further treatment.

In addition to the decrease in water and air pollution brought about by initial biodegradation of wastes, the production of energy in the form of methane or ethanol results in small but significant conservation of fossil fuels. The possible replacement of synthetic ethanol with alcohol from fermentation of glucose also conserves fossil fuels presently used in the chemical industry.

In summary, bioconversion of solid wastes is a sound environmental practice with regard to pollution abatement and energy conservation.

Economic Analysis

The difficulty of comparing the various cost estimates of the anaerobic digestion process lies in the different operational and environmental parameters prevailing in each variation of the process. For example, it is possible to include or exclude the cost of an elaborate front-end system to recover resources from city refuse; the cost analyses may or may not include the cost of scrubbing the gas to produce pipeline quality methane. The credits and penalties for municipal solid waste are not identical to those for manures. Some systems employ a recycling of the gases produced, resulting in a fuel economy within the system and lower operating costs.

The comparative costs of various processes are given in Table 14. In order to facilitate comparison of the different cost estimates, the cost of the base unit system is considered to be the gross costs involved from the point of entry of fuel into the digester, to the production of total gas at the back-end. The figures in Table 14 do not include revenues from methane, as the price per unit output should be the same for each system, nor do the tables include credit for fertilizer or feedstock value of the residues of manure digestion.

The total costs/million BTU's for each set of figures has been calculated as follows:

$$\text{Total Costs/million BTU's} = \text{Operating Cost/million BTU's} + \text{Capital Costs/million BTU's}$$

The estimates are for the plant's net energy production, and do not include internal energy leaks, energy usage for pumps, etc. These factors which are different for each system are questions of engineering judgment. The capital costs are given on the basis of a claimed lifetime of 10 years (unless otherwise indicated) assuming operation at full capacity. Note that the lifetimes may be extended to 15 years (as in the Jacobs' case) with some drop in annualized capital costs. The systems can be extended beyond their acclaimed lifetime.

The Dynatech figures are substantially higher than the others and include costs of the front-end resource recovery system and upgrading to pipeline quality. The credits will be high, however, due to the revenues from reclaimed materials and the dump fee. Dynatech has demonstrated that the ownership of the digester will make a substantial difference to the costs of

the system.[70] The example given is for a facility owned and financed with private capital. If the facility were privately owned but financed through Pollution Control Revenue Bonds, or alternatively, municipally owned and financed, the costs would be lower. For the above reasons, the figures for Dynatech are probably a little high.

The costs of the Institute of Gas Technology System[71] are for a small plant processing 571 dry tons of solid wastes and sludge per day. They include a front-end recovery system and a MEA scrubber and are for a 25-year lifetime.

The figures quoted for Dr. Pfeffer refer to a base run of a computer study involving MSW digestion at 60°C for a six day detention time.[72] The costs include a front-end recovery system, a gas purification step, and treatment of the residues. The capital cost is only the installed cost, excluding site costs, engineering costs, legal fees, etc.

The three sets of Jacobs figures[73] give some idea of the expense of scrubbing the system to remove the carbon dioxide and produce high pressure, high quality methane. Both the USDA figures and the Jacobs figures refer to digestion of manures, but the former is a thermophilic process and the latter is mesophilic. Both the Jacobs and USDA researchers feel that the residue has great potential as a feed or fertilizer. If the residues are not readily marketable, the cost of disposal will increase the costs of both processes; if the residues do find a ready market—which seems quite likely—both of these processes will be economically attractive. The Jacobs' figures are probably the best estimates available, as they are the most recent.

TABLE 14. COMPARATIVE COSTS OF ALTERNATE SYSTEMS TO RECLAIM ENERGY FROM WASTES, 1975 DOLLARS
(April 1975)

System	Gross Operational Cost/10^6 BTU Net Output	Gross Capital Cost/10^6 BTU Net Output	Gross Total Cost/10^6 BTU Net Output	Capacity (BTU/Day)
1. ANAEROBIC DIGESTION OF MANURES				
(a) Jacobs Engineering (200TPD)—15 yr. deprec., mesophilic temp.			$1.39 low press. low purity $2.82 low press. high purity $3.19 high press. high purity	1.611×10^9 BTU/Day
(b) USDA (9,120TPD)—10 yr. deprec., thermophilic temp.	$1.61	$0.53	$2.14	3.411×10^8 BTU/Day
2. ANAEROBIC DIGESTION OF MSW				
(a) Dynatech (1,000TPD) thermophilic	$2.45	$2.77	$5.22	3.25×10^9 BTU/Day
(b) Pfeffer-Biogas Case 1, thermophilic (1,000TPD)	$1.99	$1.68	$3.67	3.15×10^9 BTU/Day
(c) Institute of Gas Tech. (571TPD)—25 yr., deprec., mesophilic	$0.599	$0.18	$0.78	5.20×10^9 BTU/Day
3. ACID HYDROLYSIS OF MSW, FERMENTATION TO ETHANOL (400TPD)			$6.46	9.97×10^8 BTU/Day
4. COMBUSTION OF MSW TO PRODUCE STEAM (1,000TPD)	$0.55	$0.48	$1.03	1×10^{10} BTU/Day

TABLE 14 —— Continued

System	Gross Operational Cost/10^6 BTU Net Output	Gross Capital Cost/10^6 BTU Net Output	Gross Total Cost/10^6 BTU Net Output	Capacity (BTU/Day)
5. COMBUSTION OF MSW TO PRODUCE ELECTRICITY FROM STEAM (1,000TPD)	$1.53	$1.65	$3.18	$4x10^9$ BTU/Day
6. COFIRING MSW WITH COAL (980TPD)	$1.21	$0.64	$1.85	$3.92x10^9$ BTU/Day
7. PYROLYSIS				
(a) To produce fuel oil and char—(1,000TPD)	$0.79	$0.42	$1.21	$6.5x10^9$ BTU/Day
(b) To produce MeOH(300TPD)—15 yr. deprec.	$7.93	$2.16	$10.09	$4.94x10^9$ BTU/Day

TABLE 15. COSTS OF PRODUCTION OF METHANE FROM MANURES – JACOBS ENGINEERING FIGURES, 1975

PROCESS	Total Costs Per 10^6 BTU's Output (Gross)	Total Costs Per 1,000 cu.ft. Methane (Gross)	Total Costs Per TPD (Dry) (Gross)
Low Pressure, low purity methane	$1.39	$1.26	$11.27
Low Pressure, high purity methane	$2.82	$2.54	$22.70
High Pressure, high purity methane	$3.19	$2.87	$25.70

Source: Weisberg E. and R. Krisnan, *Engineering Design and Economic Feasibility of a Feedlot Waste Bioconversion System,* paper presented at Conference on Energy Recovery from Solid Wastes, College Park, Maryland, March 1975, pp.17-19.

Brief Comparison of the Bioconversion Process with Other Energy Recovery Systems

Comparison of the costs of the systems makes it clear that anaerobic digestion is in a cost-range that is not uncompetitive with alternate technologies. Combustion to produce steam and cofiring with other fuels is cheaper per 10^6 BTU's of net energy excluding credits and penalties to any of the systems. Anaerobic digestion produces both energy in the form of methane and residues with a potential market as a fertilizer or feed, thus eliminating a charge for disposal of the residues of digestion. The major economic output for anaerobic digestion of manures is in the upgrading of the gas produced to pipeline quality methane (see Jacobs' figures). As every effort is being made to optimize this process, it is not inconceivable that the costs will be reduced as a percentage of the total outlay of capital. The digestion of manures can be successfully accomplished at mesophilic temperatures (30-40°C), thus decreasing the need for external energy to maintain the reaction.

The use of solar energy to digest manures deserves attention. The technology has been successfully applied to a farm of 350 cattle and several firms feel that the economic rewards of the process justify large-scale ventures.

Anaerobic digestion of MSW is a little less attractive than that of manures. The front-end recovery system is expensive to install; however, it does provide additional credits for the system. (see Dynatech figures). The residues still require disposal, adding costs to the system. Digestion of MSW is very dependent upon the going market price for methane in order to be economically attractive. Given the political uncertainties of future energy policy, it is difficult to predict the future price of methane, except to indicate that it will definitely rise from the 53 cents/10^3 cubic

feet (mcf) of interstate commerce and the $1-$2/mcf of the intrastate market.

As previously mentioned, cities presently interested in energy recovery from MSW are opting for combustion or pyrolysis processes. As the technology of these alternate processes is more developed and boilers to receive the wastes are already operating in many major metropolitan areas, considering present economics, bioconversion of MSW would not be the first choice for these large population centers. The possibility remains that digesters could be added to existing inorganic resource recovery systems as proposed by Waste Management, Inc. for their Pompano Beach facility. Local factors would determine whether this was both an economic and a practical proposition. The disadvantage of steam production by combustion of wastes is that the energy is not produced in a storable form, but must be put to immediate use. Methane produced by bioconversion could be fed into local gas pipelines and used as required. Areas along the East coast of the United States, which have the highest concentration of MSW and which are most heavily dependent upon imports of natural gas, might find it feasible to investigate the anaerobic digestion of MSW. It is very possible that digestion will prove both profitable and convenient for small towns given their local conditions. The most recently conducted economic analyses may be considerably modified in light of future advances in technology and market trends.

The hydrolysis and fermentation of MSW or agricultural wastes remains as a possible alternate attractive means of energy production should ethanol be shown as a desirable additive to automotive fuel. The complete economic impact of producing ethanol to substitute for chemicals derived from fossil fuels has yet to be examined.

An indepth analysis of the possible markets for ethanol would clarify the desirability of large scale hydrolysis and fermentation of wastes. The only figures given for this process refer to the total costs of ethanol production through acid hydrolysis, and these figures appear to be comparatively high ($6.46/$10^6$BTU's). Only the production of methanol by pyrolysis of MSW is indicated as being more expensive.

The economics of the bioconversion processes discussed herein would not disqualify any of these processes from future consideration as a means of solid waste disposal.

APPENDIX A

COST ESTIMATES FOR ALTERNATE SYSTEMS TO RECLAIM ENERGY FROM CELLULOSIC WASTES

JACOBS ENGINEERING ESTIMATES FOR PRODUCTION OF METHANE BY MESOPHILIC DIGESTION OF COW MANURE

	Case 1. (low pressure, low purity CH_4)	Case 2. (low pressure, high purity CH_4)	Case 3. (high pressure, high purity CH_4)
Total Capital Costs (15 yrs.)	$1,735,000	$2,816,000	$2,935,000
Total Cost/Year*	$ 823,000	$1,657,000	$1,876,000
Total Daily Cost	$ 2,254	$ 4,540	$ 5,140
Methane gas/day(mcf's)	$ 1,790	$ 1,790	$ 1,790

If one cubic foot of methane = 900 BTU's, then 1,790 mcf's = $(1{,}790 \times 10^3 \times 900)$ BTU's = 1.611×10^9 BTU's

Capacity of the plant = 200 dry tons/day

Total Costs/10^6 BTU's = $\frac{\text{Total Daily Cost} \times 10^6}{1.611 \times 10^9}$, Total Costs (TPD) = $\frac{\text{Total Daily Cost,}}{\text{Daily Capacity}}$

Total Costs/mcf = $\frac{\text{Total Daily Cost}}{1{,}790}$

Total Daily Cost/10^6 BTU's	Case 1.	$ 1.39	Case 2.	$ 2.82	Case 3. $ 3.19
Total Daily Cost (TPD)		$11.27		$22.70	$25.70
Total Daily Cost/mcf		$ 1.26		$ 2.54	$ 2.87

Source: Weisberg, E. and R. Krishman, *Engineering Design and Economic Feasibility of a Feedlot Waste Bio-Conversion System,* paper presented at Conference on Energy Recovery From Solid Wastes, College Park, Maryland, March 1975, pp. 17-19.

*10% after tax return on investments

Cost Estimates for Production of Methane by Anaerobic Digestion of Manures, USDA

Total Capital Investment = $558,600

Capital Investment / yr. = $55,860 (for a 10 year lifetime, 6% interest)

Gross Energy of Fuel = 3.411×10^8 BTU/day

$$\text{Capital Costs}/10^6 \text{ BTU} = \frac{\$55{,}860 \times 10^6}{3.411 \times 10^8 \times 365} \times \left[\text{Index } \frac{(1975)}{(1974)} = 1.19\right]$$

$$= \$\ 0.53$$

Operating Cost = $168,365 per annum

$$\text{Operating Cost}/10^6 \text{ BTU} = \frac{\$168{,}365 \times 10^6}{3.411 \times 10^8 \times 365} \times 1.19$$

$$= \$\ 1.61$$

Total Costs = $2.14/$10^6$ BTU

Source: *Production of Power Fuel by Anaerobic Digestion of Feedlot Waste* Space Systems Department of Hamilton Standard Division, United Aircraft Corporation, for Fermentation Laboratory, Northern Regional Marketing and Nutrition Research Division, Peoria, Illinois, 1974. Appendix II, pp. 9, 12.

Cost Estimates for Production of Methane from MSW, Dynatech (Thermophilic)

These estimates exclude both penalties and credits:

Contribution of Capital Costs to Gas Cost = \$2.17/mcf

$$= \frac{\$2.17 \times 10^6}{930 \times 1{,}000} \quad /10^6 \text{ BTU}$$

$$= \$2.33/10^6 \text{ BTU} \times \left[\text{Index } \frac{(1975)}{(1974)}\right]$$

Contribution of Operating Costs to Gas Cost = \$1.92/mcf

$$= \frac{\$1.92 \times 10^6}{930 \times 1{,}000} \quad /10^6 \text{ BTU}$$

$$= \$2.06/10^6 \text{ BTU} \times \left[\text{Index } \frac{(1975)}{(1974)}\right]$$

Capital Costs/10^6 BTU = \$2.33 x 1.19 = \$2.77

Operating Costs/10^6 BTU = \$2.06 x 1.19 = \$2.45

Total Costs/10^6 BTU = \$5.22

$$\text{Capacity} = 1.222 \times 10^9 \text{ scf/yr} = \frac{1.222 \times 10^9 \times 930}{350} = 3.25 \times 10^9 \text{ BTU/day}$$

Source: Kispert, R. G., Anderson, L.C.D.H. Walker et. al., *Fuel Gas Production From Solid Waste,* Dynatech R/D Company, Report No. 1207, July 31, 1974, p. 78, 85.

Cost of Anaerobic Digestion of Waste from Figures Presented by Dr. J. Pfeffer, 1974

For the Base run

Total Costs/hr. = $405.67

Methane production (mcf/hr) = 138, Methane production $\frac{(BTU)}{hr} = 138 \times 950 \times 10^3$

$$\text{Total Cost}/10^6 \text{ BTU} = \frac{\$405.67 \times 10^6}{138 \times 10^3 \times 950} \times \left[\text{Index } \frac{(1975)}{(1974)} = 1.186\right]$$

Total Costs/10^6 BTU = $3.67

Capital Costs/hr = $185.50

$$\text{Capital Costs}/10^6 \text{ BTU} = \frac{\$185.50 \times 10^6}{138 \times 10^3 \times 950} \times \left[\text{Index } \frac{(1975)}{(1974)} = 1.186\right]$$

Capital Costs/10^6 BTU = $1.68

Operating Costs/10^6 BTU = $1.99

Capacity (BTU's/day) = $138 \times 950 \times 24 \times 1{,}000 = 3.15 \times 10^9$

Note: Capital costs are installed costs. Site costs, engineering, legal, insurance, interest during construction, etc. are not included in the capital cost.

Source: Pfeffer, John T., *Reclamation of Energy from Organic Refuse Anaerobic Digestion Processes,* paper presented at Third National Conference on Waste Management Technology and Resource Recovery, San Francisco, California, November 14-15, 1974, p. 22.

Cost Estimates for Production of Methane from MSW, Institute of Gas Tech.

For a small plant (471 TPD),

Capital Costs = $\$5.82 \times 10^6$ (for a 25 year lifetime, 5.1% interest)

Capital Costs/annum = $\$2.33 \times 10^5$ (for a 25 year lifetime)

Net Power Out = 5.20×10^9 BTU/day = $5.20 \times 10^9 \times 350$ BTU/yr

$$\text{Capital Costs/}10^6\text{ BTU} = \frac{\$2.33 \times 10^5 \times 10^6}{5.20 \times 10^9 \times 350} \times \left[\text{Index } \frac{(1975)}{(1973)} = \frac{232.5}{170} = 1.367\right]$$

$$= \underline{\$\ 0.18}$$

Operating Costs = $2,283/day

$$\text{Operating Costs/}10^6\text{ BTU} = \frac{\$2.28 \times 10^3 \times 10^6}{5.20 \times 10^9} \times 1.367$$

$$= \underline{\$\ 0.599}$$

Total Costs/10^6 BTU = Capital Costs/10^6 BTU + Operating Costs/10^6 BTU

$$= \underline{\$\ 0.78}$$

Source: Ghosh, S., and D. L. Klass, *Biogasification of Solid Wastes,* RFP submitted to NSF, P 31-3285, January 1970, p. 104.

Costs for Production of Ethanol from MSW by Acid Hydrolysis and Subsequent Fermentation

1 ton of refuse will yield 24.8 gallons of EtOH or 182 lbs. of EtOH

BTU content of ethanol is 13,698 BTU/lb

BTU content of ethanol from 1 ton refuse = $182 \times 13{,}698$

$= 2{,}493 \times 10^6$

Net cost of extracting ethanol from refuse is taken to be 52¢/gallon (1972 dollars; 6% interest assumed for 15-20 years as data is unclear)

Total Cost of ethanol production ton = $\$ 0.52 \times 24.8$

$= \$12.90$

Total Cost of ethanol/10^6 BTU $= \dfrac{\$12.90 \times 10^6}{2.493 \times 10^6}$

$= \$ 5.17 \times \left[\text{Index } \dfrac{(1975)}{(1972)}\right]$

For a 400 TPD plant, $= \$ 6.46$

For a 400 TPD plant, Capacity (BTU/day) $= 9.97 \times 10^8$

Source: *Problems and Opportunities in Management of Combustible Solid Wastes,* International Research and Technology Corporation, Washington, D.C., October 1972, pp. 136-152.

Cost Estimates for Combustion of MSW to Produce Steam

1 ton of refuse produces 3,000 Kwh or 1×10^7 BTU

For a 1,000 TPD plant,

Total Costs/ton = \$10.25

$$\text{Total Costs}/10^6 \text{ BTU} = \frac{\$10.25 \times 10^6}{10^7}$$

$$\text{Total Costs}/10^6 \text{ BTU} = \frac{\$\ 5.5 \times 10^6}{10^7}$$

$$= \$\ 0.55$$

Capital Costs/10^6 = \$0.48

Capacity (BTU/day) = 10^{10}

Source: *Problems and Opportunities in Management of Combustible Solid Wastes,* International Research and Technology Corporation, Washington, D.C., October 1972, pp. 136-152.

Cost Estimates for Combustion of MSW to Produce Electricity from Steam

1 ton of waste produces 3,000 Kwh = 1×10^7 BTU

Assuming 40% efficiency, 1 ton of waste produces 1,200 Kwh of electricity

$$1{,}200 \text{ Kwh} = \frac{10^7 \times 1{,}200}{3{,}000} \text{ BTU}$$

Heat produced / ton of refuse = 4×10^6 BTU

For 1,000 TPD,

Total Costs = \$12.75 / ton (lifetime of loan not known; assumed to be either 15-20 yrs. at 6% interest)

$$\text{Total Costs}/10^6 \text{ BTU} = \frac{\$12.75}{4}$$

$$\text{Total Costs}/10 = \$3.18$$

Operating Costs = \$6.13/ton

Operating Costs/10^6 BTU = \$6.13/4 = \$ 1.53

Capital Costs/10^6 BTU = \$ 1.65

Capacity / day = 4×10^9 BTU

Source: *Problems and Opportunities in Management of Combustible Solid Wastes,* International Research and Technology Corporation, Washington, D.C., October 1972, pp. 136-152.

Cost Estimates for Cofiring MSW as at the St. Louis Plant

Total Cost (5 days/wk) = $5.16/ton (lifetime of loan and interest are not clear from data given)

Assuming 40% efficiency of conversion from steam to electricity

1 ton of refuse will produce 1,200 Kwh of power or 4×10^6 BTU

$$\text{Total Costs}/10^6 \text{ BTU} = \frac{\$5.16}{4} = \frac{\$\ 1.65}{} \times \left[\text{Index}\ \frac{(1975)}{(1973)} = \frac{198}{176.5}\right]$$

$$= \underline{\$\ 1.85}$$

Capacity is 980 TPD.

Capacity (BTU/day) $= 4 \times 10^6 \times 980 = 3.92 \times 10^9$

Operation and Maintenance (260 day year) = $896,900/year

$$\text{Operating Costs}/10^6 \text{ BTU} = \frac{\$896{,}900 \times 10^6}{3.92 \times 10^9 \times 260}$$

$$= \$\ 1.08 \times \text{Index}\ (1.12)$$

$$= \underline{\$\ 1.21}$$

Capital Costs/10^6 BTU = $ 0.64

Source: *Problems and Opportunities in Management of Combustible Solid Wastes,* International Research and Technology Corporation, Washington, D.C., October 1972, pp. 136-152.

Cost Estimates for Pyrolysis of MSW to Produce Fuel Oil and Char

1 ton of waste produces 450 lb of oil at 12,000 BTU/lb
100 lb of char at 11,000 BTU/lb

1 ton of waste = (450 x 12,000) + (100 x 11,000) BTU

$= 6.5 \times 10^6$ BTU

For a 1,000 TPD plant,

Total Costs = \$7.88/ton (1975 dollars; lifetime of loan unknown – assumed to be either 15-20 yrs at 6% interest)

Total Cost of 10^6 BTU = $\frac{\$7.88}{6.5}$

Total Cost/10^6 BTU = \$1.21

Capital Cost / 10^6 BTU = \$0.42

Capacity (BTU/day) = 6.5×10^9

Source: *Problems and Opportunities in Management of Combustible Wastes,* International Research and Technology Corporation, EPA contract 68-03-0060, October 1972, pp. 12, 125.

Cost Estimates for Methanol Production from Pyrolysis of MSW

Capacity of plant = 300 tons/day

Production of methanol = 100,000 tons/year

Heat Content of Methanol = 8640 BTU/lb

Number of BTU/year = 8,640 x 100,000 x 2,000

$= 1.728 \times 10^{12}$

Capital Costs = 56×10^6

Capital Costs/annum = $\frac{\$\ 56 \times 10^6}{15}$ (for a 15 year lifetime)

Capital Costs/10^6 BTU = $\frac{\$\ 56 \times 10^6 \times 10^6}{15 \times 1.728 \times 10^{12}}$

= $ 2.16

Operating Costs (1st year) = 13.7×10^6 (15 year debt, 8% interest)

Operating Costs/10^6 BTU = $\frac{\$13.7 \times 10^6}{1.728 \times 10^{12}}$

= $ 7.93

Total Costs = $ 10.09/10^6 BTU

Assume a 350 day year,

Daily BTU output = $\frac{1.728 \times 10^{12}}{350} = 4.94 \times 10^9$

Source: Sheehan, Robert G., and Richard F. Corlett, *Methanol or Ammonia Production From Solid Wastes by the City of Seattle,* 169th. National Meeting, American Chemical Society, Vol. 20, No. 2, Aprii 6-11, 1975, p. 52.

APPENDIX B

METHANOL PRODUCTION BY PYROLYSIS AND A BRIEF EVALUATION OF METHANOL AND ETHANOL AS AUTOMOTIVE FUELS

Methanol Production by Pyrolysis

The bulk of the methanol that is currently produced industrially is manufactured from natural gas. The City of Seattle has plans to produce methanol by pyrolysis of city garbage, possibly using the Union Carbide Corporation's Purox system.[74] They intend to conserve natural gas as well as to exploit the possibilities of using methanol as an automotive fuel.

In the Purox System, municipal solid waste is charged down a vertical-shaft furnace where as it migrates downward, it is heated by rising gases generated from oxidation of the residues at the bottom of the shaft. The gas leaving the top of the reactor which is mainly carbon monoxide, hydrogen and water vapor, is processed through a closed gas cleaning system to remove water and impurities. After absorption removal of sulfur to prevent pollution and future catalytic poisoning, the carbon monoxide/hydrogen ratio is shifted to 1:2, the stoichiometric ratio for methanol synthesis. Carbon dioxide produced in this shift is substantial and must be removed. Under specific conditions of heat and pressure in the presence of a catalyst, the two gases combine to methanol.

$$CO + 2H_2 \longrightarrow CH_3OH$$

It is also possible to produce ammonia by variations in the shift mechanism.

Mathematical Sciences Northwest, Inc. for the City of Seattle indicate that starting from 550,000 tons/year of MSW, it is possible to produce approximately 31 million gallons of methanol/year or 120,000 tons of ammonia. Costs based on late 1974 prices indicate that for the city to break-even from the project, the net annual cost must be no greater than the current costs of landfill ($3.3 million).[75] The financial feasibility of the project depends on the prices for the two products. An economic summary of the process is found in table 16.

Methanol as an Automotive Fuel

Mathematical Sciences Northwest, Inc. conducted a study of the possibility of using methanol as an automotive fuel either alone or in blends with gasoline.[76] The blend contained up to 7% methanol and was found to increase the efficiency of the operation of the automobile on a mile/BTU basis, to decrease the emission of carbon monoxide and increases the octane number of low-grade gasolines.[77]

The biggest problem encountered was in phase separation of the blend when traces of water were present and at low temperatures. Addition of higher alcohols might solve this problem. Corrosion of some automobile systems was significant.

The use of pure methanol as a fuel would require a modification in the engine to permit a higher compression ratio and leaner equivalence ratio. These adaptions would permit the methanol to operate with an increase in efficiency of approximately 20%[78] in spite of its low heating value (8,640 BTU/lb. compared to 19,080 BTU/lb. for gasoline).

TABLE 16. MARGINAL OR "BREAK-EVEN" ECONOMICS OF SEATTLE SOLID WASTE METHANOL OR AMMONIA PROJECT (1978)

(1)	Methanol Plant (2)	Ammonia Plant (3)
Plant Nominal Product Size	300 T/Day	350 T/Day
Annual Product Yield	100,000 T/Year (31,000,000 Gal/Yr)	120,000 T/Year
Capital Cost[1]	$ 56,000,000	$ 65,000,000
Debt Service[2]	6,600,000	7,500,000
Operation and Maintenance	7,100,000	8,100,000
First-Year Costs	$ 13,700,000	$ 15,600,000
Product Sales	$ 10,400,000	$ 12,300,000
Disposal Gain[3]	3,300,000	3,300,000
	$ 13,700,000	$ 15,600,000
Marginal (Break-Even) Product Price, First Year	33.6¢/Gal.	$103/Ton

Source: Sheehan, Robert G., and Richard F. Corbett, *Methanol or Ammonia Production from Solid Wastes by the City of Seattle*, 169th National Meeting, American Chemical Society, Division of Fuel Chemistry, Vol.20, No. 2, April 6-11, 1975.

[1] Gasifiers, gas cleanup, shift process, synthesis plant, site, tankage and associated facilities.

[2] 15-year life, 8% interest.

[3] Disposal cost for equivalent transport and landfill.

Ethanol as an Automotive Fuel

While there have been many laboratory tests on the performance of stationary automobile engines operating on ethanol-gasoline blends, there has been no statistically designed fleet test of the mixture reported. Dr. Scheller and Dr. Mohr of the University of Nebraska designed a two million mile road test using 10% ethanol and 90% unleaded gas[79] which is now in progress. This comprehensive test will run for a period of 10-15 months and will involve 10 half-ton pick-up trucks and 26 passenger cars. One third of the fleet will run on the 'Gasahol' blend, one third on unleaded gasoline, and the remainder will change fuels midway through the test program.

In addition to normal vehicle maintenance, there will be periodic checks on the effect of the fuels on cylinder wear, engine valves, spark plugs, and the exhaust system. Emission tests will be performed on the 10 test cars. Preliminary analysis based on about 250,000 miles indicates that significant facts in the fuel consumption are the driver of the vehicle, average daily temperature, average relative humidity and maintenance schedule.[80] The final results of this road-test should clarify the possibilities of use of ethanol as a fuel additive.

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16. ABSTRACT

This report is a state-of-the-art summary of biological processes for converting waste cellulosic materials (agricultural, municipal and lumbering wastes) to fuels. It indicates the locations and quantities of suitable wastes and discusses the status of the current processing schemes. The processes discussed are:

- o acid hydrolysis followed by fermentation
- o enzyme hydrolysis followed by fermentation
- o anaerobic digestion of manure and municipal solid waste
- o biophotolysis

Cost data for these processes are given and, where possible, compared. The range of cost was $1.39 to approximately $5.00 per million BTU of net energy output.

It was concluded that energy production by these methods on a national scale can, at best, produce the equivalent of only about 3 million barrels of oil per day by 1980. These may, however, be economical and environmentally acceptable means of waste management which should be explored further.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Methane Hydrolysis Fermentation Ethanols Digestion (decomposition) Biomass Anaerobic processes Cellulose	Bioconversion Ethanol production Municipal solid waste Anaerobic digestion Acid hydrolysis Enzyme hydrolysis Methane production	10A

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