200
6-4-80 mmB

Dr. 1590

DOE/CS/20178-01

Resource Recovery Research Development and Demonstration Plan

October 1979

MASTER

Prepared for:

U.S. Department of Energy

Assistant Secretary for Conservation and Solar Energy

Office of Building and Community Systems

Urban Waste Technology Branch

Under Contract No. AC01-78CS20178

DISCLAIMER

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

DISCLAIMER

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

Available from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price:	Printed Copy:	\$22.00
	Microfiche:	\$4.00

Resource Recovery Research Development and Demonstration Plan

October 1979

Prepared by:
Dr. Alfred B. Scaramelli, P.E.
The Mitre Corporation
Bedford, Massachusetts

Prepared for:
U.S. Department of Energy
Assistant Secretary for Conservation and Solar Energy
Office of Building and Community Systems
Urban Waste Technology Branch
Washington, DC 20585

DISCLAIMER

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

NOTICE

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

ABSTRACT

Implementation of resource recovery is being retarded by technological uncertainties and institutional impediments. Development and commercialization of new competitive technologies are not proceeding rapidly because a structured development program for the industry is lacking. The U.S. Department of Energy (DOE) has recognized these problems, and as part of its overall program in energy recovery from urban waste, it is developing a near- and longer-term research, development, and demonstration (RD&D) program to accelerate commercialization of promising resource recovery technologies.

The MITRE Corporation was contracted to develop a near-term RD&D Plan for resource recovery which identifies actions which should be taken over the next three years to accelerate commercialization of existing and developing technologies. The research needs presented in this Plan exist in the industry today. The resolution, however, is not necessarily the sole responsibility of DOE, but rather calls for a combination of public and private sector efforts.

An individual research program is presented for each resource recovery technology. A program consists of a combination of bench-, pilot-, demonstration- and full-scale process and equipment evaluations as well as qualitative and quantitative studies. Each research program is tailored to alleviate the problems of a technology such that their resolution will accelerate the rate at which the technology advances toward commercial readiness and realizes commercial implementation. All the research needs identified are actions which should be taken in the next three years to advance the field of resource recovery.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

EXECUTIVE SUMMARY

Overview

With rapidly increasing energy costs and stricter enforcement of environmental standards, the demand for resource recovery as an energy producing and solid waste disposal technology is high. From an energy standpoint, 1.58 quads could theoretically be recovered from the 175 million tons of municipal solid waste (MSW) generated in this country in 1980. However, only a very small fraction of this waste is being converted into energy.

Implementation of resource recovery is being retarded by technological uncertainties and institutional impediments. Development and commercialization of new competitive technologies are not proceeding rapidly because a structured development program for the industry is lacking. The U.S. Department of Energy (DOE) has recognized these problems, and as part of its overall program in energy recovery from urban waste, it is developing a near- and longer-term research, development, and demonstration (RD&D) program to accelerate commercialization of promising resource recovery technologies.

The MITRE Corporation was contracted to develop a near-term RD&D Plan for resource recovery which identifies actions which should be taken over the next three years to accelerate commercialization of existing and developing technologies. The Plan presents non-technical and technical research needs for the various technologies listed in Table 1. Non-technical research needs include the institutional, legal, and socio-economic barriers that are retarding widespread commercial implementation of all technologies. The research needs presented in this Plan exist in the industry today. Satisfying the needs, however, is not necessarily the sole responsibility of DOE, but rather calls for a combination of public and private sector efforts.

An individual research program is presented for each technology; however, at the request of DOE, recommendations are not made as to which technologies have the greatest potential for near- and longer-term commercialization. DOE officials will make these decisions based upon the research needs and programs outlined in this Plan. Included as Appendix A is a methodology for identifying technologies which have the greatest likelihood of widespread commercialization.

Individual research programs consist of a combination of bench-, pilot-, demonstration-, and full-scale process and equipment evaluations as well as qualitative and quantitative studies. The technologies considered run the gamut of stage of development. Some technologies are at the bench-scale, while others are in commercial operation. All are experiencing problems. Each research program is tailored to help alleviate these problems and ultimately accelerate the rate at which the technologies advance toward commercial readiness and realize implementation. All the research needs identified are actions which should be taken over the next three years to advance the field of resource recovery.

The research needs for each technology were developed through site visits, personal contacts, and literature review. A list of resource recovery facilities visited during preparation of the Plan is presented in Appendix B. Dynatech R&D Company, under subcontract to MITRE, assisted in evaluation of bioconversion technologies. As a peer review of the Plan, a two-day Workshop was held in Wakefield, Massachusetts, on June 12 and 13, 1979. At this Workshop

researchers, system and equipment vendors, system operators, and Federal and utility officials in the field of resource recovery met to review the research needs and develop an industry-wide consensus on the direction of Federal support for development of the industry. Inputs from the Workshop sessions have been incorporated into the Plan. A list of the Workshop attendees is presented in Appendix C.

As a further review, MITRE presented the research needs to a special Urban Waste Panel of the National Research Council on August 13, 1979. The National Research Council is the principal operating agency of the National Academy of Sciences and National Academy of Engineering. This Panel will make recommendations to DOE for mid- and long-term R&D goals in resource recovery. Inputs from this meeting are also incorporated into the Plan. Participating members of the Panel are listed in Appendix D.

Summary of Research Programs for Resource Recovery

A summary of needed resource recovery research programs which should be conducted in addition to current DOE research programs is presented in Table 2. These research programs were developed so that they can be addressed within the expected DOE resource recovery budget of \$10 to \$15 million per year. The research programs presented in the Plan represent only a portion of DOE's work effort in resource recovery and therefore do not include such areas of funding as the Demonstration Program and other currently committed research and demonstration projects.

Additional research needs for each resource recovery technology are presented in Tables 3 through 7. For each research need, the type of research, estimated cost, estimated duration of work, and recommended start date are presented. Estimated cost is given to provide a general indication of effort. These costs will vary depending on the detailed scope of work for each research need. All estimated research costs do not include equipment and construction unless otherwise noted.

The following discussion summarizes the additional research programs needed for each technology.

Non-Technical Research Needs

Non-technical or institutional barriers are considered to be the primary causes of the slow rate at which commercially available resource recovery technologies are implemented. Major Federal effort must be directed at mitigating these barriers in order for widespread commercialization to be realized.

In addition to the current Federal programs addressing these issues, it is recommended that efforts also concentrate on the areas of wastestream control, system procurement methods, contract negotiations, energy market incentives, and IRS consistency on tax rulings. Model guidelines should be developed based on past results and existing laws for wastestream control legislation, procurement codes, facility operating contracts, and fair market value of energy products. DOE should encourage public utility commissions to actively participate in resource recovery projects. In addition, a program should be developed to educate state legislators on these issues and problems.

Generic, Technical Research Needs

Generic, technical research needs are common to all resource recovery technologies. Because they are not technology specific, little attention has been given to them by the private sector. However, resolution of these needs will have a significant effect on the near- and long-term growth of the industry.

Many new resource recovery facilities are being designed with features that have previously caused serious problems at other facilities. Although many operating facilities are experiencing similar kinds of problems, solutions are often worked out independently. Information gained from design and operation of facilities should be shared. DOE/EPA/

ASME workshops should be sponsored to encourage exchange of this information.

A major problem facing the industry is the lack of a procedure for reporting the true cost of resource recovery technologies. A standard methodology should be developed for this, and adopted industry-wide.

Standard test methods to evaluate performance of individual unit operations should be developed, likely through ASME Committee E38.08. Eventually this work should lead to development of procedures for plant evaluations.

The remainder of the research needs presented in the summary table are self-explanatory.

Table 1

Resource Recovery Technologies Evaluated for RD&D Plan Development

Mechanical Separation Systems

Preprocessing for Fuel (Feedstock) Preparation

In-Plant Materials Recovery

Combustion Systems

Mass Burning Steam Generation

Prepared Fuel Combustion

— Co-Fired Boiler

— Dedicated Boiler (100% RDF)

Controlled Air Modular Combustion

Co-Disposal

— Refuse Combustors

— Sludge Combustors

Pyrolysis Systems

Indirect Heated

Direct Heated

— Air

— Oxygen

— Steam

Bioconversion Systems

Pretreatment Techniques

Anaerobic Digestion

Landfill Gas Recovery

Acid Hydrolysis

Enzymatic Hydrolysis

Alkanes and Other Chemicals Production

Source Separation

Mechanical Separation Systems and Source Separation

Preprocessing for Fuel Preparation and In-Plant Materials Recovery. Presently there are no accepted design equations for sizing, scaling, and integrating various preprocessing and materials recovery unit operations. Product quality is a variable which cannot be controlled as a function of input characteristics.

Research should be directed at developing a fundamental understanding of unit operations through pilot- and full-scale testing so that equipment and plant design can be improved. Such improvements would produce a more consistent fuel and recovered material product and thus increase market confidence. This research should also result in greater plant availability, reduced redundancy, and lower plant cost.

Source Separation. Many of the source separation programs which have been started have failed, usually due to lack of public participation or unexpected high costs. Municipal officials are often unaware of the true expenses and revenues of different types of source separation programs. Research needs, therefore, are directed at improving the transfer of information on the technical and economic aspects of source separation to municipal officials.

One research need is the development of a methodology to determine the net energy gained by different source separation configurations, such as city curbside collection versus residential haul to a recycling center. Net energy is the difference between the energy conserved due to reuse of recyclable materials and the energy expended in transporting the materials to the reuse market. This study would be of value to Federal officials in directing the future of source separation.

A parallel effort should be directed at developing a source separation manual for municipal officials which can be used to estimate manpower, vehicle requirements, and realistic costs and revenues.

Combustion Systems

Mass Burning Steam Generation. The research program is directed at providing a better understanding of the effect of boiler operating characteristics on combustion efficiency, energy recovery, and air emissions. A detailed boiler performance test at an operational facility is recommended. This test will provide important information on the effect that MSW characteristics have on boiler performance. Because particulate emissions present a significant problem at most operating facilities, a test of a bag house at an operational facility should also be performed. While no research per se is needed for residue utilization, DOE should encourage states to initiate test road programs.

Prepared Fuel Firing in Boilers. The basic research thrust is directed at providing a greater understanding of RDF combustion through bench-, pilot-, and full-scale research programs. Bench-scale studies should develop relationships between RDF characteristics (such as particulate size, moisture and ash content, and available oxygen content) and the time required to dry, volatilize, and burn RDF. Pilot-scale studies should develop mathematical models to predict RDF combustion behavior as a function of furnace conditions and geometry. Full-scale plant evaluations should be conducted to verify bench-scale studies. The research program's goal should be the development of guidelines for design of dedicated and retrofit boilers, and pollution control equipment.

Controlled Air Modular Combustion. A number of the research needs for modular combustion may best be addressed by Federal agencies other than DOE. Evaluation of a coarse RDF feedstock and development of a management seminar for operation of modular combustion facilities are research needs that are either being addressed by EPA or align closely with current EPA programs. However, two areas that need additional Federal support are the test and evaluation of a bag house for particulate emission control and the development of a new fossil fuel control system to reduce auxiliary fuel consumption. The bag house test is considered to be a major research need at this time.

Co-Disposal

Refuse Combustors. Operational data is needed on the combustion of sewage sludge in refuse combustors. The major issue is to compare the effect on overall system performance of firing predried sewage sludge versus firing dewatered, undried sludge. To address this issue, an economic analysis of the two options should first be conducted using existing design and cost data. A plant evaluation should then be conducted to evaluate the two options. Plant evaluations are needed for the large mass burning steam generators as well as the small modular combustors. The impact of co-disposal on long-term boiler tube corrosion should also be determined.

Pilot-scale studies should be conducted to evaluate the technical and economic impact of premixing sewage sludge with MSW at an RDF facility in terms of preprocessing equipment performance, RDF/sludge mixture storage, and combustion characteristics.

Sludge Combustors. Research on co-disposal of RDF in sludge combustors is directed at determining retrofit and operating costs, as well as developing data on system performance. A general systems engineering analysis should be performed to determine retrofit costs as a function of furnace size, refuse and sewage sludge tonnages, and transportation distance from the RDF plant to the sewage treatment plant. Parallel with this study, a multi-hearth furnace (MHF) and fluidized bed furnace (FBF) should be evaluated on a pilot-scale to determine the effect of MSW preprocessing on system performance.

Results of the pilot plant tests could be validated at the Duluth, Minnesota, co-disposal facility. This facility will undoubtedly provide an excellent opportunity for full-scale evaluation of an FBF for co-disposal.

Pyrolysis Systems

The research program for accelerating development of pyrolysis is directed at the evaluation of technologies which have not reached the demonstration stage. This does not include the Purox system, the commercial feasibility of which is now being assessed through a DOE demonstration grant to Dutchess County, New York. Technical and economic evaluations of developing systems should first be conducted. One or two promising systems should be selected and evaluated at the pilot-scale. As a result of this program, one system could be selected for a demonstration project.

Bioconversion Systems

Pretreatment. Pretreatment of MSW prior to biological action can be accomplished by physical, acid, alkali, temperature and pressure, and irradiation treatments. All of these are presently being investigated at some level; however, efforts should be focused on selecting the most promising treatments for further development. The various

research programs presented are for experimental and economic evaluations. After completion of these tasks, an effort should be made to select the most promising techniques for subsequent bioconversion processes.

Anaerobic Digestion. Further research on conventional anaerobic digestion will be premature until the initial experimental program at the RefCOM facility is completed. Depending on the outcome of this program, an evaluation of alternative front-end processing schemes could be considered, particularly for removal of textiles and deformable plastics. Results of the Mechanical Separation Systems research program will provide much of this information.

High solids digestion in fixed or fluidized beds, two-phase digestion, and plug flow digestion are promising methods for improving the economics and energy recovery yield of anaerobic digestion systems. Bench-scale studies of these methods should be conducted using an MSW feedstock. Conceptual designs and cost estimates for a commercial-scale facility should be developed.

Landfill Gas Recovery. Landfill gas recovery from existing landfills with no enhancement is commercially feasible using state-of-the-art techniques. However, Federal support is needed to transfer this knowledge and information to municipal officials. This can be best achieved through DOE/EPA-sponsored regional seminars.

The enhanced-gas-from-landfill concept has been shown on a laboratory-scale to be a highly effective method to produce methane from MSW. Research has reached the point where large-scale field studies are necessary to confirm laboratory results and provide design information for a commercial-scale facility. In these studies, initial sewage and buffer addition and leachate recycling should be evaluated along with development of new drilling and gas extraction techniques. Mathematical models should also be developed to predict potential methane recovery from existing and new landfills.

The present study by Pacific Gas and Electric Company on gas utilization should provide valuable information on energy market requirements for landfill gas. The results of this study should dictate the need for gas upgrading.

Alcohol Technologies – Enzymatic and Acid Hydrolysis. Presently, acid hydrolysis and enzymatic hydrolysis are competing technologies, both in terms of end-product (ethanol) and research money. The leading developers of each technology agree that it is time to reach a crossroad and select the most promising technology for commercial development. To achieve this goal, a detailed engineering evaluation of the two technologies is needed. This evaluation would include development of a conceptual design, preliminary engineering, and capital and operating cost estimates for a commercial-scale facility. Based on this evaluation, one technology should be selected for further development.

Alkanes and Other Chemicals Production. Research must concentrate on identification of those chemicals which provide significant energy conservation potential and which can be produced by fermentation of MSW. Experimental programs coupled with engineering analysis are necessary to determine yields and economic feasibility.

Report Format

This report is divided into eight sections. As a baseline for identifying the potential contribution of resource recovery in terms of national energy production, an assessment of the quantity of municipal, industrial, forestry, and agricultural waste was made. This analysis is presented in Section 1.

Non-technical issues and research needs are discussed in Section 2, and generic technical research needs, which are common to all resource recovery technologies, are presented in Section 3. These issues and research needs are considered to be very important, and their resolution will have a direct effect on the rate at which commercialization of technologies is achieved.

Sections 4 through 8 discuss the various resource recovery technologies. Section 4 evaluates mechanical separation systems and covers preprocessing for fuel or feedstock preparation, i.e., RDF and in-plant recovery of materials, such as ferrous metals, aluminum, and glass.

Section 5 addresses combustion systems and includes an evaluation of mass burning steam generation, controlled air modular combustion, prepared fuel (RDF) combustion, and co-disposal in refuse and sludge combustors.

Pyrolysis systems are discussed in Section 6. Air, oxygen, and steam direct-heated and indirect-heated systems are evaluated.

The bioconversion processes are addressed in Section 7. Pretreatment and chemical production technologies yielding products such as methane, alcohol, and alkanes are discussed in this section. Pretreatment methods considered are physical, alkali, pressure and temperature, acid, and irradiation. Methane producing technologies include anaerobic digestion, both conventional and high-rate; landfill gas recovery from existing and enhanced landfills; and gas upgrading techniques. The alcohol producing technologies include enzymatic and acid hydrolysis of solid waste to glucose with fermentation to ethanol. The production of organic acids, alkanes, and other chemicals from solid waste is also reviewed.

Source separation as an energy conserving technology, rather than an energy producing technology, is evaluated in Section 8.

For each of the technologies considered, a brief process description is given. This is followed by a review of the technology status, which addresses the technical, economic, and environmental problems that the technology is experiencing. The current research work being conducted is also discussed. Research needs are then presented, with a justification for each need. A research program for each technology is proposed which addresses the research needs. This program indicates the type of research that should be conducted, i.e., bench-, pilot-, or full-scale testing, or paper study; scope of work; estimated cost; estimated duration of work; and recommended start date.

Table 2
Summary of Recommended Additional Research Programs
for Resource Recovery

	Program Plan					
	1980		1981		1982	
	Needed Funding (\$1000)	Primary ⁽¹⁾ Work Effort	Needed Funding (\$1000)	Primary ⁽¹⁾ Work Effort	Needed Funding (\$1000)	Primary ⁽¹⁾ Work Effort
Resource Recovery Technologies						
Non-Technical Research Needs	380/QS		100/QS		—	
Generic Technical Research Needs	260/QS		350/QS		250/QS	
Mechanical Separation Systems						
Preprocessing for Fuel (Feedstock) Preparation	900/PS, TE		650/TE		350/QS	
In-Plant Materials Recovery	—		400/PS, TE		250/PS, TE	
Combustion Systems						
Mass Burning Steam Generation	450/DC, TE		—		—	
Prepared Fuel Firing in Boilers	250/BS, TE		700/PS, TE		100/QS	
Controlled Air Modular Combustion	200/TE		75/TE		200/DC	
Co-Disposal	380/TE		350/TE		200/TE	
Pyrolysis Systems	50/QS		500/PS		500/PS	
Bioconversion Systems						
Pretreatment	180/QS, PS		125/BS		150/QS	
Methane Recovery						
Anaerobic Digestion	—		950/BS, TE		600/BS, TE	
Landfill Gas Recovery	300/DC		300/DC		—	
Methane End-Use	—		200/BS		200/DC	
Alcohol Recovery	150/QS		750/DC		2,000/DC	
Other Chemicals Production	—		50/QS		400/BS	
Source Separation	150/QS		—		—	
Total Funding	3,650		5,500		5,200	

- (1) QS— Qualitative or Quantitative Study
BS— Bench-scale Studies
PS— Pilot-scale Studies
DC— Demonstration at Commercial-scale
TE— Test and Evaluation at operating facility

Table 3
Non-Technical and Generic Technical Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
NON-TECHNICAL RESEARCH NEEDS				
1. Compile an inventory of state procurement processes and potential legal obstacles to the different procurement options.	QS ⁽²⁾	150	12-16	1980
2. Develop model procurement codes and encourage states to follow model practices.	QS ⁽²⁾	—	—	—
3. Develop model contracts based on the contract negotiations experience of earlier projects.	QS ⁽²⁾	—	—	—
4. Compile a set of model state laws and reasonable standard approaches to wastestream control.	QS	100	12	1980
5. Educate state legislators and their staffs on the legislative issues which are impeding more rapid implementation of the industry.	QS	80	9	1980
6. Examine the use of incentives to encourage the purchase of refuse-derived energy by utilities.	QS ⁽³⁾	100	12	1980
7. Develop model compensation formulae for energy products.	QS ⁽³⁾	—	—	—
8. Develop recommendations for the modification of existing utility regulations to facilitate utility purchase of waste-derived energy.	QS ⁽³⁾	—	—	—
9. Educate and encourage PUCs and PSCs to actively promote utility participation in resource recovery projects.	QS/FC	20	3-18	1980
10. Encourage clarification of IRS guidelines and develop consistency in ruling procedures.	QS/FC	30	3-18	1980

Table 3, concluded
Non-Technical and Generic Technical Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
GENERIC TECHNICAL RESEARCH NEEDS				
11. Improve methods for the exchange of information gained from operation of resource recovery plants through DOE/EPA/ASME co-sponsored workshops.	SM	100	12	1980
12. Develop standard procedures for economic analysis of resource recovery plants, including life cycle cost analysis.	QS	30	6-8	1980
13. Develop standard test methods to evaluate unit operation performance.	QS/NA ⁽⁴⁾	200	36	1980
14. Develop central, standardized public data base containing technical and economic data for resource recovery and source separation facilities.	QS	75	12	1981
15. Develop standard procedures for communities to collect and report waste generation data.	QS	20	3	1980
16. Develop standard methods for analyzing and estimating the components of MSW.	QS	30	6	1980
17. Develop a resource recovery design handbook.	QS	200	12 ⁽⁵⁾	1981
18. Develop standard engineering manuals on recommended dust, fire, noise, and explosion control practices.	FC	—	—	1980

(1)BS — Bench-scale / PS — Pilot-scale / DC — Demonstrate at Commercial-scale / TE — Test and Evaluation at Commercial Facility / QS — Qualitative or Quantitative Study / SM — Symposium / FC — Federal Coordination or Assistance / NA — No Action Necessary; work being addressed or more appropriately addressed by others / (2)Research program should include all three research needs in one contract. / (3)Research program should include all three research needs in one contract. / (4)Standard procedures may best be achieved through ASME Committee E38.08. / (5)This Task is a continual effort over many years; only one year of needed funds is presented.

Table 4
Mechanical Separation Systems and Source Separation Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
PREPROCESSING FOR FUEL PREPARATION				
<i>General</i>				
1. Develop a systems engineering approach to RDF production process design.	QS	100	10-12	1980
	QS	350	24	1982
2. Exchange experiences gained at operational RDF facilities by symposium and publication.	SM	100	12	1980
<i>Size Reduction</i>				
3. Determine effect of hammer wear on RDF size, quality, plant operating cost, and subsequent operations.	TE	80	8	1980
4. Evaluate shredder safety concepts at a pilot or test facility to determine the most effective explosion control system.	PS	75	12	1980
5. Evaluate a flail mill for size reduction at a pilot-scale facility.	PS	80	7	1980
6. Evaluate ring grinders and disc screens for removal of textile and deformable plastics at a pilot-scale facility.	PS	75	6	1980
Evaluate and compare trommels and disc screens at an operating facility.	TE ⁽²⁾	50	5	1980
<i>Materials Handling and Storage</i>				
8. Evaluate pneumatic and mechanical conveyors at operating facilities to determine economic and practical limitations.	NA	—	—	1980
9. Evaluate rotary air locks at operating facilities to determine best design.	TE	75	9	1980
10. Evaluate operating RDF storage bins and investigate alternatives.	TE	75	6	1980
11. Evaluate drying RDF to alleviate bridging and set-up problems in storage through pilot-scale testing.	PS	50	6	1980
12. Evaluate transport and storage of powdered RDF in an oil slurry through pilot-scale testing.	PS/NA ⁽³⁾	50	6	1981
<i>Densification</i>				
13. Evaluate a pellet mill and briquette press for d-RDF production.	PS	175	8	1980
	TE	50	6	1981
<i>Full Plant Evaluations</i>				
14. Conduct detailed performance tests of embrittlement and wet-pulped processes at fully operational facilities.	TE	500	12	1981

Table 4, concluded
Mechanical Separation Systems and Source Separation Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
IN-PLANT MATERIALS RECOVERY				
<i>Ferrous Metals Recovery</i>				
15. Develop mathematical models through pilot- and full-scale testing to describe magnetic removal of ferrous materials.	PS	75	6	1981
	TE	100	8	1982
16. Evaluate secondary (clean-up) unit operations for ferrous scrap recovery through pilot-scale testing.	PS	125	12	1981
17. Support development of standard recovered ferrous material specifications by ASTM that are market specific.	FC	—	—	1980
<i>Aluminum and Glass Recovery</i>				
18. Evaluate technical and economic feasibility of aluminum and glass separation based upon New Orleans Recovery I and Monroe County, New York, experiences.	TE	200	6	1981
19. Develop design equations for unit operations for aluminum and glass separation.	PS	150	12	1982
SOURCE SEPARATION				
20. Develop a methodology for determining the net energy saving or expenditure (per ton of recycled material) associated with various source separation procedures.	QS	50	6	1980
21. Develop a source separation implementation manual for municipal officials that can be used to determine manpower and vehicle requirements and realistic costs.	QS	100	12	1980

(1)BS — Bench-scale / PS — Pilot-scale / DC — Demonstrate at Commercial-scale / TE — Test and Evaluation at Commercial Facility / QS — Qualitative or Quantitative Study / SM — Symposium / FC — Federal Coordination or Assistance / NA — No Action Necessary; work being addressed or more appropriately addressed by others / (2)Trommel study presently being addressed by DOE. / (3)Work may be more appropriately carried out by the private sector.

Table 5
Combustion Systems Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
MASS BURNING STEAM GENERATION				
1. Evaluate performance of a bag house for particulate emission control at a fully operational plant.	DC	200	18	1980
2. Conduct a detailed performance test at a fully operational facility.	TE	250	8-12	1980
3. Evaluate the effects of boiler operating characteristics on air emissions.	(2)	-	-	-
4. Develop end-use for combusted residue through further initiation of road paving demonstration projects.	FC	-	-	1980
5. Improve boiler design and tube metallurgy to increase upper limit in operating temperature and pressure.	NA	-	-	-
6. Conduct a demonstration of European crane technology at a fully operational facility.	FC	-	-	1981
PREPARED FUEL FIRING IN BOILERS				
<i>Co-Fired Boilers</i>				
7. Examine RDF combustion on a bench-scale to develop relationships between RDF properties, furnace residence time and combustion conditions.	BS	100	9-12	1980
8. Conduct detailed boiler performance tests at fully operational RDF co-fired facilities to examine combustion characteristics.	TE	125	8	1980
9. Develop mathematical models based on pilot-scale study to predict the combustion behavior of RDF as a function of RDF properties and furnace conditions and physical characteristics.	PS/TE	300	18-24	1981
10. Evaluate alternative emission control devices at a fully operational facility.	DC	150	12-24	1981
11. Develop guidelines for design of dedicated and retrofit boilers specific to co-firing RDF.	QS	100	8	1982
12. Develop an accounting procedure for use in determining the true cost of co-firing RDF.	QS	35	4	1980
<i>Dedicated Boilers</i>				
13. Conduct a detailed performance test at a fully operational facility.	TE	250	12	1981

Table 5, Concluded
Combustion Systems Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
CONTROLLED AIR MODULAR COMBUSTION				
14. Evaluate the cost/benefit of a coarse RDF feedstock.	TE ⁽³⁾	200	12	1980
15. Evaluate performance of a bag house for particulate emission control at a fully operational facility.	DC	75	12	1980
16. Develop a new fuel control system to reduce auxiliary fuel consumption.	DC	100	12	1982
17. Develop a seminar program for municipal officials on management of controlled air modular combustion facilities.	FC	-	-	1980
CO-DISPOSAL				
<i>Refuse Combustors</i>				
18. Evaluate the economics of firing predried sewage sludge versus firing dewatered, undried sludge using existing design and cost data.	QS	30	4	1980
19. Evaluate firing predried sewage sludge versus firing dewatered, undried sludge on heat recovery efficiency, boiler corrosion, slagging, and air emissions at a fully operational facility.	TE	200	12-18	1980
20. Evaluate the effects of co-disposal on long-term boiler corrosion at a fully operational facility.	TE	100	24	1981
21. Evaluate the technical and economic aspects of premixing sewage sludge in an RDF processing plant, and examine the combustion properties of the RDF/sludge mixture through pilot- and full-scale evaluation.	PS	100	8-12	1981
22. Characterize ash residue at a co-disposal facility to determine disposition requirements and end use.	TE	50	6	1981
<i>Sludge Combustors</i>				
23. Develop costs to retrofit sludge combustors to handle RDF as a function of sludge combustor capacity and RDF availability.	QS	50	6	1980
24. Evaluate technical and economic impact of RDF quality on MHF and FBF operations.	PS TE	100 200	12 12-8	1980 1981
25. Evaluate air emissions as a function of RDF quality for MHF and FBF at a fully operational facility, and specify the need for pollution control equipment.	(4)	-	-	-
26. Evaluate RDF/sludge feed methods for a FBF at a fully operational facility.	NA	-	-	1980
27. Characterize ash residue and determine disposition requirements and end use.	(5)	-	-	-

(1)BS - Bench-scale / PS - Pilot-scale / DC - Demonstrate at Commercial-scale / TE - Test and Evaluation at Commercial Facility / QS - Qualitative or Quantitative Study / SM - Symposium / FC - Federal Coordination or Assistance / NA - No Action Necessary; work being addressed or more appropriately addressed by others / (2)Incorporated in Need 1 and 2 work. / (3)Work may be EPA funded. / (4)Incorporated in Need 24 work. / (5)Incorporated in Need 22 work.

Table 6
Pyrolysis Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
RESEARCH PROGRAM				
1. Survey pyrolysis systems which have not reached the demonstration stage to determine the most promising systems for future work.	QS	50	4	1980
2. Select candidate system(s) for pilot plant evaluation.	FC	—	2	1980
3. Design, construct, and evaluate pilot plant system(s).	PS	500-2000	18-30	1981
4. Consider selection of one system for demonstration.	QS	—	—	1983

RESEARCH NEEDS⁽²⁾

General

- Evaluate front-end processing trains specifically designed for pyrolysis.
- Optimize design of air feedlock mechanisms for both vertical gravity feed and ram feeder mechanisms.
- Evaluate various firing configurations for pyrolytic oil.
- Evaluate the cost of combined cycle, gas/steam turbine systems for electric power generation using pyrolysis gas.
- Conduct preliminary economic analyses of pyrolysis end-product conversion technologies.

Indirect-Heated Systems

- Evaluate different heat-conducting materials for use in kilns or externally heated equipment.
- Evaluate char handling systems and char furnace design, including a char/ash separation system.
- Develop uses for product char.
- Evaluate improved kiln configuration designs.

Direct-Heated Systems

Air-Fired

- Improve feed mechanism for vertical bed systems.
- Evaluate improved methods for handling entrained tars and particulates in fluidized bed systems.
- Evaluate the effect of feedstock density on system performance.
- Determine maximum allowable moisture content of feed when co-firing refuse and sewage sludge.

Oxygen-Fired⁽³⁾

- Evaluate more economical methods of refuse infeed.
- Evaluate the effect of degree of front-end processing on system performance.
- Evaluate operation at elevated pressure (40 psig).
- Evaluate alternative methods of gas cleaning to reduce pressure drop and gas velocity.
- Evaluate requirements for wastewater treatment.

Steam-Heated

- Evaluate different reactor vessel configurations to minimize steam/gas flow.
- Evaluate particulate entrainment levels.
- Evaluate metallic aerosol concentrations in the combustion gases.
- Evaluate gas/steam turbine design to optimize system.
- Determine sludge preheater location.

(1)BS — Bench-scale / PS — Pilot-scale / DC — Demonstrate at Commercial-scale / TE — Test and Evaluation at Commercial Facility / QS — Qualitative or Quantitative Study / SM — Symposium / FC — Federal Coordination or Assistance / NA — No Action Necessary; work being addressed or more appropriately addressed by others. / (2)Research needs are to be addressed in pilot plant evaluation of selected system(s). / (3)Research needs being addressed in DOE-sponsored demonstration grant to Dutchess County, New York.

Table 7
Bioconversion Research Needs

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
PRETREATMENT TECHNOLOGY				
<i>Physical</i>				
1. Evaluate effect of dry and wet preprocessing of MSW on digester performance through bench-scale testing.	BS	50	6	1980
2. Evaluate extent of MSW preprocessing necessary for good slurry mixing and handling through pilot-scale testing.	PS	100	8-12	1980
<i>Alkali Pretreatment</i>				
3. Develop and evaluate design concepts for alkali pretreatment to determine cost effective means of achieving high methane yields.	QS	25	4	1981
4. Determine on a bench-scale the degree of lignin removal for maximum production of methane with minimal phenol inhibition.	BS	60	4	1982
<i>Temperature and Pressure Pretreatment</i>				
5. Conduct conceptual design and economic analyses on the "steam gun."	QS	30	3	1980
6. Evaluate the economic benefit of temperature pretreatment for improving methane yield.	QS	15	2	1982
<i>Acid Pretreatment</i>				
7. Evaluate sulfur dioxide pretreatment and autohydrolysis of MSW on a bench-scale.	BS	100	6	1981
8. Conduct economic evaluations of sulfur dioxide pretreatment and autohydrolysis of MSW based on results of bench-scale studies.	QS	30	3	1982
<i>General</i>				
9. Evaluate results of previous experimental and economic evaluations and identify pretreatments which are most promising for subsequent bioconversion processes.	QS	50	6	1982
METHANE RECOVERY TECHNOLOGY				
<i>Anaerobic Digestion</i>				
<i>Conventional Anaerobic Digestion</i>				
10. Complete RefCOM experimental program.	FC	—	—	1980
11. Evaluate alternative front-end processing schemes at RefCOM to improve digestability, particularly removal of textiles and plastics.	TE	500	12	1981
12. Evaluate a wet-pulped RDF feedstock at RefCOM.	TE	500	12	1982
<i>High Solids Digestion Technology</i>				
13. Conduct bench-scale evaluations of fixed and fluidized bed digestion of MSW, and develop conceptual designs and cost estimates for a commercial-scale facility	BS/QS	250	12-24	1981
<i>Multi-Stage Digestion</i>				
<i>Two-Stage Digestion</i>				
14. None	—	—	—	—

**Table 7,
Bioconversion Research Needs**

	Type of Research ⁽¹⁾	Estimated Cost (\$1,000)	Estimated Duration of Work (Months)	Estimated Start Date
<i>Two-Phase Digestion</i>				
15. Conduct a bench-scale evaluation of two-phase digestion of MSW to determine conditions for maintenance of microbial populations and maximum production of methane using kinetic control.	BS	100	12	1981
16. Conduct detailed engineering/cost analysis of two-phase digestion system.	QS	50	4	1982
<i>Plug Flow Digestion</i>				
17. Conduct a bench-scale evaluation of plug flow digestion of MSW to develop kinetic data.	BS	90	12	1981
18. Conduct detailed engineering/cost analysis of plug flow digestion system.	QS	35	4	1982
<i>Landfill Gas Recovery</i>				
19. Increase technology transfer of landfill gas recovery through Federally sponsored regional seminars.	SM	100	12	1980
20. Demonstrate enhanced methane recovery from landfills.	PS/DS ⁽²⁾	400	12-24	1980
21. Evaluate health and environmental effects of enhanced landfill operation.	DS	—	—	1982
22. Develop models for predicting potential methane production from existing and new landfills, with and without enhancement techniques.	NA ⁽³⁾ QS	— 100	— 12	1980 1981
23. Evaluate utilization alternatives for landfill gas.	NA	—	—	1980
24. Evaluate shredded versus conventional landfill for gas recovery.	NA	—	—	1980
<i>Methane End-Use Technology</i>				
25. Complete DOE RefCOM and landfill gas utilization evaluations to determine need for gas purification systems.	FC	—	—	1980
26. Develop lower cost gas scrubbing technology — e.g., water scrubbing, membrane processes.	PS/DS ⁽⁴⁾	200	12	1981
27. Evaluate sequential biological shift conversion and methanation at high pressure in bench-scale studies.	BS ⁽⁴⁾	100	12	1981
28. Evaluate simultaneous biological shift conversion and methanation at moderate pressure in bench-scale studies.	BS ⁽⁴⁾	100	12	1981

**Table 7, Concluded
Bioconversion Research Needs**

ALCOHOL TECHNOLOGY

Enzymatic and Acid Hydrolysis

29. Perform conceptual designs and preliminary engineering for commercial-scale enzymatic and acid hydrolysis of MSW facilities. Conduct economic analyses to determine feasibility of each system.

QS 150 8 1980

30. Demonstrate enzymatic or acid hydrolysis of MSW to ethanol at a 50 tpd semi-works facility.

DS 5,000-10,000 60 1981

31. Continue bench- and pilot-scale evaluations of enzymatic or acid hydrolysis of MSW to optimize process.

BS/PS 500 24 1981

OTHER CHEMICAL PRODUCTION TECHNOLOGIES

32. Review prior work on aerobic and anaerobic digestion of biomass and sewage sludge, and identify product chemicals of interest.

QS 50 6 1981

33. Conduct bench-scale studies on promising digestion techniques for chemicals production using an MSW feedstock.

BS⁽⁵⁾ 400 12-18 1982

(1)BS - Bench-scale / PS - Pilot-scale / DC - Demonstrate at Commercial-scale / TE - Test and Evaluation at Commercial Facility / QS - Qualitative or Quantitative Study / SM - Symposium / FC - Federal Coordination of Assistance / NA - No Action Necessary; work being addressed or more appropriately addressed by others. / (2)Field testing using 1-acre plot. / (3)Support present work by PG&E and Dynatech R&D Co. / (4)Necessity to conduct research is dependent on outcome of Need 25. / (5)Results of similar on-going biomass studies should be completed prior to initiation of work with MSW.

ACKNOWLEDGEMENTS

The authors wish to thank Dynatech R&D Company, which assisted in the evaluation of bioconversion technologies and also provided support at the Research Needs Workshop. The many knowledgeable people who participated in the Research Needs Workshop provided important insight into development of research programs which match the time needs of the resource recovery industry. The exchange with the National Research Council Panel on Urban Waste also provided much valuable information in development of the research, development, and demonstration plan.

DE

PS

31

2

1

TABLE OF CONTENTS

	<u>Page</u>
List of Tables	xxx
List of Illustrations	xxxiv
SECTION 1 AVAILABILITY OF WASTES AS FUELS	1
1.1 Municipal Solid Waste and Sewage Sludge	1
1.1.1 Quantities and Composition	3
1.1.2 Availability for Processing	5
1.2 Industrial Solid Wastes	5
1.2.1 Quantity and Composition	11
1.2.2 Availability for Processing	11
1.3 Forestry Wastes	14
1.3.1 Quantity and Composition	14
1.3.2 Availability for Processing	16
1.4 Agricultural Wastes	
1.4.1 Quantity and Composition	20
1.4.2 Availability for Processing	23
SECTION 2 NONTECHNICAL ISSUES AND RESEARCH NEEDS	29
2.1 Introduction	29
2.2 Current Debates on Implementation Approach	29
2.3 Assumptions for Evaluation of Research Needs	31
2.4 Resultant Problems in the Implementation Process	31
2.4.1 Wastestream Control	34
2.4.2 Markets for Recovered Fuel and Energy Products	38
2.4.3 Inherent Problems in the Implementation Process	42
2.4.4 Complexities and Inconsistencies in IRS Regulations and Rulings on Financing	44
SECTION 3 GENERIC, TECHNICAL RESEARCH NEEDS	47
3.1 Introduction	47
3.2 Research Needs and Recommended Research Programs	47

TABLE OF CONTENTS (continued)

	<u>Page</u>
SECTION 4 MECHANICAL SEPARATION SYSTEMS	55
4.1 Preprocessing for Fuel (Feedstock) Preparation	55
4.1.1 Technology Description	55
4.1.1.1 Fluff RDF	57
4.1.1.2 Densified RDF	59
4.1.1.3 Powdered RDF	60
4.1.1.4 Wet-Pulped RDF	61
4.1.2 Technology Status	62
4.1.2.1 Technical	62
4.1.2.2 Economic	73
4.1.2.3 Environmental	74
4.1.3 Research Status	74
4.1.4 Research Needs for MSW Preprocessing	78
4.1.4.1 General	78
4.1.4.2 Size Reduction	79
4.1.4.3 Materials Handling and Storage	81
4.1.4.4 Densification	82
4.1.4.5 Full-Plant Evaluations	83
4.1.5 Research Programs for Mechanical Separation Systems	83
4.1.5.1 General	83
4.1.5.2 Size Reduction	85
4.1.5.3 Materials Handling and Storage	87
4.1.5.4 Densification	88
4.2 In-Plant Materials Recovery	89
4.2.1 Ferrous Metal Recovery	89
4.2.1.1 Technology Description	89
4.2.1.2 Technology Status	90
4.2.1.3 Research Status	94
4.2.1.4 Research Needs for Ferrous Metal Recovery	94

TABLE OF CONTENTS (continued)

	<u>Page</u>
4.2.2 Aluminum Recovery	97
4.2.2.1 Technology Descriptions	97
4.2.2.2 Technology Status	97
4.2.2.3 Research Status	101
4.2.2.4 Research Needs and Research Programs for Aluminum Recovery	102
4.2.3 Glass Recovery	102
4.2.3.1 Technology Description	102
4.2.3.2 Technology Status	103
4.2.3.3 Research Status	104
4.2.3.4 Research Needs and Research Programs for Aluminum and Glass Recovery	105
 SECTION 5 COMBUSTION SYSTEMS	 111
5.1 Mass Burning Steam Generation	111
5.1.1 Technology Description	111
5.1.2 Technology Status	113
5.1.2.1 Technical	113
5.1.2.2 Economic	121
5.1.2.3 Environmental	122
5.1.3 Research Status	122
5.1.4 Research Needs for Mass Burning Steam Generation	124
5.1.5 Mass Burning Steam Generation Research Programs	128
5.1.5.1 Summary	128
5.1.5.2 Detailed Research Programs	129
5.2 Mass Burning, Controlled Air, Modular Combustor with Heat Recovery	131
5.2.1 Technology Description	131
5.2.2 Technology Status	133
5.2.2.1 Technical	133
5.2.2.2 Economic	140
5.2.2.3 Environmental	140

TABLE OF CONTENTS (continued)

	<u>Page</u>
5.2.3 Research Status	140
5.2.4 Research Needs for Controlled Air, Modular Combustors	143
5.2.5 Research Program for Controlled Air, Modular Combustors	146
5.3 Prepared Fuel Combustion Systems	148
5.3.1 Co-Fired Boilers	148
5.3.1.1 Technology Description	148
5.3.1.2 Technology Status	150
5.3.1.3 Research Status	159
5.3.1.4 Research Needs for Prepared Fuel Co-Firing in Boilers	160
5.3.1.5 Research Program for Prepared Fuel Co-Firing in Boilers	164
5.3.2 Dedicated Boilers	165
5.3.2.1 Technology Description	165
5.3.2.2 Research Needs for Prepared Fuel Firing in Dedicated Boilers	167
5.3.2.3 Research Program for Prepared Co-Firing in Dedicated Boilers	167
5.4 Co-Disposal of MSW and Sewage Sludge	167
5.4.1 Technology Description	168
5.4.2 Technology Status	169
5.4.2.1 Technical	169
5.4.2.2 Economics	177
5.4.2.3 Environmental	178
5.4.3 Research Status	181
5.4.4 Research Needs for Co-Disposal	182
5.4.4.1 Refuse Combustors	182
5.4.4.2 Sludge Combustors	184
5.4.5 Research Programs for Co-Disposal	185
5.4.5.1 Refuse Combustors	185
5.4.5.2 Sludge Combustors	187

TABLE OF CONTENTS (continued)

	<u>Page</u>
SECTION 6 PYROLYSIS SYSTEMS	193
6.1. Indirect-Heated Systems	196
6.1.1 Technology Description	196
6.1.2 Technology Status	198
6.1.2.1 Technical	198
6.1.2.2 Economic	202
6.1.2.3 Environmental	202
6.1.3 Research Status	203
6.1.4 Research Needs for Indirect-Heated Pyrolysis Systems	204
6.2 Direct-Heated Systems	205
6.2.1 Air-Fired, Direct-Heated Systems	209
6.2.1.1 Technical Description	209
6.2.1.2 Technology Status	210
6.2.1.3 Research Status	212
6.2.1.4 Research Needs for Direct-Heated, Air-Fired Pyrolysis Systems	213
6.2.2 Oxygen-Fired, Direct-Heated Systems	215
6.2.2.1 Technology Description	215
6.2.2.2 Technology Status	215
6.2.2.3 Research Status	218
6.2.2.4 Research Needs for Oxygen-Fired, Direct-Heated Systems	218
6.2.3 Steam Direct-Heated Systems	220
6.2.3.1 Technology Description	220
6.2.3.2 Technology Status	220
6.2.3.3 Research Status	222
6.2.3.4 Research Needs for Steam Direct-Heated Systems	223
6.3 Other Systems	224
6.3.1 Description	224

TABLE OF CONTENTS (continued)

	<u>Page</u>
6.4 Additional Uses for Pyrolytic Products	226
6.4.1 General	226
6.4.2 Application to this Analysis	226
6.5 Summary of Pyrolysis Research Needs	227
6.5.1 Research Needs Applicable to Pyrolysis in General	227
6.6 Pyrolysis Research Program	230
SECTION 7 BIOCONVERSION PROCESSES	235
7.1 Pretreatment Technology	235
7.1.1 Physical Pretreatment	235
7.1.1.1 Technology Status	235
7.1.1.2 Research Status	237
7.1.1.3 Research Needs for Physical Pretreatment	237
7.1.1.4 Research Program for Physical Pre-treatment	239
7.1.2 Alkali Pretreatment	239
7.1.2.1 Process Description	239
7.1.2.2 Technology and Research Status	239
7.1.2.3 Research Needs for Alkali Pretreatment	241
7.1.2.4 Research Program for Alkali Pretreatment	241
7.1.3 Temperature and Pressure Pretreatment	242
7.1.3.1 Process Description	242
7.1.3.2 Technology and Research Status	242
7.1.3.3 Research Needs for Temperature and Pressure Pretreatment	243
7.1.3.4 Research Program for Temperature and Pressure Pretreatment	243
7.1.4 Acid Pretreatment	244
7.1.4.1 Process Description	244
7.1.4.2 Technology and Research Status	245
7.1.4.3 Research Needs for Acid Pretreatment	246
7.1.4.4 Research Program for Acid Pretreatment	247

TABLE OF CONTENTS (continued)

	<u>Page</u>
7.1.5 Irradiation Pretreatment	247
7.1.5.1 Process Description	247
7.1.5.2 Technology and Research Status	248
7.1.5.3 Research Needs for Irradiation Pre-treatment	249
7.1.6 Summary of Pretreatment Research Needs	249
7.1.7 General Research Approach for Pretreatment Technologies	249
7.2 Methane Technology	249
7.2.1 Anaerobic Digestion	251
7.2.1.1 Conventional Digestion	251
7.2.1.2 High Solids Digestion	265
7.2.1.3 Multi-Stage Digestion	269
7.2.1.4 Summary of Anaerobic Digestion Research Needs	277
7.2.2 Landfill Gas Recovery	277
7.2.2.1 Gas Extraction from Existing Landfills	277
7.2.2.2 Methane Enhancement in Landfills	284
7.2.2.3 Research Needs for Landfill Gas Recovery	291
7.2.2.4 Research Program for Landfill Gas Recovery	296
7.2.3 Methane End-Use Technology	297
7.2.3.1 Acid Gas Scrubbing	297
7.2.3.2 Biomethanation of Synthesis Gases	301
7.3 Alcohol Technology	308
7.3.1 Enzymatic Hydrolysis to Ethanol Technology	308
7.3.1.1 Process Description	308
7.3.1.2 Technology and Research Status	312
7.3.1.3 Research Needs for Enzymatic Hydrolysis	319
7.3.1.4 Research Program for Enzymatic Hydrolysis	320

TABLE OF CONTENTS (continued)

	<u>Page</u>
7.3.2 Acid Hydrolysis to Ethanol Technology	322
7.3.2.1 Process Description	322
7.3.2.2 Technology Status	322
7.3.2.3 Research Status	325
7.3.2.4 Research Needs for Acid Hydrolysis	327
7.3.2.5 Research Program for Acid Hydrolysis	328
7.4 Organic Acid, Alkanes, and Other Chemical Production Technology	330
7.4.1 Process Descriptions	331
7.4.2 Technology and Research Status	331
7.4.3 Research Needs for Other Chemical Production Technologies	335
7.4.4 Research Program for Other Chemical Production Technologies	337
SECTION 3 SOURCE SEPARATION	349
8.1 Technology Description	349
8.2.1 Technical	349
8.2.2 Economic	352
8.2.3 Environmental	353
8.3 Research Status	354
8.4 Research Needs for Source Separation	357
8.5 Research Program for Source Separation	358
APPENDIX A METHODOLOGY FOR RD&D PLAN DEVELOPMENT	363
A.1 Ranking of Technologies	365
A.1.1 Net Tipping Fee	367
A.1.1.1 Weighting of Cost Components	367
A.1.1.2 Weighting of Tipping Fee Ranges	369
A.1.1.3 Calculation of Net Tipping Fee	369
A.1.1.4 Evaluation of Net Tipping Fee Criterion	373
A.1.2 Potential Service Area	374

TABLE OF CONTENTS (concluded)

	<u>Page</u>
A.1.3 Energy Product Value	374
A.1.4 Material Product Value	377
A.1.5 Potential for Environmental Pollution	379
A.1.6 Waste Type Flexibility	379
A.1.7 Readiness for Commercialization	379
A.2 Summary of RD&D Plan Development Methodology	379
APPENDIX B FACILITIES VISITED DURING RD&D PLAN PREPARATION	385
APPENDIX C LIST OF WORKSHOP ATTENDEES FOR DOE RD&D PLAN REVIEW	389
APPENDIX D MEMBERS OF PANEL ON URBAN WASTE, URBAN RESEARCH COUNCIL	393
GLOSSARY	397

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1-I	Energy Potentially Recoverable from Wastes - 1980	2
1.1-I	Municipal Solid Waste Generation	4
1.1-II	Typical Heating Values of MSW Components	6
1.1-III	Typical Proximate and Ultimate Analyses of MSW (Raw Refuse)	7
1.1-IV	Typical Chemical Composition of Raw and Digested Sludge	8
1.1-V	Energy Potentially Recoverable from MSW	9
1.1-VI	Energy Savings Through Materials Recycling	10
1.2-I	Typical Industrial Solid Wastes	12
1.2-II	Energy Potentially Recoverable from Industrial Wastes	13
1.3-I	Estimated Residue Generation for Forestry Wastes	15
1.3-II	Heating Values of Various North American Tree Woods and Barks	17
1.3-III	Heating Value of Foliage (Softwood)	18
1.3-IV	Energy Potentially Recoverable from Forested Wastes	19
1.4-I	Animal Waste Generation Projections	21
1.4-II	Characteristics of Typical Animal Manures	22
1.4-III	Energy Potentially Recoverable from Agricultural Wastes	24
2.4-I	Nontechnical Research Needs	35
3.2-I	Summary of Generic, Technical Research Needs	48
4.1-I	Comparative RDF Characteristics	58
4.1-II	RDF Facilities Operating or in Shakedown	63
4.1-III	Process Sequence of Fluff RDF Facilities	69
4.1-IV	Research Status of Preprocessing Unit Operations	76
4.2-I	Facilities with Ferrous Separators	91

LIST OF TABLES (continued)

<u>Table</u>		<u>Page</u>
4.2-II	Research Needs for Ferrous Metal Recovery	95
4.2-III	Status of Aluminum Recovery from MSW	98
4.2-IV	Recovered Aluminum Specifications	99
4.2-V	Research Needs for Aluminum and Glass Recovery	106
5.1-I	Status of Mass Burning Steam Generators	114
5.1-II	Technical Research Needs for Mass Burning Steam Generation	125
5.2-I	Status of Controlled Air, Modular Combustors with Heat Recovery	134
5.2-II	Comparison of Modular Incinerator Costs	141
5.2-III	Research Needs for Controlled Air, Modular Combustion	144
5.3-I	RDF Co-Combustion Experiences	151
5.3-II	Current RDF Prices	158
5.3-III	Research Needs for Prepared Fuel Co-Firing in Boilers	161
5.4-I	Applicability of New Source Performance Standards to Co-combustion of MSW and Sewage Sludge	179
5.4-II	Co-Disposal Technical Research Needs	183
6.1-I	Status of Indirect-Heated Pyrolysis Systems	199
6.5-I	Technical Research Needs for Pyrolysis	228
6.6-I	Schedule for Pilot-Scale Evaluation of Pyrolysis Systems	231
7.1-I	Summary of Research Needs for Pretreatment Technologies	250
7.2-I	Economic Analysis of Conventional Anaerobic Digestion	262
7.2-II	Filtrate-Centrates Characteristics [39]	264
7.2-III	Summary of Research Needs for Anaerobic Digestion Technology	278
7.2-IV	Major Landfill Gas Recovery/Processing/Utilization Projects in the United States	279
7.2-V	Economic Analysis of Conventional Landfill Gas Recovery	285

LIST OF TABLES (continued)

<u>Table</u>		<u>Page</u>
7.2-VI	Research Projects on Enhanced Landfills	288
7.2-VII	Economic Analysis of Enhanced Landfill Gas Recovery	292
7.2-VIII	Research Needs for Landfill Gas Technology	294
7.2-IX	Cost Summary of Gas Purification Systems [86] Delivery Pressure: 1000 psig	299
7.2-X	Cost Summary of Gas Purification Systems [86] Delivery Pressure: 125 psig	300
7.2-XI	Heat Requirements for Selected Gas Purification Systems [86]	302
7.3-I	Saccharification Developments at Natick Laboratory, 1973 - 1978 [91]	314
7.3-II	Economic Analysis of Enzymatic Hydrolysis to Ethanol Production	318
7.3-III	Summary of Research Needs for Enzymatic Hydrolysis	321
7.3-IV	Economic Analysis of Acid Hydrolysis to Ethanol Production	326
7.3-V	Research Needs for Acid Hydrolysis	329
7.4-I	Economic Analysis of Alkane Production from Municipal Solid Waste	334
7.4-II	Summary of Research Needs for Organic Acid, Alkanes, and Other Chemical Production Technologies	336
A.1-I	Evaluation of Resource Recovery Technologies	366
A.1-II	Evaluation of Criterion 1 - Net Tipping Fee	368
A.1-III	Capital Cost Calculation - Bioconversion Technologies	370
A.1-IV	Net Tipping Fee Calculation Bioconversion Technologies	371
A.1-V	Evaluation of Potential Service Area	375
A.1-VI	Evaluation of Criterion 3a - Energy Product Value	376
A.1-VII	Evaluation of Criterion 3b - Material Product Value	378

LIST OF TABLES (concluded)

<u>Table</u>		<u>Page</u>
A.1-VIII	Evaluation of Criterion 4--Potential for Environmental Pollution	380
A.1-IX	Evaluation of Criterion 5--Waste Type Flexibility	381
A.1-X	Evaluation of Criterion 6--Readiness for Commercialization	382

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
4.1-1	Cumulative Distributions of Raw Waste	56
5.1-1	Typical Mass Burning Steam Generator	112
5.2-1	Typical Controlled Air, Modular Combustor	132
6.1-1	Basic Moderate Temperature (1000°-1400°F) Horizontal Retort Pyrolysis System	197
6.2-1	Basic High Temperature Vertical Bed Pyrolysis Reactor	207
6.2-2	Typical Vertical Fluidized Bed Pyrolysis Reactor	208
7.2-1	Flow Diagram Illustrating Processes Involved in the Anaerobic Digestion of Municipal Solid Waste	252
7.2-2	Flow Sheet of Anaerobic Digestion Process for Solid Waste Utilization used for Dynatech Economic Analysis [35]	253
7.2-3	Material Balance for Waste Digestion Process [35]	259
7.2-4	Heat and Mechanical Power Requirements for the Waste Digestion Process [35]	260
7.2-5	Packed Bed Anaerobic Digester	267
7.2-6	A Cross-sectional Diagram of an Enhanced Sanitary Landfill	287
7.2-7	Biological Shift Conversion and Methanation Flowsheet [87]	304
7.2-8	Unit Cost for CH ₄ Production from MSW including Effluent Disposal Costs [87]	305
7.3-1	Enzymatic Hydrolysis to Ethanol--Flowsheet	309
7.3-2	Process Design of Pilot Plant for Cellulase Produc- tion at U.S. Army Natick Research and Development Command, Natick, Massachusetts	310
7.3-3	Process Design of Pilot Plant for Hydrolysis of Newspaper at U.S. Army Natick Research and Development Command, Natick, Massachusetts	311
7.3-4	Material Balance for Enzymatic Production of 95% Ethanol from Cellulosic Substances	317
7.3-5	Acid Hydrolysis to Ethanol--Flowsheet	323
7.4-1	Process to Produce Liquid Hydrocarbon Fuels from Biomass	333

SECTION 1
AVAILABILITY OF WASTES AS FUELS

Soaring energy prices and a decreasing availability of raw materials have led a growing number of government agencies, businesses and individuals to look toward wastes as a valuable and replenishable fuel source. The reuse of materials can result in significant energy savings while alleviating certain environmental problems.

Conversion of wastes into energy has progressed furthest in the municipal solid waste field. Only limited efforts have been directed toward energy extraction from industrial solid wastes. Use of forestry waste is also small, being centered mainly in the forest products industry. Limited work is being done on recovery of methane from animal wastes, but use of agricultural crop residues as a feedstock for methane production by anaerobic digestion appears economically unfeasible.

The energy potentially recoverable from all solid wastes represents about one-tenth of the current 75 quads of energy consumed annually in the U.S. Even so, many additional benefits will be realized through using wastes as fuel. Less refuse will have to be disposed of, which will extend the life of present sanitary landfills. Also, virgin materials and fossil fuels can be conserved.

Municipal, industrial, agricultural and forestry wastes are usually the major concern in waste utilization, and each is discussed separately in this section. Table 1-I is a summary of the total energy potentially recoverable from these wastes in 1980 if all are used as energy sources.

1.1 Municipal Solid Waste and Sewage Sludge

Municipal solid waste (MSW) can be defined as the wastes generated by the residential, commercial and institutional sectors of a population. Usually this definition excludes mining wastes, demolition and construction debris, junked automobiles and street

Table 1-I 9

Energy Potentially Recoverable From Wastes - 1980

Waste Type	Total Quantity Generated (10^6 Tons)	Available Energy (Quads)	Barrels/Year ^a Crude Oil Equivalent (10^6 Barrels)
Municipal Solid Waste	175	1.58	272
Sewage Sludge	5	0.07	12
Industrial	83	1.00	171
Agricultural Manures	54	0.65	112
Crops	367	3.90	669
Forestry	<u>120</u>	<u>2.03</u>	<u>351</u>
Total	804	9.23	1,587

^aOne barrel of crude oil = 5.8×10^6 Btu.

sweepings. The large quantities of MSW generated and the methods used in its disposal constitute a major environmental concern. In some standard metropolitan statistical areas (SMSA), MSW may be suitable for large-scale central processing; but in other rural areas, it is still prohibitively expensive to collect and aggregate these wastes.

Municipal sewage sludges, which are excluded from MSW, are also generated in sufficient quantities so that their disposal can have significant effects on the environment. The solids fraction of such sludge is typically 40 to 60 percent volatile organic material with the remainder of the solids being minerals, metals and inert compounds.

1.1.1 Quantities and Composition

Municipal solid waste flows vary widely in composition and generation rate, and consequently no one estimate can be considered the most accurate. A need for waste flow data on a municipality-by-municipality basis is apparent, since nationwide totals cannot be used for local planning purposes.

In 1975, the EPA, using government and industry trade association statistics, estimated that 136 million tons of solid waste were generated by the residential and commercial sectors of the U.S. (3.4 lbs/capita/day) [1]. This is shown in Table 1.1-I, with projections for 1980, 1985 and 1990. The 1975 EPA estimates are the standards for most recent studies on municipal solid waste flows.

The paper, glass and metals fractions of MSW still dominate the waste materials category. The present recovery of these constituents is small and opportunities for energy recovery are not being fully realized.

Roughly 80 percent of all municipal post-consumer waste is a potential source of energy [2]. This organic portion of the waste stream has a heating value of about 4500 Btu/lb -- this heating value will no doubt rise in the future with the projected increase in the paper and plastics fractions of MSW. Typical heating values

Table 1.1-I
Municipal Solid Waste Generation ^a
(10⁶ Tons)

	<u>1975</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>
Total Gross Discards ^a	136	175	201	225
Net Waste ^b Disposed	128	156	166	167

^a Residential and Commercial sector waste generation only.

^b Net waste refers to total gross discards minus materials recovered.

of components of MSW are shown in Table 1.1-II. A typical proximate and ultimate analysis of raw refuse is shown in Table 1.1-III.

Municipal sewage treatment plants produce about 5 million dry tons of sludge per year [5]. Of this amount, 35 percent is presently being incinerated, with the remainder of the sludge being landfilled, ocean dumped, or spread on agricultural land.

The composition of sludges varies considerably over time and from one treatment plant to another. Unfortunately, there is limited data available on the change in sludge characteristics as a function of plant location. The data presented in Table 1.1-IV show a typical composition of primary and digested sludge.

1.1.2 Availability for Processing

Table 1.1-V shows the energy potentially recoverable from MSW in 1975, 1980, 1985 and 1990. Assuming MSW has an average heating value of 4500 Btu/lb, 1.58 quads could theoretically be recovered from the 175 million tons of MSW projected in 1980. Table 1.1-VI shows the maximum potential energy saving from recycling the glass, ferrous and nonferrous metal fractions of MSW.

In summary, while waste flow estimates and recycling potentials of MSW and sewage sludge have been presented in many recent studies, the analyses were invariably based on data collected in 1975 or earlier. Therefore, if more accurate national waste generation estimates are needed, this information should be updated.

1.2 Industrial Solid Wastes

Industrial solid wastes are made up of process and nonprocess solid wastes. The nonprocess solid wastes typically consist of office and cafeteria wastes, which are normally included in municipal solid waste flows. These wastes are common to most industries and are collected either privately or publicly. Process wastes are the wastes generated from the manufacturing process itself; they vary from industry to industry, depending on the product being produced.

Table 1.1-II

Typical Heating Values of MSW Components

<u>Component</u>	<u>Btu/lb.</u>
Food Waste	
Garbage	8,484
Fats	16,700
Rubbish	7,572
Paper	7,096
Leaves	7,693
Grass	6,000
Wood	8,613
Brush	7,900
Greens	7,077
Dirt	3,790
Oils, Paints	13,400
Plastics	14,368
Rubber	11,330
Rags	7,652
Leather	8,850

Source: Reference 3.

Table 1.1-III

Typical Proximate and Ultimate Analyses of MSW
(Raw Refuse)

Proximate Analysis

Moisture	27.0%
Volatiles	44.0%
Fixed Carbon	7.0%
Noncombustibles	22.0%

Ultimate Analysis

H ₂ O	27.0%
Carbon	25.5%
Hydrogen	3.4%
Oxygen	21.5%
Nitrogen	0.6%
Noncombustibles	22.0%

Heating Value	4500 Btu/lb
---------------	-------------

Source: Reference 4.

Table 1.1-IV

Typical Chemical Composition of Raw and Digested Sludge

Item	<u>Raw Primary Sludge</u>		<u>Digested Sludge</u>	
	Range	Typical	Range	Typical
Total dry solids (TS), %	2.0-7.0	4.0	6.0-12.0	10.0
Volatile solids (% of TS)	60-80	65	30-60	40
Grease and fats (ether soluble, % of TS)	6.0-30.0	...	5.0-20.0	...
Protein (% of TS)	20-30	25	15-20	18
Nitrogen (N, % of TS)	1.5-4.0	2.5	1.6-6.0	3.0
Phosphorus (P_2O_5 , % of TS)	0.8-2.8	1.6	1.5-4.0	2.5
Potash (K_2O , % of TS)	0-1.0	0.4	0.0-3.0	1.0
Cellulose (% of TS)	8.0-15.0	10.0	8.0-15.0	10.0
Iron (not as sulfide)(mg/l)	2.0-4.0	2.5	3.0-8.0	4.0
Silica (SiO_2 , % of TS)	15.0-20.0	...	10.0-20.0	...
pH	5.0-8.0	6.0	6.5-7.5	7.0
Alkalinity (mg/l as $CaCO_3$)	500-1,500	600	2,500-3,500	3,000
Organic acids (mg/l as HAc)	200-2,000	500	100-500	200
Thermal content (Btu/lb dry solids)	6,800-10,000	7,600 ^a	2,700-6,800	4,000 ^b

a

Based on 65 percent volatile matter.

b

Based on 40 percent volatile matter.

Source: Reference 6.

Table 1.1-V

Energy Potentially Recoverable from MSW

<u>Year</u>	<u>Total Quantity^a MSW Generated (10⁶ tons)</u>	<u>Energy Recoverable^b (Quads)</u>
1975	136	1.22
1980	175	1.58
1985	201	1.81
1990	225	2.03

^a1975 assumes 3.4 lbs/capita/day.
 1980 assumes 4.3 lbs/capita/day.
 1985 assumes 4.7 lbs/capita/day.
 1990 assumes 5.0 lbs/capita/day.

^bBtu value of MSW = 4500 Btu/lb.

Source: Reference 1

Table 1-1-VI

Energy Savings Through Materials Recycling

<u>Material</u>	<u>Amount Available in SMSAs in 1975 (10⁶ tpy)</u>	<u>Estimated Recovery Efficiency</u>	<u>Potential Recovery (10⁶ tpy)</u>	<u>Energy Savings (10⁶ Btu/Ton)</u>	<u>Total Potential Material Energy Savings (Quads)</u>
Glass	9.8	64	6.3	2.5	0.016
Ferrous	8.1	94	7.6	42.2	0.321
Aluminum	0.3	80	0.24	64.5	0.015
Other Nonferrous	0.7	70	0.49	241.5	<u>0.118</u>
					0.470

Source: Reference 7.

1.2.1 Quantity and Composition

The amount of industrial wastes generated yearly is estimated by the EPA at about 379 million tons [8]. This figure includes 10 to 15 percent hazardous wastes, which leaves 320 to 340 million tons of nonhazardous industrial waste. The wastes from a single industry can consist of chemical sludges, metal scraps, waste plastic, and packaging wastes. Usually 70 to 80 percent of these wastes are disposed of by the industry on its own property [8]. At present, few states have any authority over an industry's methods of disposal.

Some typical solid industrial wastes are shown in Table 1.2-I with their respective fuel values. Paper-making industries tend to have very little seasonal variation in their production rates. An approximate composition of their wastes is 48 percent paper, 43 percent sludge, 4 percent fly ash and metals, and 5 percent wood and miscellaneous scrap [10]. Chemical industries normally generate wastes that are approximately 30 percent combustible, and these wastes also do not vary significantly with the season. The sludge portion of chemical industry wastes is typically the most difficult to handle, and it is often classified as hazardous. Some other major industries that produce large quantities of wastes are the food-processing, primary metals, and the petroleum industries.

1.2.2 Availability for Processing

The energy potentially recoverable from industrial wastes is shown in Table 1.2-II. Since only 25 percent of industrial wastes are available for off-site processing, one quad could theoretically be recovered. This value assumes a heating value for industrial wastes of about 6000 Btu/lb.

It is estimated that industrial waste generation will increase with a growth rate of about 3 percent per year [8]. Increased use of pollution control equipment accounts for a large part of the growth forecast. Methods used for disposal of these wastes will also undoubtedly become more tightly regulated as the Resource

Table 1-2-I

Typical Industrial Solid Wastes^a

<u>Waste</u>	<u>Fuel Value (Btu/lb, dry basis)</u>
Manufacturing Scrap -	
Wood	8,000
Plastics	17,000
Textiles	8,000
Fabrics	10,000
Rubber	12,000
Refuse	6,000
Cardboard	7,500

^aFor reference: The fuel value of Pittsburgh coal is 13,200 Btu/lb.

Source: Reference 9.

Table 1.2-II

Energy Potentially Recoverable from Industrial Wastes
1980

<u>Industrial Wastes</u>	<u>Total Quantity^a (10⁶ Tons)</u>	<u>Energy Potentially^b Recoverable (Quads)</u>
Generated	330	3.9
— Available (disposed of off-site)	82.5	1.0

^aOn a wet weight basis.

^bAssumed heating value of industrial wastes = 6000 Btu/lb.

Conservation and Recovery Act becomes more widely implemented and enforced.

1.3 Forestry Wastes

Forestry wastes are a combination of mill and forest residues. Mill residues are the residues generated from the primary manufacture of timber into various products such as lumber and plywood. Forest residues include logging residues, intermediate cuttings, understory removal and trees killed by natural causes.

Neither mill nor forest residues have value at the present time. The inaccessibility of forest residues has made them uneconomical to retrieve or transport. Mill residues, while more localized, have only been utilized as an energy source by the forest products industry [11]. Mill residues have been used on a limited basis for the co-generation of electricity in forest products plants, but not yet as an energy source in large power grids.

1.3.1 Quantity and Composition

Mill residues are presently generated in very large quantities. Less than half the volume of logs delivered to a mill is used in producing the final product [12, 13]. The total amount of mill residues generated in 1976 was estimated at about 13 million tons dry weight [14]. Table 1.3-I shows projections of forestry waste generation for 1980, 1985, and 1990. These figures include residues generated in the manufacture of lumber, plywood, and miscellaneous wood products such as cooperage, shingles, pilings, and posts.

Logging residues, which can include the stump root systems left in the ground, represent the only widely and readily available source of forest residues. Generally, the above-ground portions of logging residues consist of branches, foliage, and stems too small or defective to be used in producing conventional wood products. The total amount of logging residues left in forests in 1976 was estimated at about 102 million dry tons [14].

Table 1.3-I

Estimated Residue Generation for Forestry Wastes^a

<u>Residue</u>	<u>1976</u>	<u>1980</u>	<u>1985</u>	<u>1990</u>
Mill	13	11	9	6
Forest	102	109	116	124

^a10⁶ dry tons/year

Source: Reference 14

The heating value of mill residues depends on the species of tree, the wood-bark content, and the amount of moisture present. Heating values of representative North American tree species and bark are shown in Table 1.3-II. The values for wood range from about 7,900 to 9,700 Btu/lb on an oven-dry basis (8 percent moisture). Fresh residues will normally have moisture contents of between 40 and 60 percent. The heating values of bark are normally higher than those of wood of the same species because of the higher resin content in bark. Foliage can sometimes be an important component of forest residues, but, unfortunately, little data are available on its heating values. The range of heating values of some softwood foliage is shown in Table 1.3-III.

The ultimate analysis for the wood and bark of various tree species does not vary greatly, and the ash content is low compared with MSW and coal (3 percent or less for wood, 2 to 10 percent for bark). The sulfur content of wood and bark is also negligible when compared with that of coal and heavy fuel oils. Therefore, less sulfur dioxide emissions are produced when wood and bark are burned. The ultimate analysis for foliage appears to be similar to that of wood and bark.

1.3.2 Availability for Processing

The potential recoverable energy from forestry wastes is shown in Table 1.3-IV. These figures pertain only to commercial forest lands and do not include surplus growth or noncommercial timber. In 1976, 115 million tons (dry weight) of mill and logging residues were produced, with an energy content of 1.96 quads [14]. An increase in wood residue production to 125 million dry tons is projected for 1985, which would increase the energy theoretically available to 2.12 quads.

Table 1.3-II

Heating Values of Various North American Tree Woods and Barks

<u>Species</u>	Heating Value (Btu/lb., oven-dry ^a)	
	<u>Wood</u>	<u>Bark</u>
Western Red Cedar	9,700	8,790
Douglas Fir	8,890	9,790
Black Cottonwood	8,800	9,000
Southern Pine	8,600	9,360
Western Hemlock	8,410	9,400
White Oak	8,150	7,070
Red Oak	8,050	8,080
Red Alder	7,990	8,410

^aOven-dry assumes approximately 8% moisture.

Sources: Smith, 1974; Howard, 1973; Mason, 1975; Forest Products Research Society.

Table 1.3-III

Heating Value of Foliage (Softwood)

<u>Species</u>	<u>Range</u>	Heating Value
		<u>(Btu/lb., Oven-dry^a)</u>
Lodgepole Pine		9,050
Southern Pine	8,937 - 9,104	
Ponderosa Pine		
Current Needles	8,267 - 8,690	8,478
1-year-old Needles	8,698 - 8,885	8,791
2-year-old Needles	8,638 - 8,861	8,750
Western White Pine		8,674
Grand Fir		8,651
Western Larch		7,999

^aOven dry assumes approximately 8% moisture.

Source: USDA. Forest Service, 1976

Table 1.3-IV
Energy Potentially Recoverable from Forestry Wastes

<u>Year</u>	<u>Total Quantity Generated (Estimated) (10⁶ Dry Tons)</u>	<u>Energy Recoverable (Quads)</u>
1976 - Mill & Logging Residues	115	1.96
1985 - Mill & Logging Residues	125	2.12

Source: Reference 14

The demands for forestry wastes are expected to increase rapidly in the future because of the projected rapid growth of residue-based industries (pulpwood - double, buildingboard - triple) [15]. The quantities of mill residues generated per board should also decrease with the implementation of improved sawmilling techniques. The expected decrease in the availability of mill residues is shown in Table 1.3-I.

1.4 Agricultural Wastes

Agricultural wastes, as distinguished from food processing wastes, consist of animal wastes and agricultural crop residues. Animal wastes, or manures, are generated in large daily quantities, with large amounts coming from feedlots and poultry farms. Such manures are already available for central processing.

Agricultural crop residues are the plant parts left over in the field or packing shed after the crop is harvested. Field residues, because of their dispersed nature, are usually plowed under and returned to the soil at a minimal disposal cost. Packing shed residues are often sold as cattle feed or disposed of at some cost to the enterprise [16].

1.4.1 Quantity and Composition

The total quantity of animal waste generated in the United States in 1975 is estimated at about 47 million tons (dry weight) [17]. Feedlots are the largest source of this waste; one beef cattle feedlot can generate more than ten dry tons per day. Smaller quantities of residue are generated by animals on hog and poultry farms. Table 1.4-I shows the wastes generated by major farm animals in 1975 and projections for 1985 and 2000.

The heating value of manure depends on the volatile solid content of the dry solid. For livestock waste, this is normally about 80 percent of the total solids (Table 1.4-II). The high moisture

Table 1.4-I

Animal Waste Generation Projections
(10⁶ dry tons)

<u>Animal Manure</u>	<u>1975</u>	<u>1985</u>	<u>2000</u>
Cattle on Feed	19.0	23.6	33.5
Dairy Cattle	17.2	21.3	23.4
Hogs, Market	3.6	6.9	8.8
Broilers/Fryers	4.0	4.4	4.4
Hens, Pullets	<u>3.6</u>	<u>4.5</u>	<u>5.1</u>
Total Animal Manure	47.4	60.7	75.2

Source: Reference 17

Table 1.4-II

Characteristics of Typical Animal Manures

<u>Animal</u>	<u>Total Wet Weight (lb/day)</u>	<u>Solids Content (% of Wet Weight)</u>	<u>Volatile Solids (% of Total Solids)</u>
Dairy Cow (1200 lb)	70	21	80
Beef Steer (800 lb)	50	20	78
Pig (100 lb)	10	25	82
Sheep (60 lb)	6	35	
Egg-Laying Chicken (5 lb)	.4	20	76
Horse	55	20	

Source: Reference 18

content of manure, consequently, makes it uneconomical for use as a fuel or fertilizer. The fertilizer value of manure is greater for the farmer, but even so, the "hottest" chicken manure cannot compare with commercial fertilizer [10]. The expense of transporting manure long distances will have to be weighed against its worth as a fertilizer.

Agricultural crop residues were estimated at about 360 million tons (dry weight) in 1975 [17]. The annual production of major United States agricultural crops in 1980 and 1990 is projected at 367 and 417 x 10⁶ dry tons, respectively. Some of these major crops are corn, wheat, soybeans, sorghum grain, oats, and barley. Agricultural crops frequently have moisture contents well above 55 percent, and ash contents that range from about 20 percent to as high as 40 percent in rice and sugarcane [16]. Seasonality of harvest will affect these values and also the nitrogen, phosphorus, and sulfur contents in the residue. Consequently, the energy content of residue can vary greatly with the season. Normally the energy equivalency of crops is from 15 to 17 x 10⁶ Btu/dry ton.

1.4.2 Availability for Processing

Increased use of animal feedlots in recent years has eased the difficulty of waste collection, but has also led to such nuisances as objectionable odors and flies. The value of manure as an energy feedstock has to be weighed against its potential as a fertilizer or soil conditioner. The energy potentially recoverable from the 47 million tons (dry weight) of animal wastes generated in 1975 was estimated at about 0.57 quads [17]. Projections for 1985 and 2000 are shown in Table 1.4-III.

Agricultural crop waste flows are seasonal. Relatively small amounts of crop residues are available during the winter months. The energy equivalency of the total 1975 United States crop residue of 360 million dry tons is estimated at approximately 3.9 quads [17]. Since residue generation is seasonal, each region of the country should be evaluated individually to determine whether energy

Table 1.4-III

Energy Potentially Recoverable from Agricultural Wastes

Waste Type	1975		1980		1985		1990	
	Tons Available (millions)	Quads Available	Tons Available (millions)	Quads Available	Tons Available (millions)	Quads Available	Tons Available (millions)	Quads Available
Manure	47	0.57	54	0.65	61	0.73	65	0.78
Crop	360	3.9	367	3.9	388	4.1	417	4.4

Source: Reference 12

recovery from crop waste is feasible. The fuel values of crop residues also have to be weighed against the possible ecological implications of their removal. Plant residues are important in maintaining the quality of the soil and environment, and hence their removal for use as an energy source must be weighed against the energy needed to replace them artificially (fertilizer). At present it seems that crop residues should not be harvested for energy conversion because their role in agriculture and in maintaining the ecosystem is more important [17].

REFERENCES: SECTION 1. AVAILABILITY OF WASTES AS FUELS

1. Office of Solid Waste, U.S. Environmental Protection Agency, Fourth Report to Congress, "Resource Recovery and Waste Reduction: Chapter 2, Post-Consumer Solid Waste Generation and Resource Recovery Estimates", (SW-600) 1977.
2. Congress of the U.S., Office of Technology Assessment, "Materials and Energy from Municipal Waste", Volume II - Working Papers, July 1978.
3. Bechtel Corporation, "Fuels from Municipal Refuse for Utilities Technology Assessment," Electric Power Research Institute, EPRI (26-1), March 1975.
4. R. S. Hecklinger, "The Relative Value of Energy Derived from Municipal Refuse," ASME National Solid Waste Processing Conference, Boston, MA, May 23-26, 1976.
5. U.S. Environmental Protection Agency, "Solid Waste Facts, A Statistical Handbook," SW-694, August 1978.
6. U.S. Environmental Protection Agency, "Municipal Sludge Management: Environmental Factors," EPA 430/9-77-004, October 1977.
7. NCRR Bulletin, "Energy Potential of Municipal Refuse," Vol. III, Number 3, 1978.
8. J. P. Lehman, "Growth Potential in the Hazardous Waste Management Service Industry", presented at National Solid Wastes Management Association International Waste Equipment and Technology Exposition, Chicago, Ill., June 2, 1976.
9. W. K. Lombard, "The Economics of Energy Recovery from Industrial Waste Incineration," ASME National Solid Waste Processing Conference, Chicago, Ill., May 7-10, 1978
10. D. G. Wilson, ed., Handbook of Solid Waste Management, Van Nostrand Reinhold Company, New York, NY, 1977.

11. K. Howlett and A. Gamache, "Silvicultural Biomass Farms: Forest and Mill Residues as Potential Sources of Biomass", The MITRE Corporation, MTR-7347, Volume VI, May 1977.
12. J. P. Schuldt and J. O. Howard, "Oregon Forest Industries, Wood Consumption and Mill Characteristics, 1972", Oregon State University Extension Service, Corvallis, OR, 1974.
13. R. H. Page and H. O. Baxter, "A New Look at Residues from Georgia's Primary Wood Manufacturing Industries", Georgia Forest Research Paper No. 78, Georgia Forest Research Council, Macon, GA, 1974.
14. U. S. Department of Agriculture, Forest Service, "Forest Statistics of the U. S. 1977", Review Draft 1978.
15. A. E. Gamache, "Supply-Demand Scenarios", Working Paper prepared for The MITRE Corporation, 1976.
16. Electric Power Research Institute, "Evaluation of the Potential for Producing Liquid Fuels from Biomaterials", University of Oklahoma, AF-974, January 1979.
17. K. A. Miller and G. Crooks, "Availability and Cost of Agricultural and Municipal Residues for Use as Alcohol Fuels Feedstocks", SRI International, SRI Project 7734, September, 1978.
18. K. C. Loehr, "Pollution Implications of Animal Waste - A Forward Oriented Review," U.S. Environmental Protection Agency, Robert S. Kerr, Water Research Center, Oklahoma Special Publication, 1968.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SECTION 2

NONTECHNICAL ISSUES AND RESEARCH NEEDS

2.1 Introduction

Nontechnical research needs address institutional, legal and socio-economic impediments to the resource recovery system implementation process. In resource recovery implementation, certain nontechnical problems consistently arise regardless of the unique circumstances under which each project is initiated. For example, some of the major problems are the establishment of long-term contracts with reluctant energy markets, coordination of the roles of numerous governmental jurisdictions, determination of appropriate financing mechanisms, determination of and compliance with evolving environmental standards, and the organization of multi-community solid waste disposal solutions that meet the needs and requirements of the individual communities and provide an economy of scale in resource recovery. Such institutional problems are directly related to the assumptions that are made about resource recovery, the rationale behind its implementation, and the methods by which it will be procured.

2.2 Current Debates on Implementation Approach

Some experts believe that economically optimal resource recovery systems can best be achieved through large-scale operation. They argue that there are economies of scale which should be taken advantage of in system planning. Their opponents do not believe that such economies are real or that they are significant if they do exist. Economies of scale, they feel, might show up on paper, but in reality they are not sufficient justification for the extensive effort required to bring a large-scale facility on-line.

Another point of disagreement involves the objectives which underlie resource recovery implementation. Some advocate resource recovery as the most economical long-term solution to the problem of solid waste disposal. Their measure of a "best" resource recovery

solution is one which meets disposal needs and has the lowest tipping fee. Others would cite immediate concerns for health and environmental protection as the most important reasons for pursuing resource recovery. The only "best" resource recovery facility for these people is one that is reasonably swiftly implemented and operating.

Any assessment of a "best" resource recovery alternative is complicated by the fact that there is no clear and accepted method by which a set of alternatives can be evaluated. There are numerous qualitative aspects of solid waste disposal solutions that are difficult to measure and compare. To date, given that no resource recovery technology is proven and widely accepted and that no one solution is obviously preferable, the dollar-per-ton index is often the only parameter which can be calculated with some degree of equity. However, a dollar-per-ton figure usually does not fully account for the less tangible costs, risks, and liabilities associated with a project and therefore can be misleading to local decision-makers.

In the past few years, experience in resource recovery implementation has led to the emergence of a preferred procurement approach. This method is the selection of a single firm as a full-service contractor through the evaluation of competitive industry proposals and negotiation of a contract for facility design, construction, and operation. However, this approach carries with it requirements for a lengthy and involved contractor selection process, and often an equally involved contract negotiation process with the selected firm. There are some who feel that this approach is not worth its cost in time and money.

In the same vein, preferred approaches to financing resource recovery have evolved with experience. It is felt that over the next five to ten years resource recovery systems will be financed most often through the issuance of tax-exempt revenue bonds, perhaps in conjunction with equity participation.

2.3 Assumptions for Evaluation of Research Needs

To discuss nontechnical research needs, one must consider a specific procurement and financing approach to implementing resource recovery systems. The following assumptions are considered by MITRE to be valid for the resource recovery industry as it is today, and we anticipate that they will remain valid through the next few years of resource recovery implementation efforts. The list is based on analysis of our project experience and that of other projects across the nation.

- The preferred method for procuring a resource recovery facility is to select a full-service contractor through the evaluation of competitive industry proposals and negotiation of a contract with a single firm for facility design, construction, and operation.
- The majority of resource recovery facilities should be financed through the sale of revenue bonds and not capitalized as general obligations against state or local governments.
- Large-scale, localized, multi-community projects are often the most economical and most responsive solutions to waste disposal problems.
- Long-term financing and operating contracts are necessary elements of such solutions.
- Leadership in the implementation of resource recovery must be at the state level.

2.4 Resultant Problems in the Implementation Process

Together, the above assumptions define a resource recovery implementation process which is complex and time-consuming. Institutional problems can cause delays which further lengthen the implementation process to the point where it is not only costly but also more prone to ultimate failure.

For example, economies of scale and cooperative regional approaches to solid waste management argue for large-scale facilities which carry with them high capital costs. Because of uncertainties, such as the amount of waste that will be delivered to the facility, and because of the potential high financial risk, cities and private firms are often reluctant to proceed with plant implementation. Unfortunately, past resource recovery projects have experienced such problems.

High capital investments call for long-term financing approaches, and it is difficult to get all parties involved to agree to long-term contracts for waste control, the purchase of energy and materials products, and disposal service. Such long-term contracting is sometimes illegal, and obtaining release from legal restrictions or instituting changes in legislation can be excessively time-consuming.

Multi-community agreements necessitate the involvement of numerous local officials, decision-makers and concerned citizens who must be educated about resource recovery planning, procurement and implementation if they are to work effectively and efficiently toward a waste disposal solution. Progress is often slow where numerous local decision-making processes must be incorporated into final decision-making.

When the cumulative effect of numerous delays causes the elapsed time for implementation to exceed political terms of office, valuable continuity in a resource recovery program can be lost and more time expended as new participants are initiated into a project. Also, a lengthy implementation process often results in the problem of dealing with changing environmental regulations.

It is apparent that efforts must be made to reduce unnecessary delays in the resource recovery implementation process if systems are to be brought on-line in a timely manner. Solid waste disposal solutions are needed now, and jurisdictions that desire resource

recovery should have this option made more readily available. Past experience in implementation can and should be used to learn how nontechnical problems can best be met and resolved in future efforts.

The following institutional problems are nationwide in impact. They are considered by MITRE to be the most significant problem areas which might be addressed in the Department of Energy's research and development program.

1. Wastestream Control
2. Securing Markets for Recovered Fuel and Energy Products
3. Inherent Complexity in the Implementation Process
4. Complexity and Inconsistency in IRS Regulations and Rulings on Financing.

MITRE recognizes that the following current Federal programs are directed at the resolution of some of the major problems:

- DOE's loan guarantee program
- Enforcement of environmental standards and regulations for landfills and incinerators which do not comply with present regulations
- Proposed increases in investment tax credits for resource recovery facilities as part of the National Energy Act and short depreciation periods for energy recovery facilities
- DOE's program of Implementation Assistance (a combination of training, technical assistance, and financial support) and EPA's Technical Assistance Panels and President's Urban Policy Programs
- Evaluation of economic incentives in the form of price supports (market guarantees, price guarantees and revenue guarantees)

- Revision by the ICC of discriminatory freight rates against recycled or secondary materials
- Exemption of resource recovery facilities from EPA's air quality offset regulations.

These activities and programs are expected to address effectively many of the nontechnical barriers to implementation. However, in the following discussion MITRE identifies further important actions which should be taken to substantially reduce the delays in implementation that result from the four major institutional barriers. The recommendations for nontechnical research needs are summarized in Table 2.4-I.

2.4.1 Wastestream Control

One of the most frequently cited institutional barriers to resource recovery is the matter of wastestream control. Control over the wastestream must be secured so that the waste can be contractually committed for delivery to the new facility, and thus guarantee throughput and disposal fee revenue as well as energy and material product revenue.

Many resource recovery technologies are currently economically competitive only at large scale, and a large-scale operation often must look to a regional service area in order to achieve the necessary amount of solid waste input. Multi-community solutions complicate the task of acquiring control of the wastestream. In general, community participation is voluntary. There are few states that are willing to seek or use mandatory districting powers. In regions of the country where home rule is strong, the logic behind specific regional resource recovery solutions (economy, efficiency, ecological soundness) must be very persuasive or state planning based on such logic will have little impact.

In addition to determining the feasibility of a resource recovery project, control of the wastestream also influences design considerations. Planners must decide if the plant should be designed to accommodate only those wastes for which commitments exist,

Table 2.4-I

Nontechnical Research Needs

- Compile an inventory of state procurement processes and potential legal obstacles to the different procurement options.
- Develop model procurement codes and encourage states to follow model practices.
- Develop model contracts based on the contract negotiations experience of earlier projects.
- Compile a set of model state laws and reasonable standard approaches to wastestream control.
- Educate state legislators and their staffs on the legislative issues which are impeding more rapid implementation of the industry.
- Examine the use of incentives to encourage the purchase of refuse-derived energy by utilities.
- Develop model compensation formulae for energy products.
- Develop recommendations for the modification of existing utility regulations to facilitate utility purchase of waste-derived energy.
- Educate and encourage PUCs and PSCs to actively promote utility participation in resource recovery projects.
- Encourage clarification of IRS guidelines and develop consistency in ruling procedures.

or whether allowances should be made for additional wastes which would seek entry after alternative disposal sites closed or became economically unattractive. In many areas industrial and commercial wastes do not lie within a community's collection responsibility, and therefore a community cannot guarantee that waste.

Industrial waste is ordinarily handled under short-term contract by independent private haulers who will, in most cases, haul to the place of disposal that is least expensive. In sizing the resource recovery facility, planners can choose to ignore the industrial waste and force the private hauler to seek increasingly scarce landfills, or they can choose to accommodate the industrial waste and negotiate who will bear the risk if the industrial waste is not disposed of at the facility. Past attempts by the public sector to control the flow of wastes through ordinances have met with opposition from private haulers and landfill operators. Control of the wastestream poses a serious equity problem to those already in the waste disposal business. They will argue that a resource recovery project does not have the right to take waste away from an existing disposal site in order to lower the costs at the resource recovery facility.

The method of compensation for waste disposal service can indirectly dictate control of the waste. Frequently, payment is made directly to the facility on the basis of a per ton tipping fee. If the tipping fee is lower than the cost at alternative disposal sites then there will probably be no problem attracting waste and securing commitments for its delivery. However, if the tipping fee is higher, then jurisdictions will have trouble directing the waste to a resource recovery facility. The problem may stem from the reluctance of a community within the region to commit its waste, but more often it is a problem of acquiring the commercial and industrial waste that is controlled by private haulers.

Alternatively, a user charge can be used to control the waste. This method was recently instituted in Montgomery County, Ohio and has been used successfully in Tacoma, Washington for 50 years. With

a user charge there is a zero tipping fee at the facility, or, in other words, there is no fee collected at the time of waste delivery. Instead, communities participate (usually voluntarily) in a jurisdiction-run waste disposal plan, and are billed a user charge for waste disposal service. The actual place of disposal is determined by the local jurisdiction. The user charge can be based on various factors such as property value or estimated waste generation rate. Ideally, the charge will closely reflect the cost of disposing of the predicted waste volume from a given source. The use of a user charge gives a local jurisdiction control of the waste in participating areas, but the jurisdiction must be willing to accept responsibility for the disposal of commercial and industrial solid waste as well.

Another possibility is the establishment of a franchise system for waste disposal whereby resource recovery system operators would be assigned a specific service area or waste shed. At present, an informal franchise system is used in Michigan for the collection of waste. The legality of such a system needs to be examined, however, and initiation of such a scheme would probably have to be on the Federal level.

Another incentive to the dedication of the wastestream is an artificially low tipping fee. In this case, part of the fee is passed through to taxes.

Even where communities are willing to guarantee the disposal of their waste at a facility, the establishment of the guarantee can often be delayed because of legislation which forbids communities to enter into long-term disposal contracts.

The following research need is aimed at enabling each state to efficiently resolve the issue of waste control.

- Research wastestream control legislation in states having major resource recovery activity, document alternative approaches that have been taken, assess their advantages and disadvantages, and

compile a set of model state laws and reasonable standard approaches to the wastestream control problem. It is evident that the wastestream control problem will be faced by virtually every forthcoming regional waste disposal project. States and procuring jurisdictions need information and guidance in dealing with this problem. It is important to minimize the time expended and costs borne by projects while the waste control issue is being resolved. States should be able to anticipate complications in the waste control process and take action to establish appropriate legislation prior to project inception. Cost of this study to analyze about a dozen states with differing legislation would be about \$100,000, with a 12 month duration.

2.4.2 Markets for Recovered Fuel and Energy Products

Another major deterrent to resource recovery implementation is the difficulty met in securing a commitment and an equitable price for the purchase of energy products. Investor-owned electric utilities are promising long-term energy markets, and, on a local level, there are civic pressures which encourage utility participation. However, utilities have been reluctant to become involved because of the risks associated with the utilization of waste-derived fuels.

The primary responsibility of electric utilities is to provide reliable electric service to their customers at the lowest reasonable cost and at the same time provide an adequate rate of return to their shareholders. They are required to pass any fuel cost savings or increases on to their ratepayers. Thus, in order for Public Utility Commissions to encourage utility commitment in resource recovery projects, they must be assured that through the use of waste-derived fuel products the reliability of service will not be impaired, the net cost to the ratepayer will not be increased, capital investment risks will be minimized, and environmental standards will continue to be met.

A number of factors have delayed utility involvement in the resource recovery field. The most serious factor is the unknown

impact that firing RDF will have on power plant reliability and operating and maintenance costs. Utilities are also concerned about the lack of full-scale demonstration of resource recovery facilities, problems associated with facility siting, and the possibility of noncompliance with present and future environmental regulations. Most importantly, utilities lack economic incentive to commit themselves to long-term purchases of uncertain products.

In addition to needing a reliable data base on technical issues, electric utilities need clarification and resolution of economic and contracting issues so that they can enter projects with full understanding of the project risks. At present, severe financial constraints hamper utility involvement. Utilities have limited capital resources, and the high financial risk associated with resource recovery can prevent utility participation. They have a need for precise contract terms, and will ordinarily require contracts with risk-limiting provisions in order to reduce or eliminate such risks as increasing fuel costs and increasing O&M costs. Utilities may require test periods before the signing of long-term contracts, and will probably require guarantees of fuel quantity and quality.

Industrial energy markets are reluctant to purchase refuse-derived energy for many of the same reasons as electric utilities. However, the feature of a real fuel cost savings makes this option more attractive.

The following four research needs are intended to supplement efforts to clarify and manage the risks associated with the purchase of refuse-derived energy products.

- Examine the basis of compensation for energy products between resource recovery facilities and energy purchasers, assess and document the various compensation methods that have been used, and develop model compensation formulae for use in negotiations. The basis for compensation for energy products varies widely from project to project. This is to be expected where the type of energy product differs, however, it is also observed in payment formulae

for the same type of energy product. For example, in Dade County, Florida the price paid for electricity is based on the full system-wide average production cost including average fuel, capital, and operating and maintenance costs. In Northeast Massachusetts only the fuel cost, albeit the incremental fuel displacement cost, is paid. Documentation of such differences and the incentives provided to purchasers under each approach would serve to inform and protect the seller (communities or industry) and reassure the buyer that he is entering a well-planned and well-defined project. Again, the contract negotiations process would be shortened.

- Examine the use of various incentives to encourage the purchase of RDF by energy markets. Utilities feel a need to be compensated for the risks that they take in purchasing and utilizing RDF. These risks have been a major obstacle to attracting energy purchasers, and have resulted in depressed prices for RDF products. Economic incentives in the form of revenue guarantees, price guarantees and market guarantees could reduce the economic uncertainty of projects without placing unreasonable or prohibitive demands on an energy purchaser. Such price supports would enable energy purchasers to pay a reduced price for the energy product, at least until the risks to utilities had been minimized. At the same time, the project would not be placed in financial jeopardy because of initial difficulty in commanding an adequate price for energy products. Experiences with price supports in the commercialization of other industries should be evaluated to see if such incentives would truly be beneficial to the resource recovery industry. Other questions to address are the length of time price supports should be provided and the effect when price supports are withdrawn.

Utilities are motivated to increase the rate of return for their shareholders. Their requirement to pass through any increases or decreases in costs to their ratepayers therefore negates the value of a savings in costs to utilities and does not adequately

compensate utilities for the risks they may be asked to take. Utilities might be more motivated to participate in resource recovery projects if any costs savings could be divided between their ratepayers and their shareholders. Thus, the possibility of releasing the utilities that purchase refuse-derived energy from pass-through requirements should be explored. Interaction between Public Utility Commissions and the Federal Economic Regulatory Commission must be encouraged to resolve the present situation.

- Make recommendations for the modification of existing utility regulations in order to facilitate the purchase of waste-derived energy products by utilities. Based upon the previously mentioned examination of incentives to energy purchasers and the study of compensation methods, recommendations for the modification of existing utility regulations should be developed. These recommendations should clearly set forth the modification that is recommended, the justification for the modification, and identification of who should be responsible for enactment of the change.

Such regulations might include provisions for compensation to be based upon considerations in addition to cost, such as contributions by the utility to solving other public sector problems (e.g., waste disposal).

It is recommended that the above three research needs be addressed under one contract. Cost of this work would be about \$100,000, with a 12 month duration.

- Educate and encourage Public Utility Commissions and Public Service Commissions actively to promote utility participation in resource recovery projects. Public Utility Commissions (PUCs) and Public Service Commissions (PSCs) must be made aware of the status and needs of the resource recovery programs in their states, and the important role that utilities can play in the success of these programs. This could be accomplished by a combination of letters and meetings between Commission officials and DOE officials. For this

task, DOE personnel would play a major role, with minor support from consultants. Subsequent meetings or seminars should be planned on a state or regional level to present the recommendations for modifications to existing utility regulations. PUCs and PSCs should be provided with specific suggestions on how they could promote utility involvement. Such promotion might simply involve the announcement of their support of the concept of cooperation between resource recovery facilities and public utilities, or it might involve immediate enactment of regulatory change. Cost of consultant support for meeting preparation and attendance would be about \$20,000.

2.4.3. Inherent Complexity of the Implementation Process

Constructing a resource recovery facility is more complex than traditional public works projects such as building a highway or a water treatment plant. Few municipalities have the necessary experience and expertise to deal with elements of the planning and procurement process such as determining system costs and revenues, technology evaluation, marketing of products, financing, and legal requirements and constraints. New procurement and financing approaches to resource recovery are continually being tested and revised, and most of these will be unfamiliar to the municipal official.

In past years, some effort has been directed at educating municipal officials in the implementation and management of resource recovery systems. This should be continued; however, the problems in getting these systems on-line are often beyond local control or jurisdiction. In fact, the resolution of many institutional problems requires legislative change at the state level. Unfortunately, education of state legislators on the legal issues which are retarding growth of this technology is an area which has basically been overlooked. These people must be informed if state laws are to be changed.

The following research needs address the problems that result from the complexity of the implementation process, the inexperience of local officials in dealing with resource recovery acquisition, and the lack of familiarity of state legislators with the legal issues that arise in resource recovery implementation.

- Compile an inventory of state procurement processes and pertinent legislation for states that have, or will be, procuring resource recovery; identify potential obstacles to procurement, such as restrictions on competitive negotiations, long-term contracting, or the use of revenue bond financing; document the level of success of past procurement efforts and the reasons for their success or failure. Clear documentation of past project experiences in system procurement would help to set precedents for future efforts and would eliminate the need to expend excessive project time in identifying an acceptable procurement approach. Through an analysis of state procurement laws, states would be made aware of the constraints which they might face and thus could make timely efforts to initiate legislative changes. States and procuring jurisdictions would also learn of the different advantages of the A&E, Turnkey, and Full-Service approaches, and would be better prepared to select the approach best suited to their own capabilities and desires.

- Translate the knowledge gained from the survey and assessment of state procurement processes and pertinent legislation into model procurement codes for the alternative procurement approaches; encourage states to follow model practices. Model procurement codes will provide a framework to be followed after a procurement approach has been selected. Such a framework will provide guidance to those involved in the procurement process. Deviations from the model will be anticipated and planned for in advance, thus avoiding the delays which can result from a shortsighted and uninformed approach to resource recovery procurement.

- Document the contract negotiations experience of earlier resource recovery projects and develop model contracts based upon these experiences to serve as a framework for future contracts. Communities are anxious to learn about the risk posture assumed in earlier projects as well as the basis for risk allocation in each case. This knowledge will be helpful to communities in deciding

which risks they could appropriately assume. Once a risk posture has been defined, the model contracts will provide options and facilitate the selection of a type of contract that is consistent with the desired risk posture. At present, communities do not fully understand the implications of risk assignment and have difficulty in determining how to allocate risks to their projects' best advantage. The availability of model contracts will minimize the time spent dealing with the negotiation of contracts and ensure that written contracts will be of good quality.

It is recommended that the above three research needs be addressed under one contract. Cost of this work would be about \$125,000 to \$150,000, with a 12 to 16 month duration.

- Educate state legislators and their staffs on the legislative issues which are impeding more rapid implementation of the industry. A series of seminars should be developed which address the institutional problems in resource recovery. The staffs of state legislators should attend these seminars. They can communicate the information back to the legislators, and it will be these people that will be drafting any new legislation. Cost to develop and hold a seminar program, including preparation of background information document and seminar summary, would be about \$80,000. If initiated quickly, the seminar could be held in mid-1980.

2.4.4 Complexities and Inconsistencies in IRS Regulations and Rulings on Financing

Another deterrent to an efficient implementation process concerns IRS regulations and rulings. As stated earlier, general obligation bond financing is generally not desirable for most resource recovery projects. Because of the large capital requirements of these projects, a jurisdiction is ordinarily unwilling or unable to back general obligation bonds with its full faith and credit. Thus, tax-exempt revenue bonds are used, often as part of more complex financing packages which involve private equity to obtain additional

tax advantages. Each such financing package requires an individual ruling from the IRS which takes at least six months. This is not only a cause of uncertainty in a project, but the delay also adds to the capital cost of the facility. The IRS should be encouraged to address the problem in the following manner.

- Encourage clarification of IRS guidelines on the use of financing mechanisms and the development of consistency in ruling procedures. At present, financing arrangements for resource recovery facilities are subject to case-by-case rulings by the IRS. The extent to which the use of tax-exempt revenue bonds has been allowed in the financing of resource recovery facilities and the requirements for utilization of investment tax credits and depreciation allowances have varied. Uncertainty in the outcome of IRS rulings results in legal costs and project delays. IRS rulings should be standardized so that the tax status of a resource recovery project can be determined with more certainty and with less delay.

The level of effort required to achieve this goal is uncertain; however, contact of IRS officials by DOE to explain the problems with the present situation should be the first step in addressing this issue. Consultant support from a financial underwriter to prepare for a meeting with IRS would cost about \$30,000.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SECTION 3

GENERIC, TECHNICAL RESEARCH NEEDS

3.1 Introduction

Generic, technical research needs are common to all resource recovery technologies. In MITRE's opinion, resolution of generic needs will have significant impact on the rate at which commercialization of resource recovery systems proceeds. Because these needs are not technology specific, little attention has been given to them by system or equipment vendors, i.e. the private sector. A well directed government effort to resolve these needs is a necessary step toward reducing some of the technical barriers to rapid and successful implementation.

3.2 Research Needs and Recommended Research Programs

Table 3.2-I presents a summary list of generic, technical research needs. This section presents justification for each need along with a recommended plan to resolve the need. It is recommended that DOE address all these needs over an appropriate period of time.

- Improve methods for exchange of information gained from operation of resource recovery plants through DOE/EPA/ASME co-sponsored workshops. Every resource recovery plant supervisor has had to modify his plant's process train or equipment characteristics (operating or design) to make them function with MSW. Knowledge of processes and equipment items that work well or require modification (or elimination) should be shared.

ASME has provided a forum for exchange of this type of information; however, participation and technology transfer have been lacking. It is recognized that with the advent of full service contracting, much technical information is proprietary to the system vendor. However, to provide maximum exchange of information, DOE/EPA/ASME interaction should be encouraged.

Table 3.2-I

Summary of Generic, Technical Research Needs

- Improve methods for the exchange of information gained from operation of resource recovery plants through DOE/EPA/ASME co-sponsored workshops.
- Develop standard procedures for economic analysis of resource recovery plants, including life cycle cost analysis.
- Develop standard test methods to evaluate unit operation performance.
- Develop central, standardized public data base containing technical and economic data for resource recovery and source separation facilities.
- Develop standard procedures for communities to collect and report waste generation data.
- Develop standard methods for analyzing and estimating the components of MSW.
- Develop a resource recovery design handbook.
- Develop standard engineering manuals on recommended dust, fire, noise, and explosion control practices.

The primary source of this information would be those people responsible for the daily operation of the plants. While a questionnaire could be circulated to various facilities, this approach would likely be insufficient for extracting valuable information. Personal interviews with plant operators at each facility would provide a better information transfer; however, some type of monetary incentive may be necessary. Information obtained from these interviews could be compiled into a report that would be issued to all plant operators. A workshop for plant operators, co-sponsored by DOE/EPA/ASME, could then be held to discuss operational problems and solutions, and the report could act as a supplement for discussion. Participation of European plant operators is recommended. The report would be updated on a yearly basis and an annual workshop would be held. Proceedings could be the means for technology transfer. The cost to compile a report and to hold a workshop would be about \$50,000, depending on the number of workshop attendees, plus an additional \$50,000 to produce proceedings.

- Develop standard procedures for economic analysis of resource recovery plants, including life cycle cost analysis. Standard accounting procedures for reporting and analyzing information on resource recovery facility economics should be developed. The present EPA guide is not in sufficient detail and is not widely used or accepted. The costs currently reported for facilities and processes cannot be used for comparison or evaluation because of the different methods used for development. In many cases, actual costs cannot be determined because of overlapping municipal accounts or hypothetical revenue credits. Methods for determining life cycle costs are variable and need to be standardized. Finally, the costs of the unit operations are often neglected during facility evaluations. A high priority is given to addressing this research need. The cost of a study to develop this format, including a national peer review, would be about \$30,000, with a six to eight month duration.

- Develop standard test methods to evaluate unit operation performance. At the present time, the only standard test methods for evaluation of resource recovery facility performance are the ASME procedures for determining boiler efficiencies. It is important to develop performance testing procedures for other equipment items such as shredders and trommels to permit comparative evaluations. An important element of the research is the need for definitions of performance for each unit operation. Following this, standard test procedures can be formulated and evaluated. The cost to develop a test procedure for a unit operation would be about \$30,000, with a six month duration. This would include a peer review of the procedure.

The development of standard input loads, both normal and extreme, will be an essential supplementary task to ensure that the testing procedures are carried out using similar waste streams. A standard load could be a specified mix of refuse components; however, there would be significant difficulty in preparing the tons of material that would be needed for a valid equipment evaluation. A more realistic approach would be to use a single material as a standard load. This material should have uniform characteristics, e.g., size distribution, moisture content, hardness, and be available in large quantities at a relatively low cost. Many other industries use the concept of comparing product quality with a known standard material which is different from the production product.

Subsequent to this work, procedures should be developed for evaluation of entire systems and facilities.

Development of the above standard test procedures may best be achieved through ASTM Committee E38.08 on Processing Equipment and Unit Operations.

• Develop a central, standardized public data base containing technical and economic data for resource recovery and source separation facilities. A resource recovery data base would be a publication that contains the technical and economic specifications of each operating and planned facility. Its form would allow modification of the contents in response to process alterations and economic changes. The information recorded would include:

- composition and variability of MSW
- process train, equipment manufacturers
- mass balance and energy balance for each unit operation.
- composition and variability of all products, including rejects
- capital, operating, maintenance, and life-cycle cost of facilities and component unit operations
- availability factor of facilities and component unit operations.

A data base is necessary for adequate evaluation of resource recovery projects. At present there are no central listings for such information, and it is difficult and inefficient to gather it from the existing literature. The cost of compiling this data into one central listing would be about \$75,000, with a twelve month duration. This includes collection, evaluation and reduction of data, and development of a comprehensive listing of facility information. There would also be an additional annual cost to keep the data base current.

It is recognized that because of the proprietary nature of certain systems, data will be limited. While a number of facilities have already been evaluated, there has been a lack of critical analysis of data. Future evaluations should stress data analysis with development of empirical correlations.

- Develop standard procedures for communities to collect and report waste generation data. Without weighing records, communities have been unable to measure waste generation accurately. Because of this, designers of resource recovery facilities have had to rely upon questionable empirical methods to estimate daily waste generation. These estimates are critical in determining plant size. Too often, the low tipping fees predicted in feasibility studies have not been realized in actual practice because the actual waste generation rate was much lower than originally estimated. The resulting escalation of tipping fee has had a negative effect on the confidence and acceptability of the resource recovery concept to the public.

A standard procedure needs to be developed for communities to properly conduct their own weighing programs. A data reporting format should also be developed so that the data can be meaningfully used by a consultant without duplication of effort. Frequently, data collected by communities is incomplete and unusable to estimate daily and annual waste generation rates. The cost of this study would be about \$20,000, with a three month duration.

- Develop standard methods for analyzing and estimating the components of MSW. There is no standard method for conducting a composition analysis of MSW. There is a need to define categories and determine what products are in each category. Procedures are also needed to determine particle size, density, and shape. Statistically valid sample sizes, sampling frequencies, and methods need to be developed. Multi-component items, such as bi-metallic cans, should be classified, and standard terminology defined and adapted. The cost to develop this procedure would be about \$30,000, with a six month duration.

While a number of studies have been conducted on the subject, an accepted procedure has not been adopted. At a minimum, a common reporting format should be encouraged.

A statistically valid method to estimate compositional analysis is another research need. The revenues of whole facilities and the performance of unit operations depend upon estimation of the combustible, moisture and metallic fractions of MSW -- each of which varies with region, population density, and season. An important aspect of the estimation method would be the formation of a refuse composition data base.

It is recognized that ASTM Committee E38.94 on Long Range Planning has identified this research need as a task to be addressed. If ASTM can address this issue in the near future, then it is best that it develops the procedures.

- Develop a resource recovery design handbook. A standard handbook for the purpose of resource recovery facility design should be developed. As the state-of-the-art and operating experience advance, the contents would be altered and refined. This handbook would be similar to those (Mark's, Merrit, and Perry's) in other engineering disciplines, containing all relevant information necessary for the evaluation and design of resource recovery facilities. Initially, much of the information in the handbook would be of a conceptual design nature, likely in looseleaf format. This research need would require a major and continual effort over many years in order to develop a comprehensive design handbook. However, now is the time to direct efforts toward that future goal. It could be expected that up to \$200,000 per year could be spent in the first several years of development of this handbook, with major effort being placed on critical analysis of data to develop empirical design relationships.

- Develop standard engineering manuals on recommended dust, fire, noise, and explosion controls practices. Dust, fire, noise, and explosion are the main safety concerns in a resource recovery facility. Standard practices for their control must be developed, and this effort should be undertaken in conjunction with the

Occupational Safety and Health Administration (OSHA) and other appropriate organizations. Support of ASTM Committee E38.07 on Health and Safety Aspects of Resource Recovery should be encouraged.

SECTION 4

MECHANICAL SEPARATION SYSTEMS

4.1 Preprocessing for Fuel (Feedstock) Preparation

Mechanical and chemical methods may be used for preprocessing municipal solid waste to enhance its value as a fuel, separate usable materials, and facilitate processes such as pyrolysis and anaerobic digestion. Preprocessing of MSW is required for all waste-utilization alternatives other than mass burning incineration. These alternatives are attractive because they increase the number of potential beneficiaries of the solid waste stream by developing:

- Refuse-derived fuels (RDF) that can be used in conjunction with normal fossil fuels
- Energy-producing processes suitable for regions with stringent air emission regulations
- RDF that can be transported to combustion facilities that are separate from processing facilities
- Materials separation processes that extract metals or glass for reuse by secondary material markets.

MSW is characterized by extreme diversity in material size, density, and composition. This heterogeneity is a formidable barrier to the effectiveness of unit operations used in preprocessing systems, most of which have been developed for other, more homogeneous, materials. Figure 4.1-1 displays the typical particle-size distribution of the predominate raw waste components. The particle sizes vary from 0.02 to 10 in., a situation further complicated by intermingled constituents, irregular shapes, and variable densities.

4.1.1 Technology Description

Five categories of preprocessing systems can be identified according to their product form: coarse RDF, fine RDF, densified RDF (d-RDF), powdered RDF, and wet-pulped RDF. Both coarse and fine RDF

Figure 4.1-1. Cumulative Distributions of Raw Waste

may be described as "fluff RDF" because of their shredded nature. Table 4.1-I compares the physical properties of the various RDF forms.

4.1.1.1 Fluff RDF. Coarse RDF is produced by a single pass through a mechanical device that reduces the MSW particle size and homogenizes the combustible elements. This may be followed by air classification, magnetic separation, or trommeling to reduce the inert content, with stoker boilers as the intended recipient of the product. Constructed, full-scale facilities use hammermill shredders, with and without grates, to pulverize the refuse and create a 4- to 6-in. fuel. Trommels, containing internal lifters, and flail mills are being used in pilot-scale plants, but particle size information on the output is not available.

Coarse RDF is produced to meet the following goals:

- Compatibility with stoker coal boilers
- Stability with regard to putrescence
- Relative constancy of Btu value for 100 percent RDF-fired boilers
- Reduction of excess air with regard to mass burning
- Creation of feed suitable for certain pyrolysis and bioconversion systems.

Fine RDF is produced by adding a second grinding or shredding process to reduce the particle size further. Particles produced are as small as 3/4 to 1 in. nominal size. Full-scale facilities use air classification between the shredding steps for removal of inerts. The intended uses of this product include firing in suspension boilers, densification, pyrolysis, and anaerobic digestion. Removal of inert material is critical for firing and densification to reduce slagging, ash handling, and equipment wear. Power consumption of the second shredder is also significantly affected by the quantity of inerts remaining in the feed material.

Table 4.1-I

Comparative RDF Characteristics

	<u>Coarse</u> ^a	<u>Fine</u> ^b	<u>Densified</u> ^c	<u>Powdered</u> ^d	<u>Wet-Pulped</u> ^e
Higher Heating Value as received (Btu/lb)	5,319	5,610	6,000	7,740	3,600
Ash (percent)	15-17	17	25	15-25 ^f	25
Moisture (percent)	NA	23	10-16	2.0	55
Nominal Particle Size (in.)	4-6	1.5	0.5x1.25	0.015	NA (<1)
Bulk Density (lb/ft ³)	4-6(est.)	8	28	30-34	NA
Handling/Storage Characteristics	poor	poor	good	good	NA

NA: Not Available

a Hamilton, Ontario [2]

b Ames, Iowa [3]

c Hagerstown, Maryland, test burn [4]

d Arthur D. Little, Inc., pilot plant [5]

e Franklin, Ohio [6]

f East Bridgewater, Massachusetts [7]

Disadvantages of fluff RDF are:

- Necessity for expensive live-bottomed bins for fluff RDF storage
- Requirement for covered conveyance systems to prevent the release of dust and fine particles from fluff RDF
- RDF bridging and jamming caused by small irregularities in conveyors and chutes, such as welded seams or surface roughness
- RDF tendency to increase in density and agglomerate into an unmovable mass when stored for long periods.

4.1.1.2 Densified RDF. At present, densification is accomplished by pellet mills from the animal feed industry. Fine RDF is extruded through dies under pressure from a rotating wheel, resulting in pellets typically 1/2 by 1-1/4 in. The refuse must have a moisture content of less than 30 percent to form the pelletized product; material with a higher moisture content crumbles and reverts to fine RDF. The minimum moisture required for pelletization is around 20 percent, but this has not been determined experimentally.

Fine-shredded RDF may be densified to produce a fuel that is easier to store and transport than fluff RDF. Densified RDF is more desirable to the user because it requires little modification to existing storage, conveying, and boiler injection systems. The problems with fluff RDF arise from its low density and its tendency to agglomerate (bridge) and cement (set up). Densification overcomes many of the negative characteristics of fluff RDF.

Densified RDF can be stored for extended periods in open piles and can be loaded and conveyed like lump coal. The disadvantage of the densification process is, of course, its additional cost, which is aggravated by equipment erosion due to the abrasive nature of the material.

4.1.1.3 Powdered RDF. MSW can be turned into a powder by a combination of chemical, thermal, and mechanical action. The resulting material is dry and free-flowing, and of 0.15 mm average size. RDF in this form has potential use in suspension boilers, co-firing with either oil or pulverized coal. The small particle size offers the following advantages over fluff RDF:

- Potential for complete burnout in suspension boilers
- Potential for stable suspension in oil with attendant transport by pumping or trucking
- Simple storage and transport without bridging or setting-up
- Increased surface area better suited for certain pyrolysis and bioconversion technologies.

Disadvantages of the process include:

- Presence of inerts in powdered form increases the potential for slagging and air emissions
- The effect of residual acid on boilers is unknown
- Process acid requires careful handling
- Small particle size increases potential for dust explosion.

The embrittling process uses shredded (or flailed) MSW that has undergone screening and magnetic separation. The screening may be accomplished by trommeling or air classification and is critical for ultimate product utility. Acid is added next, and the material is placed in a ball mill for mechanical abrasion and thermal conditioning. The steel balls are heated externally after recycle from the lower end of the mill to produce temperatures from 200°F to 400°F in the ball mill. The cellulosic chains of the combustible fraction are broken chemically (acid-catalyzed hydrolysis) and the brittle reaction product is subsequently fractured into a fine powder.

4.1.1.4 Wet-Pulped RDF. The wet pulping process of RDF production uses water as a suspension medium for particle-size reduction, inerts separation, surge storage, and conveyance. Particle size reduction of MSW is achieved by a wet-pulper, which may be likened to a household blender. The pulper grinds the organics, paper, plastics, glass, and soft metals in a water medium to particles of one inch or less and rejects all other material. The pulped slurry proceeds to a liquid cyclone where the inerts are separated, and then to mechanical dewatering operations. Sewage sludge may be added to the combustibles prior to final dewatering, which is achieved in a cone press by applying mechanical pressure against a screen. The fibrous character of the RDF enables the sludge-pulp mixture to reach a level of solids higher than can be achieved for sludge alone. The addition of sludge can increase the inert content of the fuel, depending upon how efficiently grit is removed at the wastewater treatment plant.

Although there is an energy penalty to be paid during combustion of the 50-percent moisture product, the following advantages may be gained over dry shredding systems during the preprocessing operations:

- Explosion-proof shredding
- Dust-free and spillage-free processing
- Simple RDF conveyance as a 3-percent solids slurry.

Disadvantages inherent to the wet-pulping process include:

- High moisture content of fuel
- Biological contamination of process water
- Build-up of dissolved and suspended solids in process water
- Potential biological contamination of recovered materials
- Necessity for a dedicated boiler (that is, a combustion unit that is an integral part of the RDF facility).

4.1.2 Technology Status

4.1.2.1 Technical. The RDF production plants presently operating represent first-generation facilities whose processes have undergone extensive and continuous modification. Many operational problems have been solved in the field, while others have merely been identified as areas requiring further research.

Table 4.1-II lists 15 existing RDF facilities, either operational or in shakedown. These plants may be described as commercial, demonstration, or experimental facilities, depending upon their size and purpose. Demonstration plants are really small-scale solid waste disposal facilities, but were not established to produce RDF as the ultimate disposal method. The number of facilities in each category is shown below:

<u>RDF Type</u>	<u>Commercial</u>	<u>Demonstration</u>	<u>Experimental</u>
Coarse	2	2	2
Fine	4	1	0
Densified	0	0	2
Powdered	1	1	0
Wet Pulped	1	1	0

Fluff RDF

The problems of fluff RDF production have received the most attention due to fluff RDF's non-proprietary status. The preprocessing systems are not proprietary, as they are for the powder and wet-pulp methods, and therefore have a wider appeal. In general, the status of the technology may be described as "ad-hoc". Equipment has been adapted from other industries for use with MSW, and the problems encountered have been solved mostly by the plant operators. The greatest problem facing the industry is the lack of information concerning the fundamental operation of each unit when it is applied to a solid waste stream:

- There are no accepted design equations for the sizing and scaling of unit operations

Table 4.1-II

RDF Facilities Operating or in Shakedown

RDF Product	Participants	Process	Status	Capacity (tpd) Design/Operating	Capital Cost (\$million)	Comments
Coarse	Hamilton, Ontario Hamilton-Wentworth Region: Owners Tricil, Ltd: Operators (since Feb. 1978)	<ul style="list-style-type: none"> • Primary shred • Fe separation • Spreader-stoker dedicated boiler 	Operational since 1972	600/460	8.4 Canadian (1972)	<ul style="list-style-type: none"> • Modified Tollemache pulverizers, vertical shaft • No inert removal • Rexnord live-bottom tipping floor • No surge storage • 95% MSW as RDF • Problems <ul style="list-style-type: none"> – bridging at transition points – discontinued use of Atlas silo: floor wear, setup of RDF
Coarse	Tacoma, Wash. City of Tacoma: Owner/Operator	<ul style="list-style-type: none"> • Primary shred • Air classification • Fe separation • Surge storage • Truck transport 	Construction and shakedown complete, will become operational when RDF market is found	500	2.5 Exclusive of shredder (1978)	<ul style="list-style-type: none"> • Boeing horizontal air classifier • Settling chamber from ADS serves as surge storage • Exposed pan conveyor subject to freezing
Coarse	Avondale, Md. Bureau of Mines: Owner/Operator	<ul style="list-style-type: none"> • Flail mill • Air scalp • Fe separation • Air classification 	Intermittent operation	1 tph	NA	<ul style="list-style-type: none"> • Bureau of Mines pilot plant • Classification of refuse for communities • Basis for Monroe County (Raytheon)
Coarse	New Orleans, La. Waste Management, Inc. Owner/Operator	<ul style="list-style-type: none"> • Trommel • Shred • Air classify 	Operational	700	9.1 (1977)	<ul style="list-style-type: none"> • Trommel with internal lifters to break bags • 55/45 mass split at trommel • Trommel unders air classified; lights rejoin RDF • Heil vertical-shaft and Gruendler horizontal-shaft shredders • Triple-S air classifier • Product landfilled

Table 4.1-II (Continued)

RDF Product	Participants	Process	Status	Capacity (tpd) Design/Operating	Capital Cost (\$million)	Comments
Coarse	Toronto, Ontario Ministry of Environment: Owner B.F.I.: Operator	<ul style="list-style-type: none"> Primary shred Air scalp Air classification Pneumatic transport Hooper surge bin Composting of heavy organics 	Shakedown; 2,000 tons processed to date	300 tpd	14.1 Canadian (1978)	<ul style="list-style-type: none"> Ministry of Environment experimental facility Williams shredder Victor Brown designed air classification Fairfield composter RDF used for test burns or landfilled 50% MSW as RDF Explosion in shredder, winter 1979
Coarse, Densi-fied	Richmond, Calif. University of California, Berkeley: Owner/Operator	<ul style="list-style-type: none"> Primary shred Air classification Trommel Densification 	Operational	2.7 tph	NA	<ul style="list-style-type: none"> University of California experimental facility Gruendler horizontal-shaft shredder, variable speed Variable-speed, variable-tilt, variable-hole trommel Modular, variable-sequence unit operations Self-designed air classifier California pellet mill densifier
Fine	Ames, Iowa City of Ames: Owner/Operator	<ul style="list-style-type: none"> Primary shred Fe separation Screening Secondary shred Air classification Pneumatic transport Atlas storage silo Suspension burning with pulverized coal (Ames Electric Co.) 	Operational since 1975	400/170	6.19 (1975)	<ul style="list-style-type: none"> American Pulverizer shredders Rader 1½ and ½ in. disc screens Rader air classifier 80% MSW as RDF Problem areas: <ul style="list-style-type: none"> erosion of pneumatic line elbows jamming of drag conveyor pluggage of pneumatic lines pluggage of airlocks floor abrasion in storage silo setting up of RDF in silo power consumption of secondary shredder explosion and two fires in shredder

Table 4.1-II (Continued)

RDF Product	Participants	Process	Status	Capacity (tpd) Design/Operating	Capital Cost (\$million)	Comments
Fine	Chicago, Ill. City of Chicago: Owner/Operator	<ul style="list-style-type: none"> • Primary shred • Fe separation • Air classification • Secondary shred • Pneumatic transport • Atlas storage silos • Suspension burning with pulverized coal (Commonwealth Edison, Crawford Station) 	Not operating due to modification of secondary shredder and replacement of pneumatic line rotary airlocks. Functioning of unit operations being researched by plant supervisor. 15,000 tons processed to date.	1200/600	16 (1978)	<ul style="list-style-type: none"> • Williams horizontal-shaft primary shredder • Triple-S "vibro-elutriating" air classifier • Modified Carborundum vertical-shaft ring-grinder • 70% MSW as RDF • Problem areas: <ul style="list-style-type: none"> — achieving 1½ in. nominal particle size — erosion of pneumatic line elbows — jamming and erosion of rotary airlocks — pluggage of pneumatic lines — erosion of positive displacement ADS fan
Fine	Eugene, Oreg. Lane County: Owner Western Waste Corp.: Operator	<ul style="list-style-type: none"> • Primary shred • Air classification • Secondary shred • Peerless surge bin • Truck transport • No RDF market 	800 tons processed to date; not operating due to process modification: replacement of RDF air seal at ADS cyclone with rotary airlock and larger screw conveyor.	500	2.1 (1978)	<ul style="list-style-type: none"> • Allis Chalmers horizontal-shaft shredders <ul style="list-style-type: none"> — hydraulic pin-pullers — 180-deg rotor exposure — reject door — no blast panels • Allis Chalmers "dual-vortex" air classifier • Secondary shredder bypass • Problem areas: jamming and bridging of screw conveyor
Fine, Densified	Cockeysville, Md. Baltimore County: Owner Teledyne National: Operator	<ul style="list-style-type: none"> • Primary shred • Fe separation • Air classification • Trommel • Secondary shred • Densification • Truck transport • Test firing, bulking agent for composting, landfill 	Operational since 1976, 2,000 tons of d-RDF produced	1500/670	8.5 (1976)	<ul style="list-style-type: none"> • Tracor horizontal-shaft shredders • Montgomery Industries air classifier • Triple-S trommel • California Pellet Mill densifier • 60% MSW for RDF • Problem areas <ul style="list-style-type: none"> — fabric blockage of dies — die wear — moisture content affecting pellet integrity

Table 4.1-II (Continued)

RDF Product	Participants	Process	Status	Capacity (tpd) Design/Operating	Capital Cost (\$million)	Comments
Fine	Milwaukee, Wis. Americology, Inc.: Owner/Operator	<ul style="list-style-type: none"> • Primary shred • Air classification • Secondary shred • Fe separation • Disc screen • Compaction • Truck transport • Fluff conveyor • Atlas storage bin • Pneumatic transport • Suspension firing with coal (Wisconsin Electric Co.) 	In shakedown but operating at full capacity	1600/800-1400 (seasonal)	18 (1978)	<ul style="list-style-type: none"> • Williams horizontal-shaft primary shredder • Americology air classifier • Heil vertical shaft cutter • Radar disc screens • Heil stationary compactor • 55% MSW as RDF • Halogenated hydrocarbon explosion suppression • Problem areas: <ul style="list-style-type: none"> — initial slagging in boilers — gas tank explosion on shredder infeed conveyor
Powdered	East Bridgewater, Mass.: Owner/Operator	<ul style="list-style-type: none"> • Flail mill • Fe separation • Trommel • Air separation • Trommel • Embrittling agent • Ball mill • Screen • Pneumatic conveyance • Storage • Truck transport • Suspension co-firing with oil (Century Brass, Waterbury, Conn.) 	Operational	1000/0-500	10-12	<ul style="list-style-type: none"> • Longhorn 250 H.P. flail mill • Triple-S primary trommel for flail mill recycle • Gruendler secondary trommel • 50% MSW as RDF • Problem areas: <ul style="list-style-type: none"> — explosion in ball mill — erosion of pneumatic elbows • Gravity discharge storage hopper • Fuel used by Century Brass, Waterbury, Conn.

Table 4.1-II (Concluded)

RDF Product	Participants	Process	Status	Capacity (tpd) Design/Operating	Capital Cost (\$million)	Comments
Powdered	Bridgeport, Conn. Connecticut Resources Recovery Authority C.E.A., Inc.: Operator	<ul style="list-style-type: none"> • Trommel • Flail or shred • Fe separation • Air classification • Secondary trommel • Embrittling agent • Ball mill • Screen • Storage • Truck transport • Suspension cofiring with oil (United Illuminating) 	Preprocessing operations in shakedown, fuel production operations under construction	1800	53 (1978)	<ul style="list-style-type: none"> • C.E.A. Carter-Day trommel • C.E.A. Carter-Day flail mill • C.E.A. Carter-Day shredder • C.E.A. Carter-Day air classifier
Wet-pulp	Franklin, Ohio Town of Franklin: Owner Black-Clawson: Operator	<ul style="list-style-type: none"> • Wet pulping • Liquid cyclone • Gravity dewatering on inclined screw conveyor • Sludge addition • Mechanical dewatering • Combustion in dedicated fluid-bed incinerator without heat recovery 	Operational since 1971; to be discontinued	150/50	4 (1971)	<ul style="list-style-type: none"> • 53% MSW as RDF • Problem areas <ul style="list-style-type: none"> — ash content of fuel — injection location into sand bed — solids buildup in process water
Wet-pulp	Hempstead, N.Y. Parsons & Whittemore: Owner/Operator	<ul style="list-style-type: none"> • Wet-pulping • Liquid cyclone • Gravity dewatering • Mechanical dewatering • Pit storage • Overhead crane transport • Combustion in dedicated stoker-spreader boiler 	In shakedown	2000	73 (1979)	<ul style="list-style-type: none"> • Has achieved 800 tpd processing • No glass to date • Burnable fuel • More ash than expected

- It is impossible to predict what the output from a piece of equipment will be, given the characteristics of the input stream
- There are no methods to develop the proper sequence of unit operations nor to predict the effects of an alteration in an established sequence
- There are no design equations or models to allow the optimization of a particular sequence.

The nine commercial and demonstration facilities display significant variability in process sequence, with unquantified effects on product specification or system reliability. These process trains are displayed in Table 4.1-III. The table does not list individual equipment specifications because, without a unifying method for calculations, such information cannot be interpreted.

A description of problems that have occurred in operating RDF plants follows. Although these problems may seem condemnatory, in fact, many have been overcome and the facilities do function. There are unit operations that work well and reliably, but this information has not been formally exchanged. The literature and symposia proceedings describe whole systems evaluations and do not properly reflect the useful experience gained by plant operations.

Removal of Inerts

The waste stream is highly abrasive because it contains glass, grit, and wire, causing rapid attrition of all mechanical components of the preprocessing line. These materials also contribute to slagging, and grate and ash-handling problems within the receiving boilers. Ames had experienced excessive wear and power consumption with its secondary shredder until the disc screens were installed in the fall of 1978. Chicago's positive displacement blower on the air

Table 4.1-III
Process Sequence of Fluff RDF Facilities

<u>Location</u>	<u>Product</u>	<u>Shredding</u>	<u>Air Classification</u>	<u>Other</u>
Toronto, Ontario	Coarse	Horizontal shaft	Primary: air scalp Secondary: air classification	
Hamilton, Ontario	Coarse	Vertical shaft	No	Fe separation
Tacoma, Washington	Coarse	Horizontal shaft	Yes, horizontal	Fe separation
New Orleans, La.	Coarse	Horizontal shaft	Yes	Trommel before shred Trommel unders air classified
69 Ames, Iowa	Fine	Two horizontal shaft	Yes, after secondary shred	Disc screen between primary and secondary shred
Chicago, Illinois	Fine	Primary: horizontal shaft Secondary: vertical cutter	Yes, between primary and secondary shred	Fe separation prior to air classification
Eugene, Oregon	Fine	Two horizontal shaft	Yes, between primary and secondary shred	
Cockeysville, Md.	Fine	Two horizontal shaft	Yes, after primary shred	Trommel after air classification
Milwaukee, Wis.	Fine	Primary: horizontal shaft Secondary: vertical cutter	Yes, after primary shred	Disc screen after secondary shred and Fe separation

classifier has had to be repaired and rebalanced due to erosion after only 15,000 tons of MSW had been processed. Both plants have experienced severe problems with pneumatic lines such as:

- Air locks jamming with wires and other oversized objects
- Air locks and elbows on pneumatic lines wearing out
- Plugs in pneumatic lines caused by RDF bridging on rough surfaces
- Plugs caused by slugs or grit settling out.

Each plant has installed hardened liners on the elbow portions, and Ames is using replaceable liners within the airlocks. Ames and Hamilton have experienced excessive wear on their storage silo floors, causing Ames to resurface and Hamilton to abandon use of the facility. The Ames silo floor needs resurfacing again. The boiler tubes at the Ames and Wisconsin Electric Companies have experienced slagging, which was directly caused by the inert content of the fuel. It is hoped that adding disc screens in each facility will correct the problems.

The commercial plant experience has shown that air classification alone is inadequate for complete inerts removal. Some method of screening is necessary. Air classifiers cannot respond to instantaneous changes in the composition and density of the feed stream, nor can they properly reject inert material of certain shapes and sizes. There are, however, a number of untried devices, such as Boeing's horizontal, Allis Chalmers' dual vortex, and AENCO's rotary air classifiers. The three alternatives available are trommels, disc screens, and vibrating screens. The first two, as shown by Table 4.1-III, are in use in four locations. The third has been shown to be inadequate for MSW processing by Alter [8], Savage et al. [9], and the experience in Ames. The disc screen, manufactured by Rader Systems, Inc., is a relatively new device that employs sprocketed rollers for refuse transport. The undersized material falls through the gaps between the rollers.

Conveying and Storage

The conveying and storage of MSW and RDF are areas of concern for existing plants. A few examples are given below:

- Ames has experienced broken links in its drag conveyor due to jamming by oversize materials; plugging of its pneumatic lines caused by bridging at rough internal surfaces; and jamming of airlocks by oversized objects. Material left in the silo for six weeks set up and had to be dynamited and dislodged by hand.
- Chicago's problems with pneumatic line plugs are similar to those at Ames.
- Hamilton has experienced bridging at transition points and set-up of RDF in the storage silo.
- Baltimore's storage silo experience was the same as Ames', requiring dynamite and manual removal.
- The screw conveyor at Lane County was too small, causing jamming and bridging.

The airlocks have been modified by flexible-tipped blades at Ames and a cutter bar at Chicago. The Hamilton transition chutes have been enlarged and steepened. The screw conveyor at Lane County has been redesigned, and an airlock has been added to maintain an air seal in the air classifier cyclone. All facilities report some reliable conveying systems -- the most successful seem to be pan conveyors with covered components, piano-hinged steel conveyors, and rubber-belted trough conveyors.

Storage and retrieval of RDF remains a problem, due to the material's propensity for compaction and setting up. The Hamilton plant stores MSW on a live-bottomed Rexnord conveyor and shreds only to feed the boilers. Lagging response to load is overcome by operating one shredder in a base mode and the other on demand. This technique may be used only in conjunction with a dedicated boiler.

The Toronto facility is experimenting with an S.W. Hooper bin, which stores material in a vertical column and pushes it out the bottom on a first-in/first-out basis by wedge-shaped reciprocating bars. Its operation has been too limited to evaluate. The Atlas bin has had problems because the first-in/last out retrieval and continuous inner pressure of the heavy sweeps have increased the RDF's tendency to set up. Another storage configuration is the auger feed of the Miller-Hofft bin, first tried at St. Louis and now in use at Kodak's facility in Rochester, New York and Akron, Ohio. There have been no detailed reports in the literature on this unit's performance.

Particle Size Reduction

Particle-size reduction is accomplished by a variety of devices, the principal one being the hammermill shredder. Hammermills vary in grate size, rotational speed, power input, explosion protection, weight, size, and configuration of the hammers. All are characterized by high maintenance requirements, high energy demand, dust generation, and the potential for explosion. The particle size distribution of the output and its variability with hammer wear directly affect the performance of the subsequent unit operations and the ultimate quality of the product. Although this is realized by systems designers, the concept of total system optimization has not been addressed. Decisions such as hammer retipping versus throw-away or size of grates are made by plant managers. Explosions are a concern and the response differs with the various plants: Milwaukee and New Castle, Delaware, have installed suppression devices; Toronto, Ames, and Baltimore County use blow-out panels for venting; and Lane County employs a reinforced shredder with a reject door and large conveyor openings. The incidence of explosions in shredding installations is well documented by Nollet [10] and Zalosh et al. [11].

Deformable objects can pass through shredder grates and have caused plugs, burnouts, and ash-handling problems at the Ames Electric and Commonwealth Edison (Chicago) generating plants. Cutter

mills and grinders are devices that may overcome this problem, but the efficiency of such systems has not been documented.

Flail mills are lower energy devices than hammermills, but their function is restricted to bag breaking or simple shredding. The vertical Tollemache pulverizers at Hamilton produce a similar product due to their narrow, light hammers and low operating power. The effects of their use in preprocessing systems have not been quantitatively investigated, although the Bureau of Mines uses flailing for primary size-reduction.

Trommeling to achieve bag breakage is currently in operation at New Orleans, but actual size reduction is accomplished by shredding. AENCO's rotary air classifier is a trommel-like device containing internal lifters for violent tumbling of the refuse. It was claimed that a suitable RDF product resulted from the year-long demonstration, but few evaluative tests were performed [7]. The apparatus has since been dismantled.

Powdered and Wet-Pulped RDF

The status of these technologies is similar because of their proprietary nature. Powdered RDF is marketed by Combustion Equipment Associates as Eco-Fuel II, and wet-pulp, from the Black-Clawson process, was developed by Parsons and Whittemore, Inc.. Both processes have been demonstrated and will receive their full-scale tests in Bridgeport and Hempstead, respectively. Production problems need not be investigated by the public sector because of the full-service contractual arrangements. Public research should address full-plant evaluations to determine the overall merit of the systems. These research needs are listed in Section 4.1.4 and the later "combustion systems" sections.

4.1.2.2 Economic. The true costs of any of the operating commercial facilities are unknown at this time because:

- the facilities are undergoing continuous modifications
- the costs are confused by municipal accounting systems.

Ames will serve as our example. •

During 1978, two necessary process alterations took place: the installation of dust collection equipment and disc screens. Present operating costs with the new equipment on line have not yet been determined. There is also equipment such as the paper baler, aluminum recovery system and wood chipper which was purchased and installed but has not operated for a considerable period of time.

The accounting system for the solid waste plant does not report expenses incurred by the electric company resulting from their use of RDF. The RDF is purchased at the same price as coal (on a Btu basis), but it costs an additional \$2/ton for increased maintenance and does not yield an equivalent burnout [12]. If the utility were not a captive market, the RDF price would certainly have to be discounted, thereby reducing the revenues to the RDF plant.

4.1.2.3 Environmental. The internal atmospheres at these facilities are certainly dust or aerosol laden. Dust control systems have been installed in most plants, but their effectiveness and relative merits have not been evaluated.

The wet-pulping process produces a process water that concentrates suspended solids and bacteria, requiring treatment and possible discharge to municipal sewage systems. The quantity and characteristics of these potential effluents are unknown for the full-scale Hempstead plant and also require evaluation.

4.1.3 Research Status

Organizing research activities by categories simplifies the task of describing their status and state of development. The three types of research that would be most useful for advancing MSW preprocessing equipment are listed below:

- **Fundamental Research.** Investigating single pieces of equipment on a pilot scale under variable conditions to learn internal operations, produce design equations, and model the changes produced in the waste stream.

- Field Evaluation. Testing equipment at operating facilities under normal load conditions in order to compare vendor designs, establish a data base, and verify design and modeling equations.

- User Interpretation. Transforming the results of fundamental research and field evaluations into forms useful to equipment designers, system designers, and plant operators.

The desired result of such a research program is the ability to design, sequence, and optimize unit operations to produce a specified product from a given waste stream. Based upon the preceding categories, ten research activities are identified in the following paragraphs and summarized in Table 4.1-IV.

Shredding

Fundamental studies have been well advanced by G. Trezek at the University of California, Berkeley [14]. Limited field evaluations have been completed by Cal Recovery Systems, Inc., under contract to the EPA [15], and more efforts of this type should be undertaken with emphasis on comparative performance of vendor equipment and establishment of a shredding data base. Due to the lack of a data base, there are no current research activities in the area of user interpretation. However, knowledge about shredding of MSW is the farthest advanced of all the unit operations, and most ready for incorporation into a user's manual.

Flail Milling

Although flails are in use in two facilities, one pilot and one demonstration plant, little has been reported concerning their operating characteristics, power and maintenance requirements, size distribution of the output, and applicability of the output for other unit operations.

Grinding and Cutting

Except for the inclusion of a Carborundrum vertical ring-grinder in Cal Recovery's field testing program, grinders and

Table 4.1-IV

Research Status of Preprocessing Unit Operations

<u>Unit Operation</u>	<u>Fundamental</u>	<u>Field Evaluation</u>	<u>User Interpretation</u>
Shredding	Good	Fair	NA
Flail Milling	NA	Poor	NA
Grinding and Cutting	NA	Fair	NA
Air Classification	Fair	Planned	NA
Trommeling	NA	Fair	NA
Disc Screening	NA	NA	NA
Densification	Planned	Fair	NA
Embrittlement	Fair	NA	NA
Conveyors	NA	NA	NA
Storage and Bins	NA	NA	NA
Dust Control	Fair	NA	NA

NA: No Activity

cutters have not been adequately evaluated as an alternative to hammermill shredding.

Air Classification

The operations of a few air classifiers have been studied with respect to overall separation of components [16, 17], but the field testing of these units has been neglected during facility evaluations. Cal Recovery, Inc., will be performing classifier evaluations at RDF plants, but the scope of work is unknown at this time. The operational equations available in the literature pertain to discrete particles and are not usefully applied to the highly heterogeneous MSW. Design and scale-up equations have not been reported and are presumably vendor-specific and proprietary.

Trommeling

Trommel design equations have not been reported, although they are presently under investigation by Hecht and Trezek [18]. Pilot- and commercial-scale operating experiences have been obtained and are reported in the literature [19, 20, 21]. The proper location of trommels in the preprocessing sequence, their design, and their effect on other unit operations are unknown.

Disc Screening

Due to proprietary development, disc screens have not yet been the subject of public investigation or evaluation.

Densification

NCRR and Teledyne have had the principal operating experiences in the densification of RDF, but the bulk of the published results have concerned burn tests. Trezek is investigating the fundamental concepts of densification and relationships with extrusion theories of plastics. NCRR and Muehlberg have published economic estimates concerning d-RDF production, but the viability of the concept has not been adequately evaluated [22, 23].

Embrittlement

Hecht has studied the chemical nature of the embrittlement process and has made economic estimates for powdered RDF production [24]. Because of its proprietary development by Combustion Equipment Associates in conjunction with Arthur D. Little, Inc. field evaluations and user interpretations are not available.

Storage and Retrieval Systems

Comparative evaluations and user interpretations of conveyors and storage bins are available by word-of-mouth from operating facilities and are not available in the literature.

Dust Control Systems

Dust emissions from RDF unit operations have been studied by NCRR [13] and MRI [25], but these investigations were limited to uncontrolled equipment. Microbiological and particle-size analyses showed that respirable dusts are generated and represent a potential source of disease. No evaluative work has been done for facilities equipped with dust control systems.

4.1.4 Research Needs for MSW Preprocessing

4.1.4.1 General.

● Exchange the experiences gained at operational RDF facilities by symposium and publication:

- Principal contributors should be plant operators and supervising engineers
- Identify successful vendor-supplied equipment
- Describe successful equipment modifications
- Outline problem areas and equipment.

This activity would contribute to the field evaluation needs of all the unit processes.

- Develop mathematical models to describe unit operations:
 - Design and scaling equations
 - Power consumptions
 - Input/output component characterizations.

Models development is needed to enable system designers and plant engineers to determine proper sequencing of equipment and plant optimization.

- Develop a system engineering approach to RDF production process design:

Design of RDF facilities is on a component-by-component basis, with no understanding of the interrelationships and compatibilities of the various unit operations. Development of mathematical models and design equations to predict unit operation performance is the first major step toward a system engineering design approach. The results of these individual unit operation studies need to be incorporated into a model which can describe facility performance as a function of feedstock characteristics and unit operation sequence.

- Fund innovative fuel preparation systems:

The generation of new ideas for preprocessing systems should be encouraged.

4.1.4.2 Size Reduction.

- Determine the effect of hammer wear on RDF size, quality, plant operating cost, and subsequent operations such as material separation and air classification:

- Organize and interpret existing data
- Procure operating data from existing plants.

The decision to retip or replace hammers in plants is being made without adequate engineering justification.

- Evaluate shredder safety concepts at a pilot or test facility to determine the most effective explosion control system:

- Evaluation of explosion suppression systems in use on existing systems
- Evaluation of innovative explosion control systems
- Evaluation of vented and non-vented systems, such as Toronto and Lane County.

Shredder explosions are a continuous threat to plant personnel and research should be pursued for their prevention.

- Evaluate a flail mill for size reduction at a pilot-scale facility:

- Power consumption
- Particle size distribution
- Maintenance requirements.

Flail mills may be an effective alternative to shredding and should be evaluated in greater detail.

- Evaluate ring grinders and disc screens for removal of textiles and deformable plastics at a pilot-scale facility. Oversized objects jam airlocks, blind screening devices, plug pneumatic lines, plug pellet mills, and cause ash-handling problems in suspension boilers.

- Evaluate and compare trommels and disc screens at operating facilities:

- Removal effectiveness
- Power consumption
- Maintenance requirements
- Response to input variability
- Mass balances
- Heat contents of rejects
- Need for further research.

Trommels and disc screens are inert separation methods that have been shown to improve the quality of fluff and densified RDF.

4.1.4.3 Materials Handling and Storage.

- Evaluate pneumatic and mechanical conveyors at operating facilities to determine economic and practical limitations:

- Reliability
- Maintenance requirements
- Ease of maintenance
- Incorporation of results with ongoing NCRR study.

Conveying systems range from functional to inoperable for MSW and fluff RDF. Comparison among systems is necessary for reliable operation of facilities in the future.

- Evaluate rotary air locks at operating facilities to determine best design:

- Reliability
- Maintenance requirements
- Ease of maintenance
- Economics
- Size limitations.

Various designs that have been used to overcome jamming and wear problems (knife cutting edges, flexible tips, replaceable liners) need to be evaluated.

- Evaluate operating RDF storage bins and investigate alternatives:

- Reliability
- Effects on subsequent transportability of fluff RDF
- Maintenance requirements
- Ease of maintenance
- Capital and operating costs
- Needs for further research.

Storage and retrieval of RDF represent a significant fraction of capital and operating expenses. Comparative evaluation of all available systems is necessary to determine the best systems available and the need for further development.

- Evaluate drying RDF to alleviate bridging and setup problems in storage through pilot-scale testing:

- Economic
- Operational, including heat transfer coefficients.

Moisture removal would alleviate the bridging and setup characteristics of fluff RDF, and thus the feasibility of drying needs to be investigated. Drying of RDF may also facilitate pelletizing.

- Evaluate transport and storage of powdered RDF in an oil slurry through pilot-scale testing:

- Stability
- Pumpability
- Need for emulsifying agents
- Economics for stabilization/transmission.

The number of potential users of RDF would be significantly increased if powdered RDF could be transported with oil by pipelines or tankers, and stored as an oil slurry. East Coast utilities are almost entirely dependent on fuel oil for power generation. This is a large and important market for RDF.

4.1.4.4 Densification.

- Evaluate pellet mills at the pilot-scale to improve present densification procedures:

- Die metallurgy
- Die configuration
- Benefits of thermal preprocessing
- Waste oil lubrication
- Alternative methods
- Replaceable liners for dies and rollers.

Animal feed pellet mills are being used for RDF densification and NCCR has conducted some initial research on improving performance of these mills. However, additional work is needed to improve performance. Alternative approaches such as briquetting should be more thoroughly examined.

4.1.4.5 Full-Plant Evaluations.

- Conduct detailed performance tests of embrittlement and wet-pulped processes at fully operational facilities:

- Capital and operating costs
- Energy balances
- Mass balances
- Reliability
- Safety of processes and working environment
- Characteristics of rejects
- Environmental impacts.

These two proprietary systems should be evaluated on an overall basis to determine their relative advantages/disadvantages over dry RDF processes.

4.1.5 Research Programs for Mechanical Separation Systems

4.1.5.1 General. Several facilities are producing an RDF which is used as a supplementary fuel in fossil fuel boilers. However, performance of these RDF plants is erratic, with a lack of quality control. RDF characteristics vary significantly, and there is no method of adjusting product quality other than by trial and error techniques. There are no accepted design equations for sizing, scaling, and integrating unit operations, and it is not possible to predict output quality for a given input.

Research should be directed at developing a fundamental understanding of unit operations through pilot- and full-scale testing, so that equipment and plant design can be improved. Such improvements would produce a more consistent fuel product and increase RDF user confidence. This research should also result in greater plant availability, reduced redundancy, and lower plant cost.

Major effort should be directed at development of mathematical models and design equations to describe the various unit operations. It is important to have an understanding of what parameters affect system response and product quality. A fundamental knowledge of the various unit operations will lead to improved designs.

Significant initial studies have been made by Cal Recovery and MRI in understanding fundamental shredder performance. This work has led to formulation of design equations which generally describe shredder performance; a similar approach is now being applied to air classifiers. This work is being extended to trommels. Previous work on shredders should be refined and similar work on disc screens should be pursued. Subsequent research needs address this work.

An important goal to keep in mind is that the models and design equations for the individual unit operations should eventually be incorporated into a systems engineering model that could be used to predict plant performance and RDF characteristics as a function of input feedstock and processing scheme. While models to describe unit operations are presently very limited, work should now begin toward developing a systems engineering approach to process design. This effort should be directed at determining the type of data that needs to be obtained on the various unit operations, such that they can be modeled as a system. This work ideally should be conducted prior to individual unit operation evaluation, such that the proper type of data can be collected from these evaluations for future use in overall system design. However, with the pressing need for operating data on the various unit operations, it is more practical that the two research efforts be conducted in parallel. Development of a systems engineering approach to process design and a methodology for data collection and analysis of unit operations would initially cost about \$100,000, with a 10 to 12 month duration. When models are developed to describe individual unit operations, an overall systems model to describe plant performance should be formulated and validated. Cost of this type of a program would be \$300,000 to \$400,000, with a 24 month duration.

In looking at RDF facilities being constructed, many are not incorporating successful modifications made at other facilities. This is primarily due to a lack of communication. Experiences gained at RDF facilities should be shared among plant operators, supervising engineers, and facility and equipment designers. While

ASME has served this function for many years, technology transfer has not been optimum.

A joint DOE/EPA/ASME effort should be directed at sponsoring an annual symposium, with proceedings, for plant operators and designers. This same research need was recommended as a generic research need (Section 3.2); however, it is again presented to stress its importance, particularly for RDF technology. Cost to put on an annual symposium and issue proceedings would be about \$100,000.

4.1.5.2 Size Reduction. Shredders are used in every RDF facility. Research is needed to improve their performance. There is little understanding of the effect of hammer wear on RDF size, quality, power requirement, maintenance costs, and subsequent unit operations. Furthermore, there is disagreement on whether to retip or replace hammers.

A hammer wear study needs to be conducted at an operating facility to establish the above relationships. If hammer wear has a significant effect on the RDF product, then retipping may be essential. However, if wear does not significantly affect the RDF product, then disposable hammers may be appropriate. Incorporated into the above program should be an experiment to determine the cost of retipping versus disposing of hammers as a function of hammer wear. Cost of this evaluation would be about \$80,000, with an eight month duration. The Chicago Supplementary Fuel Facility has done some experimentation on retipping versus replacing hammers. These results should be examined before incorporating the hammer retipping experiment into the above program.

Shredder explosions are a major concern at all RDF facilities, and a continuous threat to plant personnel. There has been serious damage at several facilities, and the performance of a number of explosion suppression systems has been questionable. Existing and innovative explosion suppression and pressure vent systems should be evaluated at a pilot or test facility to determine the most effective explosion control system. Existing equipment should be used.

An important area to address in this study is secondary explosion in the shredder. This is due to a carry back of flames into the shredder from a downstream conveyor or air classifier after the explosion suppression system is expelled. Cost of this study would be about \$75,000, with a 12 month duration. It is expected that explosion control equipment can be obtained on loan from vendors for this test.

Recent attention has been directed toward use of flail mills as an alternative to shredders. The Bureau of Mines' pilot facility and the CEA East Bridgewater, Massachusetts, demonstration facility both have a flail mill, but performance data on their operation is minimal. Additional pilot-scale evaluation of flail mills is recommended to determine effect on MSW particle size distribution, power consumption, and maintenance requirements. Design equations should be formulated as a result of this pilot work. Cost of a pilot study using existing equipment would be about \$80,000, with a seven month duration.

Textiles and deformable plastics cause significant equipment downtime due to plugging and binding. A pilot plant program should be initiated to evaluate the effectiveness of ring grinders or disc screens for removal or reduction of these materials. The effectiveness and location of this equipment can be determined by taking outputs from different unit operations at a full-scale facility and using them as feedstocks for the pilot testing. Cost of a pilot test program would be about \$75,000, with a six month duration. Additional cost and time would be required if equipment has to be procured and installed.

A test and evaluation of trommels and disc screens at operating facilities should be conducted. The recently awarded DOE contracts for fundamental research, hardware studies, and full-scale evaluation of trommels should be sufficient for evaluation of this unit operation. However, data on disc screen performance for grit removal is now needed. Results at Ames are passed by word-of-mouth and minimal data is available. An evaluation of the disc screens at

Ames could be accomplished for \$50,000, with a duration of four to five months. The study should stress critical analysis of data in addition to data collection.

4.1.5.3 Materials Handling and Storage. Research should be directed at improving performance of conveyors, rotary air locks, and RDF storage bins. In the first of these areas, data is needed on pneumatic and mechanical conveyors at operating facilities to determine economic and engineering limitations. Information on reliability, maintenance requirements, and ease of maintenance need to be determined. However, the recently funded DOE conveyor evaluation program should be completed before full-scale testing is initiated.

Rotary air locks need to be evaluated at operating facilities to determine reliability, maintenance requirements, size limitations, and best design. Knife cutting edges, flexible blade tips, and replaceable liners should all be evaluated. This study can be limited to data collection at two facilities, using the second evaluation for validation of the first test results. Cost of the study would be about \$75,000, with a nine month duration.

RDF storage and subsequent handling presently represent a significant capital and operating cost at all facilities, as well as a major maintenance problem. The different types of RDF storage bins need to be evaluated at operating facilities. Data is needed on capital and operating costs, reliability, maintenance requirements, and RDF residence time and storability. The cost of these systems should be compared with using a concrete slab for RDF storage and front-end loaders to move the RDF. Innovative ideas for RDF storage should also be encouraged. Analysis of previously collected operating and maintenance data will be an important part of this research effort. Tracer studies should also be conducted to determine RDF movement and residence time in the storage bins. If good data have been kept on operating storage bins, then the duration of this research would be relatively short, i.e., six months, excluding a

long-term wear study. Evaluation of an Atlas, Miller-Hoft, and S. W. Hooper storage bin can be done for about \$75,000 if only limited data collection is needed.

Parallel with the above storage bin evaluation, a pilot plant study should be conducted to evaluate the feasibility of drying RDF as a method of alleviating the bridging and setup characteristics of fluff RDF. The moisture level needed to prevent bridging and the method of drying should be determined. An economic analysis should be conducted to determine the cost of drying as a trade-off of reduced storage bin maintenance and downtime. Cost of the pilot study would be about \$50,000, with a five month duration.

Transport and storage of powdered RDF in an oil slurry by pipeline or tanker offers significant market opportunities. A pilot-scale evaluation of this concept is needed; however, this may be more appropriately conducted by the private sector. Pumpability, stability over time, need for emulsifying agents, and economics should be considered. This study could be conducted for about \$50,000, including construction of a slurry loop, with a six month duration.

4.1.5.4 Densification. Additional pilot-scale development of pellet mills should be encouraged. Because of past problems with die wear and pluggage, research should concentrate on die metallurgy and die configuration. The benefit of using a predried RDF should also be examined. An RDF drying study was a recommended research need for materials handling and storage (Section 4.1.4.3). The results of that study should be used for economic justification of predrying prior to densification. Cost of a well developed pilot-scale program to more fully evaluate pellet mills would be about \$100,000, with a six month duration. This does not include the cost of procuring a pellet mill and handling equipment, which are already available at certain test facilities.

Results of the pellet mill pilot study should be used to improve design of the pellet mill at the Cockeysville, Maryland RDF

facility. A test program should then be conducted at Cockeysville to evaluate the improvement in densification operations as a result of the design changes. Cost of this evaluation, excluding design changes, would be about \$50,000, with a six month duration.

A pilot-scale program should also be initiated to evaluate a briquette press for d-RDF production. Use of a briquette press may alleviate the pluggage and die wear problems presently encountered in pellet mills. The briquette press is used successfully in a number of industries, and its adaptability to MSW should not be overlooked. An initial pilot-scale evaluation would cost about \$75,000, with a six month duration, excluding the cost of a briquette press.

Full Plant Evaluations

Test and evaluation of the embrittlement and wet-pulped RDF processes at operating facilities should be pursued. These processes are being proposed by their vendors to many cities around the country; however, little public information is available on their performance or operation. While both are proprietary, it is in the public interest that every effort be made for an open evaluation of these systems. Cost of each evaluation would be about \$250,000 to \$300,000, with a 9 to 12 month duration. However, both facilities should be operating at design conditions prior to testing, and this will postpone any evaluation for 6 to 12 months.

4.2 In-Plant Materials Recovery

4.2.1 Ferrous Metal Recovery

4.2.1.1 Technology Description. Ferrous metal recovery technology takes advantage of the fact that the material to be recovered is ferromagnetic, and, therefore, will have a large mechanical force acting on it when it is placed in a magnetic field. Devices called magnetic separators have been designed which use this phenomenon to separate ferromagnetic metal (mainly iron and steel) from MSW. The two major types of magnetic separators are the drum and the overhead belt. The magnets can be either permanent or electromagnets.

The cross section of a drum magnetic separator is a semi-circular stationary magnet inside a revolving drum. Separation is achieved when the nonferrous material falls away from the drum, and the ferrous material, attracted to the magnet inside the drum, adheres to it and is carried around to another location. The material falls away from the drum when it travels past the edge of the semicircular magnet.

The overhead belt magnetic separator consists of a stationary magnet with a belt conveyor moving around it. This device is suspended over a conveyor carrying MSW. Separation is achieved when the ferrous material, attracted by the magnet, is lifted off the MSW conveyor and adheres to the underside of the belt conveyor surrounding the magnet.

Several techniques have been developed to reduce "contamination" by nonferrous materials. These techniques include:

- a. Locating the overhead belt and drum magnets at the end of an MSW conveyor to allow the magnetic field to operate on falling and tumbling material. (Most facilities use this technique.)
- b. Preprocessing the MSW by shredding (Ames, Baltimore County, New Orleans), air classifying, or both (Akron, Lane County, Monroe County, Niagara Falls) to reduce the size and/or percent of incoming contamination.
- c. Multiple stages of magnetic separation. The material is dropped and agitated, then magnetically picked up again in order to allow the contaminants to drop off (Akron, Ames, Baltimore County, Lane County, Monroe County, Pompano Beach, Tacoma).

4.2.1.2 Technology Status. Table 4.2-I shows the status of ferrous recovery processes that are part of large resource recovery projects. (Shredding and magnetic separation with the residue land-filled was excluded from the list.)

The technology is simple, reliable, and easy to maintain once startup problems have been overcome. Meeting the market specifications for degree of contamination by organics and nonferrous metals

Table 4.2-I

Facilities with Ferrous Separators

Facility Location	Input Capacity/ Throughput (tpd)	Type of Waste Processing Prior to Magnetic Separator	Type of Separator	Additional Processing of Separated Ferrous	Ferrous Output (tpd)	Plant Status	Market Status
Akron, Ohio	1,000	Shredder, air classifier	Two-stage drum	None	60-80 ^a	To be operational 1/80	Identified potential markets, will start negotiating contracts after plant starts operation
Albany, N.Y.	750	Shredder		None	45-60 ^a	To be operational 6/80	Identified local scrap dealers as potential markets
Ames, Iowa	400/170	Shredder	Two-stage overhead belt	None	10	Operational 8/75	Five-year contract at 47.5% #1 Dealer Bundle (Chicago)
Baltimore Cty., Md.	1,200/670	Shredder	Two-stage overhead belt	None	35	Operational 1/76	Steel company open hearth furnace, price paid 86% of #2 Dealer Bundle
Bridgeport, Conn.	1,800	Flail		None	110 ^a	In shakedown	
Chicago S.W., Ill.	1,000/600	Shredder and shredder/air classifier		None	40	In shakedown	Contract signed with market. Price is 39% of #1 Dealer Bundle.
Chicago N.W., Ill.	1,600	Incineration	Trommel	None	40	Operational	Market being paid to haul away
Columbus, Ohio	1,200	Shredder		None	70 ^a	To be operational 1/82	Potential markets identified
Dade County, Fla.	3,000	Wet pulper		None	180 ^a	To be operational 1/80	Potential markets identified
Detroit, Mich.	3,000	Shredder, air classifier		None	180 ^a	To be operational 6/82	Potential markets identified
Duluth, Minn.	220	Shredder		None	15 ^a	To be operational 1/80	Potential markets identified
Franklin, Ohio	150/50	Wet pulper		None	3	Operated from 71-79	Demonstration, metal taken on experimental basis

^aEstimated.

Table 4.2-I (concluded)

Facility Location	Input Capacity Throughput (tpd)	Type of Waste Processing Prior to Magnetic Separator	Type of Separator	Additional Processing of Separated Ferrous	Ferrous Output (tpd)	Plant Status	Market Status
Hempstead, N.Y.	2,000	Wet pulper		None	120 ^a	In shakedown	Potential markets identified
Lane County, Oreg.	500	Shredder, air classifier	Two-stage overhead belt	None	30 ^a	In shakedown	Potential markets identified
Madison, Wis.	400/200	Shredder		None	10-15	Operational 1969	Being sold to detinning plant
Milwaukee, Wis.	1,200	Shredder, air classifier		None	80	In shakedown	Being sold to market (detinner)
Monroe County N.Y.	2,000	Shredder, air classifier	Two-stage overhead belt	Differential mag sep, secondary shredder additional mag sep	120 ^a	In shakedown	Contract signed with market
New Orleans, La.	700	Trommel or shredder	Single-stage drum	Air classifier, shredder, secondary mag sep, compactor	20	Operational 1977	About 200 tpm being shipped to Proter Intl.
Niagara Falls, N.Y.	2,200	Shredder, air classifier		None	130 ^a	To be operational 1/81	Potential markets identified
Pinellas County, Fla.	2,000	Incineration		None	120 ^a	May be operational 1/83	Potential markets identified
Pompano Beach, Fla.	1,000	Shredder, air classifier	Two-stage overhead belt	None	60	Operational 9/78	Being sold to market intermittently
Saugus, Mass.	1,200	Incineration	Trommel	None	70	Operational 12/75	
Tacoma, Wash.	500	Shredder, air classifier	Two-stage overhead belt	None	30 ^a	In shakedown	Potential markets identified
Wilmington, Del.	1,000	Shredder, air classifier		None	60 ^a	To be operational 1/82	Potential markets identified

^aEstimated.

on a day-to-day basis is a problem, however, for many of the present systems. This problem is reflected in a lower price per ton and an unwillingness, by many companies, to participate as a market.

In the New Orleans facility, Recovery I, the ferrous product, using only magnetic separation and air classification, ranges between 10 to 20 percent entrapped contaminants. This will not meet market specifications. The system has been modified by putting a shredder and secondary magnetic separator between the air classifier and compactor.

As previously stated, the ferrous recovery systems being considered are part of larger systems. Therefore, the economic status of ferrous metal recovery is indeterminate because cost accounting procedures cannot break out the operating and maintenance costs of each system component. In addition, there are philosophical questions as to how to set up a proper accounting procedure. For instance, since the shredder is necessary for both overall plant performance and ferrous separation, should the shredder cost, or only a portion of its cost, be charged to the cost of ferrous separation?

The technology used by the various markets is designed (and has evolved) to accept certain types of inputs with certain contaminants and variations. Ferrous metal recovered by resource recovery plants is essentially a new type of input with new contaminants and variations. This new input can be accommodated by either:

1. Changing the technology used by the market so that it can accept this new input (along with the contamination and variations), or
2. Bringing the contaminants and variations of the recovered ferrous metal within limits acceptable to the existing market technology.

The latter option has been employed, in most instances where recovered ferrous metal is being marketed. However, many potential markets have exercised a third option -- simply refusing to accommodate this new type of input.

Post-incineration ferrous metal recovery is technologically feasible, but uses for the recovered material are restricted. When the refuse is incinerated, trace metals are alloyed into the ferrous metal, making it unsuitable for most markets.

4.2.1.3 Research Status. Pilot-scale research has been conducted (mainly by the U.S. Bureau of Mines, the National Center for Resource Recovery, and equipment manufacturers) that proves the technological feasibility of recovering ferrous material from refuse. Much of this work has been used by design engineers and equipment manufacturers in designing and building full-scale facilities. There are also many areas for which only the equipment manufacturers and some design engineers have information, and even their information is not definitive.

On the market side, the same conditions prevail. Some primitive pilot-scale work has been performed to show technical feasibility. Those companies that are accepting the material on a day-to-day basis have information that is not in the public domain and therefore is difficult to transfer.

4.2.1.4 Research Needs for Ferrous Metal Recovery. Research in ferrous metal recovery is directed at establishing basic design parameters and improving the marketability of the product. Table 4.2-II lists the technical research needs which are discussed below.

- Develop mathematical models through pilot- and full-scale testing to describe magnetic removal of ferrous materials. Research is needed to determine how the product varies (degree of recovery and contamination) as a function of: input particle size, feed rate, magnetic field strength, spacing between magnet and feedstock, geometry, and prior processing. Such research will promote sound design procedures for new and retrofit facilities. Present design practices are more art than science and rely heavily on manufacturer information.

Table 4.2-II

Research Needs for Ferrous Metal Recovery

- Develop mathematical models through pilot- and full-scale testing to describe magnetic removal of ferrous materials.
- Evaluate secondary (cleanup) unit operations for ferrous scrap recovery.
- Support the development of standard recovered ferrous material specifications by ASTM that are market specific.

Pilot studies should be initiated for development of models. Cost would be about \$75,000, with a 6 month duration. This work should be validated by evaluation of several full-scale ferrous recovery systems. Cost of this evaluation would be about \$100,000, with a 6 to 8 month duration.

- Evaluate secondary (cleanup) unit operations for ferrous scrap recovery. Determine how product quality varies as a function of: additional stages of magnetic separation (with and without additional processing stages, such as screening); returning the recovered fraction through the same processing train (as could be done at the end of the day in a full-scale facility); and other cleanup operations, such as air classification. Once this is established, sound decisions could then be made on the trade-offs of additional processing at the recovery facility. Market decisions could also be made on installation of facilities to enable acceptance of lower grade material.

The above information should be developed at a pilot test facility, using existing equipment. An engineering and economic analysis should be conducted to determine the cost of additional processing as a function of additional revenues from increased quality and/or quantity. Cost of this evaluation would be about \$125,000, with an 8 to 12 month duration.

- Support the development of standard recovered ferrous material specifications by ASTM that are market specific. Uses for ferrous scrap vary widely across the country and within regions. Each use has its own requirements as to amount and type of contamination that can be tolerated in the input. These requirements are also a function of the particular recovery technology used. It would aid the marketing of recovered ferrous scrap if standard specifications were available. Additionally, to avoid confusion, standard test methods must be developed and specified along with the component amount. The proposed ASTM specifications will help alleviate this need.

4.2.2 Aluminum Recovery

4.2.2.1 Technology Descriptions. The most prevalent aluminum recovery technology employs the fact that when an electrical conductor is cut by a magnetic field and there is relative motion between them, an electrical current, called an eddy current, is caused to flow in the body. This current has a magnetic field associated with it that opposes the original magnetic field, and thus produces a force on the body in a direction perpendicular to both the magnetic field and the current. Devices making use of this phenomenon have been designed to separate aluminum from shredded and air-classified refuse after the ferrous has been removed.

There are basically three types of eddy current separators. One type consists of a nonconducting conveyor belt passing through a magnetic field (generated by electromagnets or a linear induction motor). As the material passes through the field, it is kicked off the conveyor belt (to either side of the conveyor) where it falls into collection containers. The second type is a variation of the first. Instead of the material being conveyed on a belt through the magnetic field, it falls vertically through the field and aluminum is deflected from the main stream. The third type is an inclined ramp with permanent magnets mounted at an angle underneath. The material is fed from the top, and as it slides down the ramp, the metals curve to one side and the nonconductors slide straight down.

There are two other, less prevalent technologies. One separates out the aluminum, using specific gravity and particle size. The other makes use of the differences in conductivity between metals and nonmetals which allow separation in a strong electrostatic field.

4.2.2.2 Technology Status. Table 4.2-III shows the status of aluminum recovery projects that are part of large resource recovery projects. Table 4.2-IV gives target specifications being considered by ASTM.

Table 4.2-III
Status of Aluminum Recovery from MSW

<u>Location</u>	<u>Separation Technology</u>	<u>Status of Technology</u>
Ames, Iowa	Eddy Current (conveyor belt and electro-magnets)	Shut down (did not work)
Baltimore County, Maryland	Eddy Current (vertical fall and magnets)	Used sporadically (does not produce a marketable product)
Bridgeport, Conn.	Eddy Current (conveyor belt and linear induction motor) - 2 stages	In shakedown
Franklin, Ohio	Eddy Current (conveyor belt and linear induction motor) - small particles only	Demonstration, metal taken on experimental basis
86 Hempstead, N.Y.	Heavy Media followed by jigging followed by Electrostatic Separation	In shakedown
Milwaukee, Wis.	Eddy Current (vertical fall and magnets)	In shakedown
Monroe County, N.Y.	Eddy Current (inclined ramp and permanent magnets) followed by Heavy Media	In shakedown
New Orleans, La.	Eddy Current (conveyor belt and electro-magnets)	In shakedown (shipment made to Reynolds Metals in March 1979)
San Diego County, California	Eddy Current (conveyor belt and linear induction motor)	Shutdown

Table 4.2-IV
Recovered Aluminum Specifications*

Element	Grade 1	Grade 2	Grade 3
Si	0.30 wt. %	0.30 wt. %	0.50 wt. %
Fe	0.60	0.70	1.00
Cu	0.25	0.40	1.00
Mn	1.25	1.50	1.50
Mg	2.00	2.00	2.00
Cr	0.05	0.10	0.30
Ni	0.04	0.04	0.30
Zn	0.25	0.25	1.00
Pb	0.02	0.04	0.30
Sn	0.02	0.04	0.30
Bi	0.02	0.04	0.30
Ti	0.05	0.05	0.05
Other - each	0.04	0.05	0.05
Other - total	0.12	0.15	0.15
Aluminum	Remainder	Remainder	Remainder
Organics	<2.0	<2.0	<2.0

* Presently under consideration by Committee E-38, Resource Recovery, of the American Society for Testing and Materials.

To date, because of contamination by organics and non-aluminum metals, the technology has not been able to produce a product from MSW that will meet market specifications. Additionally, the fraction of aluminum in the MSW that has been captured by the recovery system is low (50 to 70 percent).

Contamination of aluminum by organics results partly from the consumer uses of the aluminum products. Cans contain the residue of the beverage. Foil pie plates have baked-on residue. Additional contamination comes from the mixing of all wastes during collection and the shredding of the composite. Contamination by non-aluminum metals is inherent to the separation technology, which cannot differentiate between different non-magnetic metals. The low percentage of aluminum that is finally recovered is due to cumulative losses of aluminum in prior processing steps (aluminum foil may be air classified into the light fraction) as well as the efficiency of the aluminum separator.

At the Ames, Iowa, facility, initial problems were encountered with materials-handling in the aluminum recovery process, primarily due to belt conveyor failures. When these problems were resolved, it was found that the amount of aluminum in the refuse was quite low and that the aluminum recovery equipment could not produce a marketable product. The equipment is now shut down and only ferrous metals are recovered.

The Baltimore County facility has almost no aluminum in the refuse. This is due to the location of a large steel plant in the area whose workers exercise economic pressure for store owners to carry beverages packaged in steel cans.

At Franklin, Ohio, the aluminum separation process was only tested on a selected portion of the material. This experiment was run only intermittently, and all nonferrous metals were usually landfilled.

San Diego County, California, experienced materials-handling problems that were not fully solved by the time the plant was shut down. The remainder of the plants shown in Table 4.2-III are in

shakedown and no reliable results have been reported. As with ferrous metal recovery, owning and operating costs have not been separated from the total system costs because of accounting procedures.

4.2.2.3 Research Status. Pilot-scale research has been conducted (mainly by the U.S. Bureau of Mines, National Center for Resource Recovery, and equipment manufacturers) for technological feasibility of recovering aluminum from refuse. However, this work was not definitive, and although conclusions have been made, they are not strongly supported.

The New Orleans Recovery I facility's aluminum recovery system is still in shakedown. However, a commercial shipment was made to Reynolds Metals in March, 1979. The product met Grade 1 specifications, although there was a slight penalty in price because of organic contamination.

Most of the research now going on is at a few full-scale resource recovery facilities where capital was invested in the aluminum recovery technology, and adjustments to the equipment are being tried and markets are being developed in order to save the investment. Most of this work is neither methodical nor published.

Pilot-scale work to date has progressed to the point where the final aluminum-product collection receptacle contains more aluminum than contaminants -- but it has not produced a product that meets market specifications. Also, in some of the experimental equipment used, the material is hand-fed, and this can mask materials-handling problems and equipment input requirements such as the need for a single layer of feed material. Additionally, the pilot-scale work has not produced the knowledge necessary for facility design.

Projected costs for aluminum recovery either have not been attempted or have not followed standard cost accounting procedures.

4.2.2.4 Research Needs and Research Programs for Aluminum Recovery. Research needs and research programs for aluminum recovery are similar to those for glass recovery. Section 4.2.3.4 discusses the research needs and programs for both aluminum and glass recovery.

4.2.3 Glass Recovery

4.2.3.1 Technology Description. The process trains that have been proposed for recovering glass from MSW are various combinations of equipment used in the international minerals industry, including:

- Froth flotation apparatus
- Heavy media, density separator
- Hydraulic (rising current) separator
- Hydrocyclone
- Impact hammermill
- Mineral jig
- Rod mill
- Screen
- Settling tank
- Trommel.

Color sorting has also been proposed.

Proposed uses for the recovered glass include:

- Abrasive sandblasting and/or grinding
- Aggregate for road construction (glasphalt)
- Beads or chips for reflective paints and/or chemical process industry
- Building panels
- Cold-bonded brick
- Cullet for manufacturing new glass products
- Facing brick
- Fiberglass insulation
- Fired clay products (brick and tile)
- Floor tile

- Foamed glass
- Glass-plastic extrusions
- Glass-polymer castings such as sewer pipe
- Masonry block
- Oil well packing
- Shoreline erosion protection
- Slurry seal
- Terrazzo flooring.

4.2.3.2 Technology Status. Pilot-scale development of a recovered-glass color sorter has been performed by the U.S. Bureau of Mines and the equipment manufacturer (Sortex Co.) at College Park, Maryland. This glass sorter was installed at a larger scale in the Franklin, Ohio facility and reportedly produced a marketable product (although not to Glass Container Manufacturers Institute specifications). The sorter is also being installed (along with an electrostatic separator) in the Hempstead, New York facility (now in shakedown).

Pilot-scale development has been conducted for various combinations of the machinery listed in Section 4.2.3.1, operating on MSW that has been shredded, air classified and magnetically skimmed for ferrous metal. Full-scale implementation of the pilot work is being tried at various locations.

To date, no pilot- or full-scale resource recovery facility separates and markets glass on a day-to-day basis.

Baltimore County recovers glass from the light fraction by trommeling, and from the heavy fraction by shaker tables. Separating the glass from the light fraction has reduced the wear on the RDF pelletizer. To date, the glass has not been marketable, although samples have been sent to potential markets (i.e., aggregate in sewer pipe).

Occidental Petroleum Corp. had a froth-flotation glass separator at its San Diego County plant; glass recovery is not being pursued, however, at the Niagara Falls facility being designed and built by Hooker Chemical Co., a subsidiary of Occidental Petroleum.

The Monroe County facility (being built by Raytheon) will have a glass separation system based on the Bureau of Mines' pilot plant in Maryland. Input for the glass recovery train is the magnetically scalped, shredded heavy fraction from the air classifier. The stream is then trommeled and the undersized material goes to a jig to remove light organics. The remaining fraction then goes through a coarse material washer, rod mill, screen, desliming classifier, primary flotation cell, wet magnetic separator, sand filter and rotary dryer. The facility is in shakedown, and results are not yet known.

The New Orleans facility has a process train somewhat similar to that of Monroe County. The National Center for Resource Recovery is using this installation as a test facility to conduct research into glass recovery at full-scale. A total of about 15 tons of glass product was produced by August 1979.

4.2.3.3 Research Status. To date, pilot work has been incomplete and inconclusive. Total costs and energy consumption -- including energy to produce and transport chemicals -- have not been included in most analyses. At the same time, revenues from the sale of glass have been overestimated.

Definitive knowledge of how to recover a high quality glass product does not exist and must be methodically developed starting, again, at the pilot-plant level.

Most RDF manufacturing systems are going to try to remove the glass to improve the RDF. This glass is highly contaminated, but alternative markets may be able to use it. Hence, research into markets for highly contaminated glass should be pursued along with the pilot-scale work on equipment that will improve the purity of the glass product. The market research results will dictate required equipment performance.

4.2.3.4 Research Needs and Research Programs for Aluminum and Glass Recovery. The research needs for aluminum and glass recovery are targeted toward answering the basic questions of feasibility and desirability. Table 4.2-V summarizes the research needs discussed below.

- Evaluate the technical and economic feasibility of aluminum and glass separation based upon New Orleans Recovery I and Monroe County, New York experiences. Based upon the best available data from existing installations, the technical and economic feasibility of aluminum and glass separation should be determined. An economic analysis should be performed on the above two systems in terms of both money and energy; special note should be taken of the effects of the separation on downstream system performance.

Test and evaluation of aluminum and glass recovery operations at the New Orleans and Monroe County facilities will cost about \$100,000 each, including economic analysis. However, these systems must be operating at a commercial-scale before any testing should be conducted. This will probably delay testing for about 6 to 12 months.

- Develop design equations for unit operations for aluminum and glass separation. Support ASTM development of standard recovered aluminum and glass specifications that are market specific. If it is found that it is both technically feasible and desirable to recover aluminum and glass from refuse, then basic design equations should be developed for aluminum and glass recovery equipment, and standard market specifications and test methodologies should be developed and demonstrated. Design equations should be developed at the pilot plant scale, and then verified at a full-scale facility. However, initiation of the program is at least two years away.

Table 4.2-V

Research Needs for Aluminum and Glass Recovery

- Evaluate the technical and economic feasibility of aluminum and glass separation, based upon New Orleans Recovery I and Monroe County, New York experiences.
- Develop design equations for unit operations for aluminum and glass separation. Support ASTM development of standard recovered aluminum and glass specifications that are market specific.

REFERENCES: SECTION 4 MECHANICAL SEPARATION SYSTEMS

1. J. Ruf, "Particle Size Spectrum and Compressibility of Raw and Shredded Municipal Solid Waste," The University of Florida, Ph.D. Thesis, 1973.
2. Joseph Kennedy, Tricil Ltd.: personal communication.
3. J. C. Even, et al., "Evaluation of the Ames Solid Waste Recovery System, Part I," U.S. Environmental Protection Agency, EPA-600/2-77-205, November, 1977.
4. "Preliminary Findings: Use of d-RDF as a Stoker Coal Substitute - Industrial Spreader Stoker," Systems Technology Corporation, June, 1977.
5. R. M. Beningson, et al., "Production of Eco-Fuel II from Municipal Solid Waste", Conversion of Refuse to Energy, First International Conference, Montreux, Switzerland, November 3-5, 1975.
6. "A Technical, Environmental, and Economic Evaluation of the Wet Processing System for the Recovery and Disposal of Municipal Solid Waste", U.S. Environmental Protection Agency, SW-109C, 1975.
7. Thomas Lamb, Arthur D. Little Corp.: personal communication.
8. H. Alter and J. Arnold, "Screening of MSW as a Means of Upgrading RDF", National Center for Resource Recovery, Inc., TR-78-5, 1978.
9. G. Savage and G. J. Trezek, "Screening Shredded Municipal Solid Waste", Compost Science, January/February, 1976.
10. A. R. Nollet and E. T. Sherwin, "Air Classify First, Then Shred", Energy Conservation Through Waste Utilization, Proceedings of 1978 National Waste Processing Conference, May, 1978.
11. R. G. Zalosh, et al., "Assessment of Explosion Hazards in Refuse Shredders", Factory Mutual Research Corporation, for the U.S. Energy Research and Development Administration, June, 1976.

12. Don Riggs, Ames Municipal Electric System: personal communication.
13. J. E. Duckett, "Microbiological Analysis of Dusts at the Equipment Test and Evaluation Facility", National Center for Resource Recovery, Inc., TR78-2, March, 1978.
14. G. J. Trezek, "Significance of Size Reduction in Solid Waste Management", University of California, EPA-600/2-73-131, July, 1977.
15. G. M. Savage, et al., "Evaluation and Performance of Hammermill Shredders Used in Refuse Processing", unpublished document, Cal Recovery Systems, Inc.
16. R. L. Chrismon, "Air Classification in Resource Recovery", National Center for Resource Recovery, Inc., RM 78-1, October, 1978.
17. D. L. Murray, and C. R. Liddell, "The Dynamics, Operation, and Evaluation of an Air Classifier", Waste Age, March, 1977.
18. Norman Hecht, University of Dayton, and George Trezek, University of California, Berkeley: personal communications.
19. G. M. Savage, et al., "RDF; Quality Must Precede Quantity", Waste Age, April, 1978.
20. K. L. Woodruff and E. P. Bales, "Preprocessing of Municipal Solid Waste for Resource Recovery with a Trommel-Update, 1977", Energy Conservation Through Waste Utilization, Proceedings of 1978 National Waste Processing Conference, May, 1978.
21. R. L. Chrismon, et al., "Trommel Initial Operating Report, Recovery I", National Center for Resource Recovery, Inc., TR-78-3, October, 1978.
22. M. L. Renard, "Refuse Derived Fuel (RDF) and Densified Refuse-Derived Fuel (d-RDF)", National Center for Resource Recovery, Inc., RM 77-2, June, 1978.
23. P. E. Muehlberg, "Assessment of Economic Viability of the d-RDF System Concept", U.S. Environmental Protection Agency, 1978.
24. N. L. Hecht, et al., "Investigation of Advanced Thermal-Chemical Concepts for Obtaining Improved MSW-Derived Products", U.S. Environmental Protection Agency, EPA-600/7-78-143, August, 1978.

25. D. E. Fiscus, et al., "St. Louis Demonstration Final Report: Refuse Processing Plant Equipment, Facilities, and Environmental Evaluations", U.S. Environmental Protection Agency, EPA-600/2-677-155a, September, 1977.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SECTION 5

COMBUSTION SYSTEMS

5.1 Mass Burning Steam Generation

5.1.1 Technology Description

In the early stage of development, steam recovery from MSW was usually accomplished by adding waste-heat boilers to conventional, refractory wall, mechanical grate incinerators. However, because of the poor operating characteristics and high maintenance costs associated with these incinerators, this method of steam recovery is now obsolete and has been replaced by waterwall combustors. Waterwall combustors recover 15 to 20 percent more energy, require less excess air and smaller pollution control equipment, operate at a lower wall temperature and thus require less refractory maintenance, and provide better burnout of the refuse.

In waterwall combustors, as-received refuse is transferred from a receiving pit into the furnace feed hopper by means of an overhead, traveling crane with a grapple bucket. From the hopper, wastes are continuously fed to the furnace and burned on an inclined moving grate system. Noncombustible and unburned material falls off the end of the grate, where it is water-quenched. A typical waterwall combustor facility is shown in Figure 5.1-1.

The waterwalls are made of closely spaced steel tubes welded together to form a continuous wall. Water circulates through the tubes. Integrally constructed waste-heat boilers generate steam while reducing exhaust gas temperature. Superheaters and economizers are used when necessary.

There are several grate systems currently used to move the refuse through the furnace. All produce a tumbling action of the refuse, which results in more rapid ignition and better burnout.

Combustion air is introduced into the furnace beneath the grates (underfire air) to aid combustion and keep the grates cool. Air is also introduced above the fuel bed (overfire air) to promote

1. Crane	13. Rotary Valve
2. Feed Hopper	14. Fly Ash Conveyor
3. Feed Chute	15. Induced Draft Fan
4. Feeder Rams	16. Overfire Air Nozzles
5. Reverse Reciprocating Stoker	17. Waterwalls (Welded Panel Const.)
6. Undergrate Air Plenum Chambers	18. Boiler Fly Ash Hoppers
7. Hydraulic Pump	19. Steam Drum
8. Forced Draft Fan	20. Bottom Boiler Drum
9. Automatic Siftings Removal Systems	21. Economizer
10. Residue Roller	22. Economizer Fly Ash Hopper
11. Residue Discharger	23. Fly Ash Hoppers
12. Residue Conveyors	24. Electrostatic Precipitators
	25. Stack

Figure 5.1-1. Typical Mass Burning Steam Generator

mixing of the gases (turbulence) and to complete combustion of the refuse off-gases.

The combustion gases leaving the boiler sections are passed through air pollution control equipment (generally electrostatic precipitators) and exhausted to the atmosphere through a stack. Boiler efficiency is typically 63 to 68 percent.

5.1.2 Technology Status

5.1.2.1 Technical. The first large-scale waterwall combustor in the U.S. was installed by the Navy in Norfolk, Virginia in 1967. However, development of this technology began in Europe in the 1950's. The Europeans rapidly commercialized the technology in the 1960's and 1970's and there are now over 100 regularly operating waterwall incinerator installations in Europe that are producing steam or hot water.

Implementation of this technology in the U.S. has been much slower, due in part to the greater availability of landfill space and the lower cost of fossil fuel. Table 5.1-I indicates the present status of mass burning steam generators in this country. Facilities in operation, under construction or in the final design stage are listed.

While the U.S. has in operation more mass burning steam generating facilities than any other type of large-scale resource recovery facility, many of these systems are still experiencing significant operational problems. Every facility that has been constructed has undergone significant modifications. Of particular note are the RESCO and Nashville Thermal Transfer Corporation facilities. At RESCO, to make the plant operational, an additional \$15 million was required above the initial \$35 million capital cost.

All the mass burning steam generators operating in the U.S. and Canada are owned and operated by the public sector with the exception of RESCO, which is privately owned and operated, and Nashville, which is financed by pollution control revenue bonds but publicly operated. There is a significant difference between RESCO and the

Table 5.1-I

Status of Mass Burning Steam Generators

Location	Participants	Status of Development	Capacity (tpd)	Capital Cost (\$million)	Net Tipping Fee (\$/ton)	Principal Products	Problems
Chicago, Ill. (Northwest)	City of Chicago: Owner/Operator IBW-Martin, Metcalf & Eddy: Designer	Operational fall 1970. Steam line being installed for steam sale to Brach Candy Co. Steam sales expected to begin in mid-1979.	1,600	23 (1970)	17 ^a	<ul style="list-style-type: none"> 200,000 lb/hr of steam (275 psig sat.) available for sale. Brach Candy Co. will purchase about 70,000 lb/hr Ferrous metals 	<ul style="list-style-type: none"> Boiler tube erosion No steam sales High steaming rate variability
Saugus, Mass. (RESCO)	Wheelabrator-Frye, Inc.: Owner/Operator DeMatteo Construction Co.: Owner	Operational since fall 1975 Steam sold to General Electric in Lynn, Mass.	1,200	35 ^b (1975) 50 ^c	14.40	<ul style="list-style-type: none"> 320,000 lb/hr of steam (890 psig, 375° F) Ferrous metals 50-80 tpd 	<ul style="list-style-type: none"> Superheater tube corrosion High particulate emissions
Nashville, Tenn.	Nashville Thermal Transfer Corp.: Operator I.C. Thomasson & Assoc., Inc.: Designer	Operational since late 1974 Processing about 400 tpd of refuse	720	18.5 (1974)	---	<ul style="list-style-type: none"> 80,000 lb/hr of steam (400 psig, 600° F) used for heating and cooling downtown area 	<ul style="list-style-type: none"> Both ESPs passed EPA tests in mid-1978.
Harrisburg, Pa.	City of Harrisburg: Owner/Operator Gannett, Fleming, Corrdry and Carpenter, Inc.: Designer	Operational since Oct. 1972. Steam line to be completed in spring 1979 for sale to Pennsylvania Power & Light. Processing 450 tpd of of refuse.	720	8.3 (1972)	12.80 private haulers, \$20/yr ea. household	<ul style="list-style-type: none"> 90,000 lb/hr of steam (265 psig, 455° F) available for sale Ferrous metals 20 tpd 	
Braintree, Mass.	Town of Braintree: Owner/Operator Camp, Dresser & McKee: Designer	Operational in 1971. Shut down in 1976 for air emission problems. Operating at 240-290 tpd since mid-1978 with new ESP internals. Passed emission tests.	240	2.85 (1971)	8 ^d	<ul style="list-style-type: none"> 60,000 lb/hr of steam (250 psig, sat.) sold to Weymouth Art & Leather Co. and Sigma Instruments 	<ul style="list-style-type: none"> Maintaining ESP inlet gas temperature above dewpoint has resolved ESP performance problems.

^aGenerated steam is used in plant to drive all motors, fans, and pumps. No charge is taken for in-plant steam use.^cFinal capital cost after initial plant modifications.^bInitial capital cost.^dPaid by private haulers only.

Table 5.1-I (Continued)

Location	Participants	Status of Development	Capacity (tpd)	Capital Cost (\$million)	Net Tipping Fee (\$/ton)	Principal Products	Problems
Quebec City Quebec, Canada	Communities Urban de Quebec: Owner/Operator	Operational since 1974. Processing 500 tpd of refuse in winter and 1,000 tpd in summer from 10 surrounding towns.	1,000	25 (1974)	—	<ul style="list-style-type: none"> 60,000 lb/hr of steam (400 psig, 600° F) sold to Reed Paper Co. in winter months and 120,000 lb/hr in summer Ferrous metals 	<ul style="list-style-type: none"> Corrosion of furnace walls and outlet of auxiliary combustion chamber. Heavy clinkering on walls above grates. Modified furnace arch and overfire air nozzle location on #1 boiler in 12/78. Particulate emissions now acceptable.
Hampton, Va.	City of Hampton: Owner/Operator NASA-Langley Research Center: Owner Langley AFB: Owner J.M. Kenith Co.: Designer	Contract awarded to J.M. Kenith Co. in Jan. 1978. Project completed by June 1980.	200	9.9 (1978)	—	<ul style="list-style-type: none"> 300 million lb/yr of steam (350 psig sat.) to be sold to NASA-Langley for central heating and cooling 	—
Norfolk, Va.	U.S. Navy: Owner/Operator Metcalf & Eddy, Inc.: Designer	Operational since 1967. Installed ESPs in 1975. Processing 140 tpd, 5 days per week.	360	2.2 (1967)		<ul style="list-style-type: none"> 60,000 lb/hr of steam (275 psig, sat.) when co-firing with oil. Steam used for heating and laundry of ships in port. 	<ul style="list-style-type: none"> Particulate emissions Grate wear
Pinellas County, Fla.	Pinellas County, UOP, Inc.: Operator	Contract negotiations underway with UOP for full-service, 20-year contract.	2,000	68 (1979)	10	<ul style="list-style-type: none"> Electric power, 500 KW/ton will be sold to Florida Power & Light 	—

Table 5.1-I (Concluded)

Location	Participants	Status of Development	Capacity (tpd)	Capital Cost (\$million)	Net Tipping Fee (\$/ton)	Principal Products	Problems
Gloucester County, N.J.	Wheelabrator-Frye, Inc.: Owner/Operator SCA Services, Inc.: Operator	Camden area has only 300 tpd, needs 1,200 tpd to make project go, looking for more waste. Contract signed with Atlantic City Electric Co. to purchase electricity.	1,200	80 (1979)	—	<ul style="list-style-type: none"> Electric power Ferrous metals 	<ul style="list-style-type: none"> Insufficient quantity of waste
North Andover, Mass. (Northeast Mass.)	50 communities from NE Mass. and southern N.H., UOP Inc.: Operator	UOP selected as contractor for 20-year full-service system. Contracts for residential waste now being obtained.	3,000	115 (1979)	12.80 ^e	<ul style="list-style-type: none"> Electricity 	<ul style="list-style-type: none"> Difficulty in signing contracts for waste with communities
Oceanside, N.Y.	Town of Hempstead: Owner/Operator Charles R. Velzy Assoc. Inc.: Designer	Original plant placed in operation in 1965 with waste heat boilers. First waterwall boiler operational since 1974. Second waterwall boiler operational since 1977.	750	5.6 ^f (1965) 9.89	—	<ul style="list-style-type: none"> Electricity for in-plant heat, light and power Fresh water 	—
Montreal, Canada	City of Montreal: Owner/Operator	Operational since 1970. Processing about 1,000 tpd.	1,200	16 (1970)	8 ^h	<ul style="list-style-type: none"> 200,000 lb/hr of steam (225 psig, sat.) used for heating city facilities and snow melting. No steam market in summer, but now negotiating with local industry. 	<ul style="list-style-type: none"> Particulate emissions

^eDisposal fee plus shared transportation cost, assuming 3,000 tpd of MSW.^fOriginal plant.^gImprovement program.^hOperating cost only. No annual capital or revenues.

other facilities. At RESCO, all of the steam produced is available for sale to General Electric, the steam customer. The steam contract has maximum and minimum steam requirements that both parties must adhere to. RESCO also has oil-fired auxiliary boilers that must be used if sufficient steam cannot be produced from refuse. Because it is a private enterprise concerned with capital, only two waterwall incinerators were installed at RESCO, with no standby boiler capacity. In contrast, most publicly-owned facilities maintain a standby boiler. Many of these public facilities do not have steam contracts and use 25 to 50 percent of the steam produced to drive pumps and motors in the plant.

Because there has been no need for reliable production of quality steam, the public facilities have done little to improve control of the combustion process. Load-following capability is limited and steaming rate oscillates from 10 to 30 percent of average load. Typically, there is a 15-minute lag between stoker charge and change in steam rate. As more waterwall incinerator facilities enter into steam contracts, the need to improve process controls will increase.

Electric power generation for export sale will be employed at two new mass burning steam generation facilities in Pinellas County, Florida and North Andover, Massachusetts. The ability to produce higher pressure steam and to better control steaming rate is important to the long-term development and implementation of waterwall incinerators.

The major problems that facilities are experiencing are boiler tube failures and high particulate emissions. Other common problems are grate wear, crane failure, pit fires and less than optimum combustion control.

Boiler tube failures are due to corrosion and erosion, with corrosion occurring in both the wall tubes and superheater tubes. Using a silicon carbide coating on boiler wall tubes near the grate has become a common practice in most plants. This has eliminated wall tube corrosion on these areas with only-minor reduction in heat

transfer efficiency. The Nashville facility was not initially constructed with silicon carbide coverings on the lower wall tubes. These tubes began to fail after only a few months of operation and in less than a year both boilers were shut down because of tube failure. Silicon carbide has since been installed on these areas, significantly reducing the problem.

Absence of a silicon carbide covering on lower wall tubes has caused severe clinkering problems at the Quebec City facility. Clinkers, two to three feet thick, are forming on the lower wall immediately above the main grate. This is reducing both grate area and throughput. The furnaces can only be operated for two months and then must be shut down and cleaned. Plans are to install silicon carbide where the clinkering is occurring. In other locations of the boiler where silicon carbide is used, there is no clinkering.

Corrosion of wall tubes due to reducing atmospheres and high temperatures is common in many facilities. Silicon carbide is principally used to cover wall tubes near the grate and the upper portion of the tubes is left uncovered. Overheating of these upper tubes due to flame impingement or radiation can cause the chloride salt deposits on the tubes to liquefy, which then causes rapid attack of the tube metal. The presence of lead in these slag deposits can produce low melt point fluxes which also encourage corrosion.

Reducing atmospheres in the furnace are due to inadequate distribution of overfire air. This has caused wall tube corrosion problems at the RESCO, Quebec City and Nashville facilities. Overfire air nozzles and furnace arches have been modified at these facilities. RESCO increased both the under- and over-fire air to eliminate the reducing atmospheres; excess air has been increased from 100 to 130 percent.

Superheater tube corrosion is a problem at all U.S. facilities that produce superheated steam. RESCO produces the highest temperature superheated steam, 875°F, and Harrisburg produces the lowest, 455°F. Although the Harrisburg and Nashville facilities produce a

relatively low-temperature superheated steam, superheater tube failure has occurred rapidly. The initial tubes at Harrisburg lasted only half a year and those at Nashville for about one year. Based on the fire-side corrosion work by Battelle Columbus Labs [1], we can infer that the superheater tube corrosion at RESCO was a result of chloride reaction with the substrate metal, while at Harrisburg and Nashville the corrosion mechanism was a chloride-assisted sulfide reaction with the substrate metal.

Boiler tube failure due to erosion from soot blowers is another common problem of waterwall incinerator facilities. At the Chicago Northwest facility, boiler tubes in the convection section nearest the wall have been eroded by water droplets that are blown out of the soot blower lance each time the tubes are cleaned. Replacement of failed tubes recently resulted in a six-month boiler downtime; the furnace is a Martin design and delivery time of tubes from Europe is about four months.

Soot blowers are also a source of problems at the Montreal facility. The soot blowers are not of adequate size and particulates build up on the boiler tubes and cause bridging. This reduces heat transfer and also increases the velocity around the tubes, which accelerates erosion. Each boiler must be shut down every three months for manual cleaning of the tubes.

Harrisburg has considerably reduced its tube erosion problem by using soot blowers once a month instead of once every eight-hour shift as was previously done. However, heat recovery efficiency must be affected by this procedure.

The newer Von Roll mass burning steam generator design has eliminated the use of soot blowers. Slag that collects on the vertically hanging boiler tubes in the convection section is removed by rappers rather than soot blowers. The RESCO and Quebec City facilities are examples of this design.

The greatest operational problem associated with mass burning steam generators is high particulate emissions. Despite the use of electrostatic precipitators with at least two fields in all operating facilities, particulate emissions remain a problem. The facilities in Harrisburg, Quebec, Montreal and the RESCO facility in Saugus have repeatedly exceeded particulate emission standards. Analysis of the particulate catch shows a high percentage of large particles (+10 micrometers) -- mostly unburned carbon.

At RESCO, the increase in excess air from 100 to 130 percent has caused an increase in gas velocity and higher boiler tail temperature with an increase in particulate emissions. One possible explanation for the increase in particulate emissions is that the increase in underfire air would cause greater refuse bed turbulence and could result in greater entrainment of particulate due to the higher gas velocity.

Improved control over the combustion process may mitigate the many particulate problems being experienced. Additional or alternative methods of air pollution control are also necessary. The presence of large particles in the off-gas suggests the use of multi-cyclones preceding the precipitators. Bag houses may also be an attractive alternative if an acceptable bag material can be found to withstand gas temperature up to 600°F. Based on the Nashville experience, wet scrubbers do not appear appropriate for particulate control.

Wheelabrator-Frye, Inc. is evaluating a small bag house for particulate emission control using a flue gas slip stream at their RESCO facility. Carter-Day, Inc. has also developed a bag house for use on refuse fired steam generators; however, a full-scale test and evaluation has not been conducted.

Grate wear and overheating are also problems that many facilities have experienced. The reciprocating grate that is common to most facilities undergoes significant wear between the grate and

wear plate. Glass, grit and slagged aluminum become lodged between the two surfaces, and as the grate moves back and forth, wear occurs. At RESCO, grate wear was a significant problem. However, a recent change in grate design has resolved many of the problems. At the Norfolk waterwall incinerator, grate replacement due to wear is the highest maintenance cost item; some grates must be replaced every month.

All mass burning steam generator facilities in the U.S. employ a storage pit with an overhead, traveling crane and grapple bucket for feeding refuse into the furnace. The cranes are powered by AC motors, and motor overload and cable wear result in significant crane downtime. Most facilities operate two cranes with one on standby. Pit fires have occurred when an end crane has been down for repair and the refuse beneath it could not be reached by the other cranes. In many cases, the cause of the fire is spontaneous combustion.

5.1.2.2 Economic. Very little data are available on the annual cost of mass burning steam generators operating in the U.S. The newest facility, RESCO, is a private facility and only the capital cost and present tipping fee, \$14.40/ton, are known.

Different public facilities use different accounting procedures. Many of the plants use a portion of the steam produced inplant for running pumps and motors; no opportunity cost is taken for this steam, usually because the plant was constructed without a steam market contract. Often, management personnel are not counted as a salary expense because they are paid under a different city budget. It is important that the true cost of these facilities be made known to the public.

Capital cost per ton of daily capacity ranges from \$6100 for the Norfolk, Virginia facility, which began operation in 1967, to \$41,000 for RESCO, which started up in 1975. Costs for Pinellas County and the Northeast Massachusetts facilities are estimated at \$34,000 and \$38,000 per ton of installed daily capacity.

5.1.2.3 Environmental. Stack emission tests have been performed at all the mass burning steam generation facilities. Many facilities have passed emission requirements on some occasions. However, as previously mentioned, particulate emissions remain a problem. A recent EPA-sponsored detailed evaluation of the Braintree, Massachusetts combustor examined air emissions along with liquid and solid effluents [2]. Particulates, NO_x, SO₂, CO, hydrocarbons, metals, PCBs, and polycyclic aromatic hydrocarbons were monitored.

Battelle Columbus Laboratories has also completed an EPA-sponsored study at the Harrisburg facility. The study's main emphasis was the impact of co-disposal on boiler tube corrosion, but gaseous and solid effluents were also analyzed.

Additional stack testing needs to be conducted at facilities experiencing particulate problems. A data base should be developed to compare the environmental impacts of this technology with those of other solid waste disposal alternatives.

5.1.3 Research Status

There is very little research being conducted by the public sector on mass burning steam generators. Two areas of note are boiler tube corrosion and end-use of ash residue.

Battelle Columbus Laboratories has spent about seven years evaluating the mechanism of boiler tube corrosion during refuse combustion. Most noteworthy is their explanation of the role of chloride and sulfur in the corrosion mechanism, and their evaluation of the corrosion rates of various metals [1, 3-7].

Composite boiler tubes are being tested in Europe in three plants. The tubes are constructed with an outside sheet of authentic stainless steel for corrosion resistance and an inside core of carbon steel for structural integrity. These tubes have performed very well and the general concept opens up the opportunity for high-pressure steam production.

The Federal Highway Administration has recently completed seven years of research on using combusted residue for highway construction material. The most promising use of the residue is as a substitute for aggregate in bituminous concrete pavements. Using 70 percent residue and 30 percent gravel aggregate plus asphalt cement, a four-inch base course for a highway was laid in Washington, DC in 1977[8]. A similar test was conducted in Houston, Texas in 1974. About two to three percent of hydrated lime must be added to the mixture to provide good adhesion of the cement to the residue. When using residue, an additional two percent asphalt cement must be used. This may be more expensive, but the expense can be offset by the low cost, if any, of the residue.

When asphalt is mixed with residue in a base course there is no significant leaching. For this application the residue should contain less than ten percent unburned organics and the material must be screened to less than one inch for use.

Use of unprocessed residue as a surface material was unsuccessful at a 50/50 ratio with aggregate in a road test in Harrisburg, PA. However, heat treating the residue at 2000°F produces a glass frit that can be used in combination with lime, aggregate and asphalt cement as a surface course. The economics, however, are not favorable.

The best use for residue is as a base course for roads. Unfortunately, most street work is resurfacing -- not suited for residue use.

A recent study sponsored by the Federal Highway Administration is examining the economic and environmental impacts of using residue or natural aggregate in road construction. This study should enable cities to determine end-use of residue. The Federal Highway Administration has completed its residue end-use research and now expects the states to implement their own test programs.

5.1.4 Research Needs for Mass Burning Steam Generation

Research for mass burning steam generators should be directed at reducing air emissions, improving system reliability, and increasing the marketability of the technology. Table 5.1-II lists technical research needs. A justification and explanation of each need follows.

- Evaluate performance of a bag house for particulate emission control at a fully operational plant. This research need is considered to be of major importance toward accelerating commercialization of this technology. Many facilities are exceeding particulate emission standards despite the use of electrostatic precipitators (ESPs). Use of a bag house in place of an ESP may be an effective solution to the problem. Bag houses have been tested at the Prudhoe Bay, Alaska and Nashville, Tennessee (mobile bag house study) facilities. Wheelabrator-Frye, Inc. and Carter-Day, Inc., a subsidiary of Combustion Equipment Associates, have been testing small bag houses for use on mass burning steam generators.

Data from Prudhoe Bay and Nashville should first be evaluated and a bag house test should then be conducted at a fully operational facility, preferably treating the total flue gas stream. Alternatively, the test could be conducted on a gas slip stream.

Evaluation of wet scrubbers or other pollution control devices for particulate removal do not warrant further evaluation at this time. Likewise, in terms of plant waste emissions, liquid effluents do not need further examination.

- Conduct a detailed performance test at a fully operational plant. This information will provide fundamental understanding for improving boiler design and operation in order to maximize energy recovery. There is little detailed data available on the effect of refuse feed rate and composition, and furnace operating parameters on boiler efficiency and air emissions.

Table 5.1-II

Technical Research Needs for Mass Burning Steam Generation

- Evaluate performance of a bag house for particulate emission control at a fully operational plant.
- Conduct a detailed performance test at a fully operational plant.
- Evaluate the effect of boiler operating characteristics on air emissions (particulate, HCl, HC, NO_x, metals).
- Develop end-use for combusted residue through further initiation of road paving demonstration projects.
- Improve boiler design and tube metallurgy to increase upper limit in operating temperature and pressure.
- Conduct a demonstration of European crane technology at a fully operational plant.

A detailed incinerator efficiency test, e.g., ASME Power Test Code 33, should be conducted at a fully operational plant. This test would develop basic information on furnace performance on a day to day basis. All input and output streams would be analyzed to develop detailed heat and material balances. Furnace parameters such as percent of excess air, over- and under-fire air rate, flue gas oxygen content, and steam rate and conditions would be monitored. Empirical correlations would be developed between furnace parameters and energy recovery efficiency.

- Evaluate the effects of furnace operating characteristics on air emissions (particulate, HCl, HC, NO_x, metals). To date, control of air emissions from mass burning steam generators has been achieved by installing a gas cleaning device in the flue gas stream after the gas exits the boiler. However, alterations in furnace operating conditions may also have a significant effect on air emissions. There is little understanding between these relationships, and empirical correlations need to be developed between previously mentioned furnace parameters and air emissions. These tests should be conducted at a fully operational facility.

- Develop end-use for combusted residue through further initiation of road paving demonstration projects. Combusted residue from mass burning steam generators is equal to about 20 to 25 percent by weight of the input refuse. Disposal cost of this residue is typically \$1 to \$3 per ton of input refuse. An end-use of this material that will result in a revenue or no expense will reduce operating cost and eliminate a solid waste disposal problem.

The Federal Highway Administration has completed research on use of residue as a paving material, and it has initiated a number of test road projects around the country. Wheelabrator-Frye, Inc. is trying to develop a test road project with the State of Massachusetts, using residue from their RESCO facility in Saugus, Massachusetts.

While facility operators usually have been willing to enter test road projects, state and local agencies have been relatively slow in cooperating.

The knowledge of using residue in road paving is developed and does not now need further investigation. However, what is needed is encouragement from the Federal level to the state and local agencies which are responsible for such programs. This may or may not require use of Federal funds.

- Improve boiler design and tube metallurgy to increase upper limit in operating temperature and pressure. Co-generation or electric power generation are promising approaches for using steam. For this approach to be more reliable and cost effective, steam of a higher pressure and temperature needs to be produced to improve system efficiency.

Superheater tube durability is one of the main concerns of this research need. Corrosion will be enhanced with higher steam temperatures. Composite boiler tubes for greater corrosion resistance at higher temperatures should be examined.

While this research need is considered to have importance, most systems are proprietary and operators such as Wheelabrator-Frye, Inc. are conducting their own in-house research to address this subject. Therefore, Federal funding in this area does not appear to be appropriate or needed.

- Conduct a demonstration of European crane technology at a fully operational facility. Crane motor overloads, cable wear, and pit fires are all causes of downtime at most facilities. Improved equipment and operation and maintenance procedures need to be utilized. European crane technology has developed to an excellent level. Transfer of this information into U. S. plants should be encouraged. A demonstration of European technology in a U. S. plant should also be pursued; however, this research need is not considered to be of critical importance to the development of this technology.

• Other. One research area that has been explored in past years is boiler tube corrosion. Based on a consensus of system suppliers, further research on reducing tube corrosion at existing operating pressures and temperatures is not needed. All system operators expect and plan for tube wastage. Proper maintenance is scheduled and costs associated with tube replacement are a normal part of the plant operating budget.

5.1.5 Mass Burning Steam Generation Research Programs

5.1.5.1 Summary. While considerable research monies have been directed toward refuse derived fuel technologies, little money has gone toward improvement of mass burning steam generation technology. Although this technology for the most part has become proprietary, most operational plants are still experiencing problems. The environmental and technical reliability of these systems must improve if this technology is to realize wide-scale commercialization. To achieve this end, Federal support is warranted.

In summary, two basic research projects are recommended. These are the bag house study and the detailed performance test, both of which should be conducted at fully operational facilities. By expanding the scope of each study, the research for establishing relationships between furnace operating conditions and air emissions can be addressed. These studies can be initiated immediately; however, due to design and installation of the bag house, the performance test study would be the first to collect real data.

In addition to the above programs, DOE should encourage state and local agencies to initiate test road programs using combusted residue. Massachusetts would be one likely candidate to begin discussions with.

European crane technology should be considered for use in the U. S., and a demonstration of this technology in a U. S. facility should be explored by DOE. However, this research need is not considered to be of critical importance to the development of the technology.

5.1.5.2 Detailed Research Programs. The following is a discussion of recommended research programs for the bag house evaluation study and the detailed performance test at a fully operational facility.

For the bag house study, prior data taken at the Prudhoe Bay and Nashville facilities should first be examined and conclusions drawn. Then a bag house test at a fully operational facility should be conducted. Ideally, the test should be conducted on the entire gas stream, using a full-scale bag house.

For a 1000 to 1500 tpd facility, the installed cost of such a bag house would be in the \$1.5 to \$2 million range. It should be expected that the capital cost of this unit would be shared in some proportion between DOE and the facility operator. It could be negotiated that if the testing proved successful, the operator could buy back the DOE investment in the bag house. If a full-scale bag house test cannot be conducted, then a smaller bag house should be evaluated on a gas slip stream.

The bag house test should examine different filter fabrics for mass collection efficiency in the range of normally varying flue gas temperatures. Stack testing on particulates would be conducted.

Ideally, this testing program would also address the research need of examining the effect of furnace operating characteristics on air emissions. Therefore, in addition to stack testing for particulates, stack analyses would also be conducted for hydrocarbons, NO_x , HCl, and heavy metals. Boiler parameters such as excess air, boiler temperature, flue gas oxygen content, and steam rate and conditions would also be monitored. Correlations between boiler parameters and air emissions could then be developed. An understanding of these fundamental relationships would then enable a plant operator to control or correct air emissions to some degree, by regulating boiler operations.

For the bag house test, six months will be required for development of the experimental program and data analysis; two to three months will be needed for data collection. About 18 months will be

necessary to complete the entire program. This will include the evaluation of data from Prudhoe Bay and Nashville, installation and testing of the bag house, and preparation of a final report. Cost for existing data evaluation and bag house testing and analysis, excluding any capital cost for the bag house, would be approximately \$200,000.

As discussed in the previous research needs section, a detailed performance test should also be conducted at a fully operational facility. The result of this test program would be the development of empirical correlations between boiler operating parameters and energy recovery efficiency. Detailed heat and material balances would be conducted on a daily basis.

A complete analysis of air emissions should also be conducted during this testing. This information, in combination with data on boiler parameters, would be used to address the research need of the effect of boiler operating conditions on air emissions. The flue gas should be analyzed for particulates, HCl, HC, NO_x, and heavy metals.

Eight to twelve months would be required to complete the performance evaluation. This would include one month of actual testing at a fully operational plant. Cost for the study will be about \$250,000.

The research for establishing relationships between boiler operating conditions and air emissions is included in the research programs for the bag house evaluation and the detailed steam generator performance test. With sampling equipment and personnel in place during the above two research programs, it is cost effective to slightly expand the testing program to allow for comparison of air emissions with boiler operating conditions.

It would be most logical to conduct the steam generator performance evaluation first. In this manner, basic relationships between boiler operating conditions and energy recovery and air emissions could be developed. The subsequent bag filter test program would use this initial data to develop an experimental program that would refine initial relationships.

5.2 Mass Burning, Controlled Air, Modular Combustor with Heat Recovery

5.2.1 Technology Description

Controlled air, modular combustors are characteristically prefabricated package units, operated at substoichiometric oxygen requirements. It is claimed that they can meet Federal air pollution regulations without pollution control devices. The largest single module in operation processes up to 50 tpd of solid waste; however, several vendors are now claiming single module capacities of up to 250 tpd. By operating several of these units in parallel, processing capacities of several hundred tons per day can be achieved. Multiple-unit installations provide system redundancy and backup capability if one of the units is down for repair. These larger units would be equipped with ash removal equipment for continuous operation. Modular units are also sized to handle as little as 5 tpd. However, for modules of less than 20 tpd capacity, waste is typically processed on a batch rather than continuous basis.

Typical modular combustors (Figure 5.2-1) employ a two-chamber design. For most systems, as solid waste is received, it is charged into a primary refractory-lined combustion chamber, using a ram or auger-type feeder. Under-fire and in some cases over-fire air is blown into the primary chamber at sub stoichiometric oxygen requirements. The heat released from partial combustion of the organics is used for the endothermic volatilization of the remaining organic compounds. Temperature in the primary chamber is maintained at 1500°F to 1800°F by controlling refuse feed rate and combustion air flow.

Because of the relatively low air-flow rate as compared with conventional incinerators, gas velocity in the primary chamber is kept low to reduce fly ash entrainment. Hot gases from the primary chamber contain organic vapors and some fly ash (both carbonaceous and inert). The gas has a heat value of approximately 100 to 500 Btu/dscf. These gases flow into a secondary combustion chamber where they are mixed with air and fossil fuel (natural gas or oil).

Figure 5.2-1. Typical Controlled Air, Modular Combustor

A dump or exhaust stack is provided on the secondary chamber. If there is no immediate steam demand, hot gases exiting from the secondary chamber can be exhausted to the atmosphere rather than being passed through the boiler. When demand for steam is low, gas flow can be split between the boiler and the exhaust stack.

An important cost-saving advantage of the controlled air combustor is that air pollution control equipment has not been incorporated into these units because uncontrolled particulate emissions are claimed to be 0.08 gr/dscf or less which meets the Federal standard. The low combustion air requirement and, hence, air velocity in the primary chamber reduces entrainment of fly ash and mitigates the need for costly pollution control equipment.

Oil- or gas-fired burners are provided in both combustion chambers. The primary chamber burner is typically used only at system startup to help bring the contents of the chamber up to operating temperature. The secondary burner is used to maintain proper temperature to ensure near complete combustion of the off-gases from the primary chamber. Auxiliary fuel requirements in the secondary chamber range from 0.3 to 1.0×10^6 Btu/ton. Total system excess air is from 100 to 200 percent.

5.2.2 Technology Status

5.2.2.1 Technical. Modular combustors are beginning to enter the second generation of technology development. Many new systems are being privately developed to resolve recurring problems now experienced in most operating systems. Table 5.2-I shows the status of modular combustor installations with heat recovery that are either in operation, under construction, or in final planning and design. Systems currently operating are of the two-chamber refractory wall design, with a waste heat boiler for energy recovery in the form of low pressure (less than 275 psig) saturated steam. Continuous ash removal systems are now common to most installations. A ram-type feeder has been used to move the refuse and ash through the primary chamber.

Table 5.2-I

Status of Controlled Air, Modular Combustors with Heat Recovery

Location	Participants	Status	Capacity (tpd)	Capital Cost (\$million)	Net Tipping Fee (\$/ton)	Energy Products	Problems
Blytheville, Ark.	City of Blytheville: Owner/Operator	Operational since mid-1975. Batch incinerators operate 5 days/week, 17 hr/day. Recently destroyed by fire, replacement under construction.	50	0.60 (1975)	10	10,000 lb/hr of steam (40 psig, sat.) actual potential production with a large fraction being sold to Randall Co.	<ul style="list-style-type: none"> • Glass handling. • Refractory breakup due to ash cleanout
Groveton, N.H.	Groveton Paper Co.: Owner/Operator	Operational since 1975. Burns industrial and commercial waste (6 tpd) 3 days/week and residential waste (8 tpd) 2 days/week.	25	0.75 ^a (1975)	50 ^b	3,000 lb/hr of steam (125 psig, sat.) used in plant for heat and process	<ul style="list-style-type: none"> • Glass had been a serious problem, but recycling program solved the problem • Burnout was poor until an ash ram was installed. • High unit disposal cost.
N. Little Rock, Ark.	City of N. Little Rock: Owner/Operator	Operational since 9/77; however 5 major modifications were made in the first several months. Plant now operating well on 99% residential solid waste 5 days/week (70 tpd)	100	1.5 (1977)	10 ^c	Maximum 20,000 lb/hr of steam (120-140 psig, sat.). Typical daily range: 2,000-15,000 lb/hr. Koppers Corp is steam customer.	<ul style="list-style-type: none"> • Glass handling problem now corrected • High particulate emissions
Salem, Va.	City of Salem: Owner/Operator	Operations began in 10/78 Operating 5 days/week	70	1.9 (1978)	—	15,000 lb/hr. of steam (250 psig, sat.) sold to Mohawk Rubber Co.	—
Siloam Springs, Ark.	City of Siloam Springs: Owner/Operator	Operational since 1974: Batch incineration 12 hr/day, 5 days/week.	20	0.25 (1974)	10	4,700 lb/hr of steam (100 psig, sat.) sold to Allen Canning Co. for 10-12 hr/day	—

^aDoes not include cost of building where incinerator was installed.

^bBased on annual operating cost of \$100,000 and steam credit of \$3/1,000 lbs.

^cBased on analysis of annual solid waste budget for the city; includes steam revenues.

Table 5.2-I (Continued)

Location	Participants	Status	Capacity (tpd)	Capital Cost (\$million)	Net Tipping Fee (\$/ton)	Energy Products	Problems
Auburn, Maine	City of Auburn: Owner Consumat Corp.: Operator	Consumat Systems Inc. selected for 3-year full-service contract. Facility to be financed by G.O. bonds. Now in final stages of contract negotiations.	150	3.5 (1979)	--	Steam sold to Pioneer Plastics Corp.	--
Chicago, Ill.	National Energy Corp.: Owner/Operator Ragnar Benson: Designer	Facility to handle private-hauler waste under contract. Design completed. Now in process of obtaining zoning permit.	500	15.0 (1979)	--	125,000 lb/hr of steam (200 psig, sat.) to be sold to Darling Inc. under 20-year contract which has been signed. Initial steam price is \$3.45/1,000 lbs.	--
Crossville, Tenn.	Nelson-Walker Assoc.: Owner, Operator, Designer City of Crossville, Cumberland County	Startup planned for March 1979. 60-70 tpd MSW and 30 tpd rubber.	100	0.8 ^d (1979)	--	15,000 lb/hr steam (135 psig) to be sold to Crossville Rubber Products	--
Gallatin, Tenn.	City of Gallatin, Tennessee Valley Authority, Sanders & Thomas, Inc.: Designer	In final design stage	150	9.1 (1979)	--	36,000 lb/hr (250 psig) steam and possibly electric power. Local steam customers have been identified.	--
Jacksonville, Fla.	Mayport Naval Base: Owner/Operator	Facility under construction	48	--	--	Steam for use on Base	--

^dEstimate from Nelson-Walker Assoc.

Table 5.2-I (Concluded)

Location	Participants	Status	Capacity (tpd)	Capital Cost (\$million)	Net Tipping Fee (\$/ton)	Energy Products	Problems
Jacksonville, Fla.	U.S. Navy: Owner/Operator Reynolds, Smith and Hills: Designer	Start-up imminent. Process involves RDF production followed by firing into a starved air incinerator. Startup scheduled for early 1979.	40	2.0 (1979)	—	Steam for use on Base. Ferrous metals recovery.	—
Lewisburg, Tenn.	City of Lewisburg: Owner/Operator CICO Resource Recovery Systems: Designer	Facility is 70% completed. Startup planned for June 1979.	60	1.75 (1979)	—	Steam (125 psig) sold to Heil-Quaker Corp.	—
Pittsfield, Mass.	City of Pittsfield, VICON Recovery Assoc.: Operator	Vicon, Inc., selected for 15-year full-service contract. Facility to be financed by Industrial Revenue Bonds. Construction and operating agreement signed. Bonds expected to be issued in April 1979.	240	6.2 (1979)	11.59 ^e	Steam sold to Crane Paper Co.	—

^eFixed-price tipping fee guaranteed for 15 years.

The North Little Rock modular combustor facility is the only plant with heat recovery that has processed MSW with continuous feed and ash removal that has been technically evaluated. Three, one-week tests were performed under EPA sponsorship to determine heat and material balances and stack emissions. More technical information must be obtained on these systems before municipal officials can be expected to choose this type of waste disposal.

Many operating facilities experience the same problems. Present system design produces a low-pressure steam (275 psig or less) that limits its marketability. It has been used only by industry for heat and process. Large industries or some utilities could use high pressure steam more readily for either co-generation or electric power production.

Another problem is that potential steam supply often exceeds demand because of fluctuating customer requirements. In these situations, energy must be dumped to the atmosphere rather than be used to produce steam, and significant energy revenues are lost. Such is the case at North Little Rock. Steam demand of Koppers Corporation, the steam customer, varies from 2,000 to 15,000 lb/hr within a 5-minute period. Refuse feed rates cannot be adjusted to this severe fluctuation, and useful energy is lost during low demand periods. In general, present systems have poor load-following capability with slow steam response.

The classic refuse supply/steam demand problem is higher steam demand in the winter months when less refuse is generated, and lower steam demand in the summer months when refuse generation peaks. Unless the steam or hot water output from the incinerator is providing a year-round base load, considerable energy revenues can be lost during summer months.

Boiler tube fouling due to fly ash carryover from the secondary combustion chamber is a problem at all facilities. In addition to use of soot blowers, boiler tubes must be cleaned at least every two

weeks to prevent excessive fly ash fouling. However, for plants operating on a five-day week, this does not present a problem because the tubes can be manually cleaned during normal shutdown.

To date, all modular combustor facilities processing MSW have been owned and operated by municipalities. In many cases, city-employed plant operators have not been able to operate the plant correctly to provide for maximum burnout and steam production with minimum use of auxiliary fuel. There is a need to reduce operator judgment requirements at these facilities. A new visual display system was recently installed at the North Little Rock facility which shows the operator when and how much refuse to feed the system. Such systems are needed if municipal employees are to operate such facilities at acceptable operating and maintenance costs.

One of the most common problems that modular combustor facilities have experienced is glass-handling. Glass in the primary chamber slags if the operating temperature is too high. This molten glass then plugs underfire air ports and adheres to refractory walls. Glass slagging at the North Little Rock facility resulted in frequent plugging of the air plenum tubes in the primary chamber. These tubes could not be rodded-out and had to be replaced every week. Slagged glass has also caused severe bridging problems over ash removal doors. In many facilities that employ a ram-type feed system, considerable amounts of refractory have been ripped off the chamber walls by the ram -- slagged glass solidifies and adheres to the refractory walls, and, when the ram comes by and removes the glass, the refractory is also torn off the wall. In nearly all installations, the refractory has been replaced at least once for this reason. North Little Rock has reduced the glass handling problem by water-jacketing the air plenum tubes, ram face, and ash discharge port. Tube plugging and refractory removal have been reduced. However, glass still remains a problem in the ram-type feed system, causing the ram to bind as it moves through the primary chamber.

Modular combustors are typically prefabricated and shipped to site. Because of transportation weight limits, refractory thickness on large modules (+50 tpd) is less than optimum. The result is higher radiational heat loss and very high skin temperature, which present a personnel safety hazard. Energy recovery efficiencies are only 50 to 60 percent.

If modular combustors are operated under substoichiometric oxygen conditions, a significant amount of unburned fixed carbon remains in the ash. A recent EPA-sponsored evaluation of the North Little Rock facility showed 10 to 15 percent by weight of unburned carbon and volatiles in the ash. Systems that use a ram for feeding and transporting waste through the primary chamber have less than optimum burnout. Ash from presently operating facilities is now landfilled with no cost reducing or revenue producing end-use.

Auxiliary fuel requirements vary from system to system, from 0.3 to 1.0×10^6 Btu/ton under steady-state operation. This equates to a fuel operating cost of about \$1 to \$4/ton, which is significant. The lowest guaranteed fuel requirement has been 0.5×10^6 Btu/ton in a recent proposal submitted to the City of Auburn, Maine.

The Jacksonville Naval Base will be the first modular combustor facility to preprocess the waste prior to firing in the primary chamber. The system will produce RDF by shredding and air-classifying. The RDF will then be fired into the modular combustor. The intent is to produce a more homogeneous refuse so the facility can be highly automated to reduce labor requirements. However, capital cost per ton of installed capacity is about a factor or two higher than systems without front-end processing.

Co-disposal of MSW and sewage sludge with heat recovery has not been demonstrated in modular combustors. Questions raised are: the effects of co-firing sludge on auxiliary fuel requirement, particulate and heavy metal emissions, and the most effective methods of pre-drying the sludge prior to co-firing.

Modular combustors with heat recovery have a short operating history. Long-term system performance, i.e., 15 to 20 years, is unknown. Most systems do not appear to be designed to last 20 years. Investment banking firms such as Paine Webber, Jackson and Curtis recommend that these facilities be financed for 10 years or 15 years at most.

5.2.2.2 Economic. Operating cost data on most facilities are incomplete. Municipal accounting procedures often do not separate the costs of solid waste collection and disposal. Cost items such as administrative salaries are often not charged to the solid waste budget. A data base on facility costs needs to be developed.

Table 5.2-II shows cost estimates from the original proposals received in Auburn, Maine, and Pittsfield, Massachusetts for full-service operation of a modular combustor facility with heat recovery. These costs do not include steam revenues, which are projected at about \$18 to \$25/ton based on a #6 fuel oil displacement pricing formula at about \$20 to \$25/barrel.

5.2.2.3 Environmental. The only environmental data on modular combustors regularly processing MSW are from the North Little Rock facility. Recently, a test and evaluation program was completed at the facility. Particulate emissions averaged 0.15 gr/dscf. Few, if any, data have been obtained on hydrocarbon and heavy metal emissions during normal and upset conditions. Because the combustors have a charging rate of less than 50 tpd of MSW, Federal air emission regulations do not apply; however, state standards do apply. In Arkansas, the standard for particulate is 0.4 gr/dscf. Therefore, the particulate emissions for this facility during the testing period were within the applicable standard.

5.2.3 Research Status

Modular combustor technology is now in the second generation of development. Many of the problems experienced by operating systems have been addressed by new system developers.

Table 5.2-II
Comparison of Modular Incinerator Costs

Item	<u>Pittsfield, MA</u>		<u>Auburn, ME</u>	
	Consumat Systems, Inc.	Vicon Recovery Assoc.	Consumat Systems, Inc.	Waste Management, Inc.
Annual Tonnage (tpy)	44,000	44,000	30,200	30,200
Daily Capacity (tpy)	200	200	150	150
Total Capital Cost ^a (\$ million)	5.55	4.35	3.50	3.55
Annual Capital Cost ^b (\$/year)	648,000	508,200	408,900	415,000
Annual Operating Cost (\$/year)	654,000	544,000	425,000	462,000
Annual Cost per Ton ^c (\$/ton)	29.60	23.90	27.60	29.00
Capital Cost per Ton of Installed Daily Capacity (\$/ton)	27,750	21,750	23,350	23,650

a. All costs in 1978 dollars.

b. Assumes that capital cost amortized for 15 years at 8 percent interest.

c. Does not include energy revenues.

A controlled air, modular combustor labeled the Auger Combustor has been operated by Scientific Energy Engineering, Inc. on a demonstration scale in Jacksonville, Florida, for the past 1-1/2 years. The system employs a typical two-chamber design, but uses a large, open flight auger instead of a ram to convey refuse and ash through the primary chamber. The developer claims throughput is much higher per unit volume of reactor than in the conventional systems. Ash burnout appears to be superior. Optimum capacity of a single module is 250 tpd. Another important feature of the system is that the primary chamber refractory walls are air-cooled to only 400°F; at this temperature, slagging problems on the refractory will not occur. Combustion air tubes jacket the refractory wall. In this manner, all combustion air is preheated to about 350°F, and the refractory is cooled to 400°F. Additional advantages of this design are low radiational heat losses, low skin temperature, and short cooldown time. Also, the auger is the only moving part in the system; it is accessible and can be easily removed. However, the system does require preprocessing of the waste, (i.e., shredding and air classifying) and pollution control equipment. Only short-term operating experience has been obtained on the system; however, the Department of Energy is presently conducting an evaluation of the system.

Basic Environmental Engineering, Inc. has developed a controlled, waterwall combustor with a single module capacity of 125 tpd. Four of these units will probably be installed in Chicago within the year. The waterwall membrane is refractory-coated and heat recovery efficiencies are guaranteed at 70 percent, compared with 50 to 60 percent for a typical refractory wall unit. Glass slagging problems should also be reduced because of the lower temperature furnace walls.

The refuse and ashes will be transported through the primary chamber by a vibrating refractory floor (similar in concept to a vibrating conveyor). A five- to six-hour residence time is provided

and a four-foot deep bed of ashes is kept in the primary chamber. The deep bed acts as an insulator to reduce slagging on the chamber floor. The deep bed also condenses certain volatile organic compounds; which is claimed to reduce boiler tube fouling.

Two afterburner chambers are provided with auxiliary fuel and air supplied to the secondary chamber, and air alone supplied to the tertiary chamber. The third chamber combusts any unburned carbonaceous particulate material escaping the secondary chamber. The primary chamber is operated at stoichiometric air requirements, rather than sub stoichiometric. This is supposed to allow more complete combustion of the fixed carbon in the residue.

Other systems being developed address waste-handling problems and increased energy recovery. One new system uses a drag chain in the primary chamber for removal of ashes. In addition, a rotary waterwall combustor has been developed. The unit is basically a rotary kiln with a water tube wall instead of a refractory wall. Energy recovery efficiencies for the system, using the rotary tubes as a boiler-water preheat, are claimed to be 75 percent. The City of Gallatin, Tennessee plans to construct a resource recovery facility using this technology.

5.2.4 Research Needs for Controlled Air, Modular Combustors

Research on controlled air combustors must be directed to improving system reliability and economics. In most applications this system is competing with low-cost landfill disposal. The ingredient necessary to implement these systems on a large scale is municipal confidence -- that the system will work with MSW, and that the cost of the system will be competitive with a landfill solution.

Table 5.2-III lists modular combustor research needs. The following discussion justifies each need.

- Evaluate the cost/benefit of a coarse RDF feedstock. Many municipal officials have serious reservations concerning the performance of modular combustors burning MSW. Major problems with glass handling in over 20 controlled air combustors without heat recovery

Table 5.2-III

Research Needs for Controlled Air, Modular Combustion

- Evaluate the cost/benefit of a coarse RDF feedstock.
- Evaluate performance of a bag house for particulate emission control at a fully operational facility.
- Develop a new control system to reduce auxiliary fuel consumption.
- Develop a seminar program for municipal officials on management of controlled air, modular combustion facilities.

in New England, and the initial glass handling problems at the North Little Rock facility, have resulted in skeptical attitudes by many municipal officials. The question also remains as to whether these combustors can meet Federal requirements for particulate emissions without pollution control equipment. Using coarse RDF feedstock could reduce glass handling problems and maintenance. A more homogenous fuel could provide better load-following capability, reduce particulate emissions and extend system life.

The technical and economic benefits of using a coarse RDF feedstock need to be evaluated. Pre-trommelling to remove glass and other non-combustibles should be evaluated. The Jacksonville Naval Air Station controlled air combustor facility should also be evaluated because it uses a coarse RDF feedstock.

- Evaluate performance of a bag house for particulate emission control at a fully operational facility. The ability of modular combustors to comply with Federal and state air emission regulations is of major concern to elected officials. Use of a bag house for particulate control should be evaluated. This evaluation would use an "off the shelf" bag house which would be installed for testing at a fully operational facility. Gas samples taken before and after the bag house would be analyzed for particulate, HCl, HC, and heavy metals.

- Develop a new control system to reduce auxiliary fuel consumption. Auxiliary fuel use accounts for \$0.75 to \$2.50/ton of operating cost. Design of a generic control system which could be used by all equipment vendors could result in a significant cost and energy savings. The control system would reduce auxiliary fuel requirement by regulating refuse feed rate, combustion air and auxiliary fuel rate. Control system logic would first be developed. Appropriate instrumentation and hardware would be selected, and the control system would be tested at a fully operational facility.

- Develop a seminar program for municipal officials on management of controlled air modular combustor facilities. While the cities of Auburn, Maine and Pittsfield, Massachusetts have recently opted for private sector ownership and operation of their modular combustor facilities, many cities will opt for public ownership and operation of these facilities because of their relatively low capital cost. However, many elected officials and DPW heads that will be involved with implementation and operation of these facilities have little knowledge of the requirements to put such a facility into operation.

A seminar program is therefore needed to inform elected officials and future facility managers on available systems, operating procedures, manpower skill requirements, and costs. Regional seminars on modular combustors or expansion of the present EPA regional seminars would be effective approaches. Alternatively, Hofstra University now offers an annual short course for incinerator operators. This program could be expanded to offer a course on modular combustors, addressing both technical and managerial issues. This same concept could also be expanded to other similar short courses.

5.2.5 Research Program for Controlled Air, Modular Combustors

The necessary research program for controlled air combustors requires little DOE funding to complete, because a major portion of the work could be carried out by other agencies.

The cost/benefit of a coarse RDF feedstock can be determined by two facility evaluation programs. One program would be to evaluate the effects of pre-trommelling MSW prior to firing, the other program would be an evaluation of a fully operational facility using coarse RDF as a feedstock. One such facility will be at the Jacksonville Naval Air Station.

EPA plans to evaluate pre-trommelling at the North Little Rock facility in late 1979. A logical program would be for EPA to extend their work to an evaluation of the Jacksonville facility. This

approach would not require DOE funding. For the above evaluations, heat and material balances, detailed energy recovery efficiency tests, and stack testing should be conducted. The efficiency test should be similar to the ASME Power Test Code 33. Stack testing should be comprehensive, with emphasis on heavy metal emissions. The gas stream should be analyzed after the primary and secondary chambers. The trade-off between degree of ash burnout and energy recovery efficiency should also be examined. Each facility evaluation would be about a 12 month duration, including program development, testing, and data analysis. Cost for each study would be approximately \$200,000.

Evaluating the performance of a bag house for particulate emission control at a fully operational facility is an appropriate program for DOE to fund. Paying for the cost of the bag house would be negotiated between DOE and a system vendor or municipality. The test program would evaluate the performance of an "off the shelf" bag house. Gas samples taken before and after the bag house would be analyzed for particulate, HCl, HC, and heavy metals. Mass collection efficiency and particle-size distribution of the filter catch and gas streams would be determined. The effect of reducing auxiliary fuel requirements on bag house performance would also be examined. Of principle concern would be the physical integrity of the filter cloth at normal flue gas temperatures, including excursions. This program would cost about \$75,000, excluding the bag house, and would require about 12 months to complete, including delivery of the bag house. The program can be initiated immediately.

Design of a new control system to reduce auxiliary fuel consumption is not an acute research need and would be more appropriately addressed in the second or third year of funding (FY 1981 or FY 1982). Cost of auxiliary fuel is not inhibiting commercialization of this technology, but as fossil fuel costs continue to rise this operating cost will become very significant. The design approach would be to first develop control system logic. Appropriate

instrumentation and hardware would then be selected. The control system would then be installed and tested at a fully operational facility. The program would require a 12 month duration at a cost of about \$200,000.

The seminar program for management of controlled air modular combustor facilities would be best conducted by expansion of EPA's regional seminar program to include this topic. This approach would require initiating discussions with EPA, but would require little funding, if any. EPA's Peer Matching and Technical Assistance programs also provide the opportunity for municipal officials to become familiar with controlled air combustion.

5.3 Prepared Fuel Combustion Systems

5.3.1 Co-Fired Boilers

Co-combustion of RDF in existing coal-, oil-, or wood-fired boilers can reduce community disposal costs by eliminating the need to construct and operate dedicated boilers. Other benefits include the ability to participate in economies-of-scale of utility boilers and the relief of certain siting constraints for solid waste facilities.

The problems involved with co-combustion center on the specifications for the fuel products. The quantity of inert materials should be as low as possible to prevent conveying-device erosion, boiler-tube slagging, and increased air emissions. The form of the fuel should be compatible with existing conveying, storage, and injection devices to avoid expensive modification ("retrofitting"). Finally, the price of the RDF must be competitive with the fuel being replaced.

5.3.1.1 Technology Description. Co-combustion may take place in any of the following boiler configurations:

1. Suspension firing. Burning occurs while the fuel falls through the boiler. The fuel particles should be as small as possible to achieve complete combustion before the furnace base is reached. Pulverized coal requires a drop of about 25 ft for complete combustion. The suspension mode ensures good air/fuel mixing, but is also a cause of particle entrainment in the flue-gas. Ash and unburned fuel fall directly into a water-filled ash hopper at the base of the boiler, where they are quenched, accumulated, and periodically sluiced. The sluiced ash passes to a clinker grinder and is then conveyed into ash-settling lagoons or basins.

2. Semisuspension (spreader-stoker) firing. Fuel is injected pneumatically or mechanically onto a traveling grate. Partial combustion occurs during the trajectory of flight and is completed on the grate surface. Ash removal is accomplished by spill-over from the grate into a wet or dry receiving hopper. The injection process achieves balanced distribution of the fuel and limited air contact. Underfire air through the grates and overfire air above the ash bed complete the oxidation. This process lessens particle entrainment and accommodates larger fuel, but its greater excess air requirement lessens boiler efficiency.

3. Grate (stoker) firing. Fuel is allowed to form a conical pile on stationary grates; combustion occurs by under- and overfire air, either of which may be natural draft. The ash is removed manually when required. This is the least efficient of the systems, but it is commonly used to burn wood wastes. Operator control and maintenance requirements are minimal, the oven walls are refractory-lined, and steam is produced by flue-gas heat exchange. Product steam is used for noncritical applications such as source heat for wood kilns.

4. Fluid-bed combustion. Small-particle fuel is injected into a heated sand bed fluidized by the air stream. Heat from the sand is transferred instantaneously to the fuel and intimate oxygen contact occurs in the gas stream. Ash removal is accomplished by flue-gas scrubbing or sand bleeding with external separation. Process advantages include steady heat release, low combustion temperatures which reduce slagging, high heat transfer from sand to boiler tube surfaces, and sulfur removal by dry chemical addition. Disadvantages arise from the relatively new application of the technology and the greater opportunities for particle entrainment.

5.3.1.2 Technology Status.

Technical

Table 5.3-I presents locations where RDF has been co-fired with fossil fuels on either a trial or a regular basis. The present commercial use of RDF occurs in suspension boilers with either coal or oil. Both fine and powdered RDF are being used.

Suspension firing. Fluff RDF is the form most often used in suspension-fired boilers, co-combusted with pulverized coal. The significant operating experiences have been at Wisconsin Electric Co., Milwaukee, Wisconsin (70,000 tons of RDF), Ames Municipal Electric System, Ames, Iowa (40,000 tons of RDF), Union Electric Co., St. Louis, Missouri (40,000 tons of RDF), and Commonwealth Edison, Chicago, Illinois (15,000 tons of RDF).

The ash-handling problem at Ames seems to have been the most severe of all the sites. The burnout in suspension was only 65 percent, causing build-up of soggy, compacted material in the ash hopper. Nearly continuous sluicing had to be maintained to prevent the substance from matting and becoming immovable. Sluicing of the ash pit is an expensive procedure if done too frequently because of an eductor flow requirement of 1000 gal/min. The burnout problem was rectified by installing dump grates during the summer of 1978 and now combustion is essentially complete. Similar problems have not been encountered in the other facilities due to their larger size, which allows longer retention time of the RDF in the fireball.

Table 5.3-I
RDF Co-Combustion Experiences

Location	Participants	Status	RDF	Principal Fuel	Boiler	Comments
Ames, Iowa	City of Ames	Active	Fine	Pulverized coal	Suspension	<ul style="list-style-type: none"> • 136 tpd-RDF • 30 MW boiler • 0-50% RDF firing during 50-100% loading • 65% burnout in suspension, rest on dump grates • No corrosion experienced • Problems: <ul style="list-style-type: none"> – excessive particulate emissions with RDF ports above coal lines – increased sidewall slagging prior to disc screens – airlock jams, pneumatic line erosion and pluggage – ash pit pluggage prior to dump grates – clinker grinder jamming caused by wire
Ames, Iowa	City of Ames	Discontinued	Fine	Stoker coal	Spreader-stoker	<ul style="list-style-type: none"> • 136 tpd, 80,000 tons total RDF • 0-50% RDF firing during 50-100% loading • No corrosion experienced • Problems: <ul style="list-style-type: none"> – sidewall slagging (prior to disc screens) – increased excess air requirements – decreased boiler efficiency
St. Louis, Mo.	City of St. Louis, Union Electric Co.	Discontinued demonstration	Fine	Pulverized coal	Suspension	<ul style="list-style-type: none"> • 124 tpd, 21,000 tons total RDF • 125 MW boiler • 10% RDF firing • 87% burnout in suspension • No corrosion experienced • No reported ash handling problems; sevenfold increase in bottom ash • Effect on boiler efficiency not investigated • Problems: <ul style="list-style-type: none"> – erosion of elbows on pneumatic lines – bleed of air through leaks in pneumatic lines

Table 5.3-I (continued)

Location	Participant	Status	RDF	Principal Fuel	Boiler	Comments
Milwaukee, Wis.	Americology, Inc. Wisconsin Electric	Shakedown	Fine	Pulverized coal	Suspension	<ul style="list-style-type: none"> • 400 tpd, 70,000 tons to date RDF • 300 MW boiler • 12% RDF firing down to 50% load; no RDF below 50% • Burnout not measured • No critical ash handling problems; fourfold increase in ash • Problems: <ul style="list-style-type: none"> – loss of boiler and ESP efficiency due to increased excess air and I.D. fan limitations – removal of floatables in ash lagoon – aggravated slagging
Chicago, Ill.	City of Chicago, Commonwealth Edison	Shakedown	Fine	Pulverized coal	Suspension	<ul style="list-style-type: none"> • 0 to 10% RDF firing during 50-100% loading • Burnout not calculated • 15,000 tons to date RDF • Problems: <ul style="list-style-type: none"> – ash handling problems caused by wires, unburned combustibles, agglomerated plastics
Hagerstown, Md.	NCRR, Maryland Correctional Institute	Test	Densified	Coal	Spreader-stoker	<ul style="list-style-type: none"> • 1:1, 1:2, 0:1 coal/d-RDF volumetric firing • 223 total hours • No accelerated corrosion experienced • Flame temperature increase with d-RDF • Feeder throw required adjustment • Problems: <ul style="list-style-type: none"> – dust – 7 to 13% boiler efficiency decrease

Table 5.3-I (concluded)

Location	Participants	Status	RDF	Principal Fuel	Boiler	Comments
Eugene, Oreg.	Eugene Water and Electric Board	Test	Fine	Wood waste	Spreader-stoker	<ul style="list-style-type: none"> • 30% RDF firing, approximately 150 tons total • Corrosion or slagging not investigated • 5- to 8-fold increase in bottom ash • Problems: <ul style="list-style-type: none"> – severe bridging in conveyors – dust – 100% increase in particulates
			Densified			<ul style="list-style-type: none"> • 30% RDF firing, 21 tons • No handling problems • Problems: <ul style="list-style-type: none"> – wood waste burned off quickly, leaving grates exposed to d-RDF combustion
Waterbury, Conn.	Century Brass Co.	Awaiting EPA permit	Powdered	Oil	Suspension	<ul style="list-style-type: none"> • 10% RDF firing; 750 tons total fired to date • Free-flowing fuel • Dry ash pit, vacuum removal • Problems: <ul style="list-style-type: none"> – slagging limits RDF firing to 10% for economic reasons – erosion of pneumatic lines

The only other burnout measured was in St. Louis which reported 87 to 90 percent combustion in suspension [9]. A second factor to consider is the fraction of RDF fired at Ames compared with other locations: 50 percent versus 10 percent at St. Louis, 5 percent in Milwaukee, and 10 percent in Chicago. All facilities have experienced increases in the amount of bottom ash generated, necessitating more frequent sluicing. Floatable and agglomerated underburned organics, particularly plastics, also have caused occasional sluice difficulty in each instance. Wisconsin reports that the floatables from their ash lagoons have caused violations of discharge regulations.

Wire has been a particular problem at Ames and Chicago, creating jams in rotary air locks and the clinker grinder. Each occurrence is a significant cause of maintenance time. The air lock has been modified with adjustable steel blade tips and a cutter bar, but has not been in place long enough for evaluation.

None of the utilities has experienced problems with corrosion of boiler tubes from the acidic chloride gases generated. A long-term study is currently underway in Milwaukee by the boiler manufacturer, Combustion Engineering (C.E.). All the facilities have had increased slag build-up on the boiler tubes, but one, Wisconsin Electric, believes that the coal contributes as much to this problem as does the RDF. All operators agree that complete coverage of boiler tubes by sootblowers is necessary for continuation of acceptable heat transfer. The addition of disc screens at the MSW plants in Ames and Milwaukee has had positive, but unquantified, effects on the reduction of slag formation caused by the RDF.

Erosion and plugging of the pneumatic lines have plagued operations in Ames and St. Louis. This was the most severe operational difficulty in the St. Louis demonstration, even after the placement of an air classifier in the preprocessing line. Methods of overcoming this situation are discussed in Section 4.1.

Since Wisconsin Electric began co-firing RDF, the Milwaukee boilers have been less efficient because of the limitations of the induced draft (I.D.) fan. The higher excess air requirement and moisture content of the RDF cause a lowering of the quantity of infeed fuel. Reduced boiler efficiency is to be expected with RDF co-firing because of increased slagging and excess air.

Powdered RDF (Eco-Fuel II) has been burned in combination with oil at the Century Brass Co. boiler in Waterbury, Connecticut. Only 760 tons of RDF have been fired and fuel-use has been temporarily suspended pending an EPA permit for their multicyclone pollution control system. Ash is collected in a dry hopper with vacuum removal. Slagging has resulted from the RDF firing but it is kept at tolerable levels by soot blowers. It is believed that greater than 10 percent fuel addition would require an increased internal cleaning schedule. No corrosion has been noticed even though the fuel preparation process involves acid addition. The fuel presents no handling problems except for the ubiquitous elbow erosion of pneumatic lines. It was found that preheated, 500°F injection air caused premature combustion within the inlet tube and now ambient air is used for this purpose.

Spreader-Stoker Firing. Ames has had the principal experience in stoker-firing fluff RDF. The utility had to revert to suspension combustion because of excessive particulate emissions. Multicyclones constitute the pollution control for the stoker units while the suspension boiler uses an ESP. About 80,000 tons of RDF were fired in two boilers over a 2-year period. Both boilers experienced slagging on the waterwalls, but one had additional fouling at the inlet to the superheater section. Iowa State University researchers believe that the increased excess air and slagged walls decreased the boiler efficiency to such an extent that the furnace exit gas was hotter than normal, thus carrying a softer, more easily deposited fly ash [10]. This particular section of the boiler was not reached by soot

blowers. They suggest that the second boiler did not suffer fouling because of a different geometry of the inlet to the superheater section.

Fluff and d-RDF were test-fired in wood (hog fuel) boilers at the Eugene Water and Electric Board, Eugene, Oregon [11]. The co-firing of RDF in wood-waste boilers has been suggested as an appropriate use for municipal solid waste. The idea may seem reasonable at first -- a furnace burning one waste fuel (wood) should be able to accommodate another (RDF). The flaw in the scheme, however, results from the fundamental differences between wood and RDF. Wood waste is dense, clean burning, nearly ash free, and does not cause slagging. The boilers themselves are inappropriate for RDF firing, being characterized by small, short cavities that hamper oxidation of the volatiles and settling of entrained RDF particles. The volume of underfire air must be kept low when firing refuse to avoid entrainment, and this causes overheating of the grates and melting of the ash. Slagging is a particular problem on the dutch oven grates. Ash buildup and increased overfire air may be the only way to alleviate this condition -- both of these solutions cause a decrease in the burnout. The boiler tubes are closely spaced with minor soot-blower coverage, thus making them susceptible to slagging from RDF co-firing.

Fluff RDF cannot be used on typical existing hog-fuel conveying and storage equipment because of its low density and ability to set up into a hardened mass. Bridging occurs at the seams and transition points of conveyors; dust is a problem at all points; the hog fuel and RDF tend to separate due to density differences, and open storage of the RDF is impossible. Pelletizing the RDF tends to solve the above handling problems, but creates a problem in combustion. Because of its density (about 55 lb/ft³ versus 8 lb/ft³ for RDF) the heat content of the pellets can be too high for the grates, causing a stop in the feed. With the feed stopped, the wood waste burns away quickly, thereby exposing the grates to

the high combustion temperature of the slower burning pellets. This situation can be overcome, but with a more sophisticated feed metering system of the separate components.

Test burns of d-RDF have been completed by Systems Technology, Inc. at the Hagerstown (Maryland) Correctional Institute [12]. Volumetric blend ratios of 1:1, 1:2, and 0:1 with coal were burned over 223 total hours to determine handling and combustion problem areas. The results show a 7 to 13 percent decrease in boiler efficiency and overall dust problems. The d-RDF blended well with the coal, but the spreader throw had to be adjusted for even distribution. No unusual handling difficulties were encountered and metal coupons showed no corrosional effects. The flame temperature increased with the RDF blends due to its higher volatile content. The concept was considered viable although more testing was recommended in additional boilers.

Economic

The costs associated with co-firing RDF vary with each facility and are most directly affected by the quality of the fuel. The maintenance cost at Ames was estimated to be \$2/ton of RDF for 1978, and this is expected to decrease with the lesser inert content now being achieved [13]. This value includes costs associated with the storage silo (operation and maintenance), pneumatic lines, and ash handling. Commonwealth Edison in Chicago has not received enough fuel from the Southwest Supplementary Fuel Plant to ascertain true expenditures. Wisconsin Electric is currently experiencing start-up costs in excess of \$11/ton of RDF, including capital amortization, but it is believed that this will be substantially reduced once shakedown is completed [14]. RDF usage costs at St. Louis averaged \$8/ton of RDF (1975) excluding amortization, reflecting low throughput and pneumatic line maintenance.

Table 5.3-II presents current fuel prices at each location.

Table 5.3-II
Current RDF Prices

<u>Location</u>	<u>RDF</u>	<u>Price (\$/million Btu)</u>
Ames, IA	fluff	0.90 ^a
Milwaukee, WI	fluff	1.18 ^b
Chicago, IL	fluff	0.30 ^c
Waterbury, CN	powder	1.92

^aParity with coal

^bParity with coal, to be discounted for user costs

^cTo be renegotiated at future date

Environmental

RDF co-combustion causes definite alterations to the characteristics of the particulate stream. St. Louis, Hagerstown, and Eugene have shown an increase in relative quantities of smaller particles. Eugene experienced a doubling of total particulates emission rate. The results of the Ames testing indicate that variations in boiler load and amount of RDF firing can skew particle size distributions to either large or small predominance. It is evident that predictive trends have yet to be evaluated.

The most important operating factor appears to be the increased excess air demands of RDF firing. The electrostatic precipitators are designed for coal combustion and are stressed by the increased gas velocities and altered resistivities. Design parameters for co-combustion systems have not been developed.

Combustion Power Associates, Inc. markets a device known as a "dry scrubber". It has been installed at the University of Oregon's wood-waste-burning power plant and uses 100 tons of pea gravel as an impinging medium. The combustion gas undergoes local acceleration around the stones, causing particle deposition. The gravel recirculates and soot is dislodged externally in a shaker box. The soot creates a disposal problem because of its powdery consistency and elevated temperature. The material continues to smolder and re-ignite after removal from the hoppers. A 20-inch pressure drop through the apparatus has a major effect on operating costs. To date, the technique has not been evaluated.

5.3.1.3 Research Status. The preprocessing industry has neglected co-combustion technology and the burden of its development has been placed, unfairly, upon the utility and industrial users. One major consideration has been overlooked -- boiler systems are designed for specific fuels and cannot readily accommodate alternatives unless their combustion characteristics are closely matched. The suspension firing of fluff RDF has been, to date, a marginally

successful effort due to the restrictions of pulverized coal equipment because:

- Increased gas velocities, altered particle-size distributions, and changed resistivities effect ESP efficiencies
- RDF-aggravated slagging, increased excess air, and greater combustion gas volumes cause lower boiler efficiencies
- Altered characteristics of fly ash cause slagging in areas of incomplete soot blower coverage
- Bulky objects jam clinker grinders; floatables cause sluicing and lagooning difficulties
- The abrasive nature of RDF erodes pneumatic conveying and injection systems.

Research activities should focus on producing fuels amenable to existing systems and developing new equipment specific to co-firing. Densified and powdered RDF are two areas requiring expansion of effort, because of their fossil fuel compatibilities. Powdered RDF development has been the proprietary concern of Combustion Equipment Associates, but evaluations should be performed to determine combustion characteristics and oil slurry possibilities. The work in densified RDF has focused on burn testing and now requires fundamental research combined with long-term demonstrations.

5.3.1.4 Research Needs for Prepared Fuel Co-Firing in Boilers.

A summary of technical research needs for prepared fuel co-firing in boilers is presented in Table 5.3-III. The following is a description of research needs.

Table 5.3-III

Research Needs for Prepared Fuel Co-Firing in Boilers

- Examine RDF combustion on a bench-scale to develop relationships between RDF properties, furnace residence time, and combustion conditions.
- Conduct detailed boiler performance tests at fully operational RDF co-fired facilities to examine combustion characteristics.
- Develop mathematical models based on pilot-scale study to predict the combustion behavior of RDF as a function of RDF properties and furnace conditions and physical characteristics.
- Evaluate alternative emission control devices at a fully operational facility.
- Develop guidelines for design of dedicated and retrofit boilers specific to co-firing RDF.
- Develop an accounting procedure for use in determining the true cost of co-firing RDF.

- Examine RDF combustion on a bench-scale to develop relationships between RDF properties and furnace residence time and combustion conditions. Little data exists on the fundamentals of RDF combustion. This has presented design problems when retrofitting existing boilers for RDF co-firing. A greater understanding of RDF combustion behavior is needed to improve the design of systems for the variety of RDF types and boilers that exist.

All types of RDF should be evaluated to establish relationships between RDF particle size, moisture content, ash content, and available oxygen for combustion and the time required to dry, volatilize, and burn the RDF. These tests should be conducted at normal operating furnace temperatures.

- Conduct detailed boiler performance tests at fully operational RDF co-fired facilities to examine combustion characteristics. While some of this testing has been done or is underway at St. Louis, Ames, Wisconsin Electric, and Commonwealth Edison, study should be directed toward actual combustion behavior. Observations should be made on the effect of RDF properties on flame envelope size and shape, slagging and fouling, furnace temperatures, and fly and bottom ash generation. A detailed performance test should provide much of this information along with data on energy recovery. These tests should be conducted for all types of RDF.

- Develop mathematical models based on pilot-scale study to predict the combustion behavior of RDF as a function of RDF properties and boiler conditions and physical characteristics. Based on fundamental bench-scale studies, mathematical models should be developed to describe the combustion behavior of different types of RDF in a variety of furnace designs. The models, which would be developed and verified at the pilot-scale, would relate RDF properties, boiler design, and firing conditions to boiler performance, e.g., energy recovery efficiency and bottom and fly ash generation.

This capability would be extremely useful in selecting proper operating configurations and conditions prior to retrofitting, and would result in the ability to assess firing modifications off-line with a minimum of costly trial and error on-line tests.

- Evaluate alternative emission control devices at a fully operational facility:

- Bag house
- Cyclone followed by electrostatic precipitator.

The variability in composition and percent firing of RDF yields particles of continuously changing characteristics. Control devices should be evaluated to determine their effectiveness and versatility.

- Develop guidelines for design of dedicated and retrofit boilers specific to co-firing RDF. Areas needing attention include:

- Ash handling
- Grates
- Combustion chamber size and geometry
- Boiler tube configuration
- Soot blower coverage
- Injection system
- Combustion air fans
- Emission control.

Equipment designed specifically to accommodate RDF co-firing is necessary for the advancement of the technology.

- Develop an accounting procedure for use in determining the true cost of co-firing RDF. Cost factors include:

- Capital costs of equipment and modifications
- Loss in boiler efficiency
- Increase in operation and maintenance costs.

Accounting methods differ with facility; comparisons of cost are possible only with standardized procedures.

5.3.1.5 Research Program for Prepared Fuel Co-Firing in Boilers. Research on combustion of RDF is needed on a bench-, pilot-, and full-scale. The purpose of the research is to develop a rationale for proper design of co-firing systems. A proper research program should begin with bench-scale studies to develop relationships between RDF properties and boiler residence times and combustion conditions. The relationship between RDF particle size, moisture content, and ash content and the time required to dry, volatilize, and burn the RDF should be determined. Initial tests should use different types of papers, including kraft, to simulate a synthetic RDF. Studies could then be expanded to evaluate field samples of RDF from operating plants. These fundamental studies will provide much needed insight into the proper design of boilers and RDF firing systems. There are a number of laboratory facilities around the country that could be readily adapted for these studies. Duration of a study should be 9 to 12 months, including equipment setup at a cost of about \$100,000.

Additional study is also required at a fully operational facility to better understand the combustion of RDF. A detailed performance test of a boiler would provide information on heat and material balances plus the effect of RDF properties on flame envelope, slagging and fouling, boiler temperatures, and fly and bottom ash generation. Present evaluation studies underway at Ames, Milwaukee, and other facilities should be expanded to address the above scope of work. This information would be useful to utilities and boiler designers to give them a better understanding of the behavior of RDF in the boiler. Cost of this evaluation would be about \$125,000, with an eight month duration.

In addition to the above test programs, work should be conducted on development of mathematical models to predict the combustion behavior of RDF as a function of RDF properties and boiler conditions. Boiler conditions include not only temperature, excess air, and available oxygen, but boiler type, dimensions, and firing arrangement. The advantage of such models would be in design of new

boilers and, more importantly, for off-line design of boiler retrofits. Development of the models could begin at the pilot-scale, but should ultimately be verified at the plant-scale. Duration of a meaningful program would be about 18 to 24 months, at a cost of about \$300,000.

Alternative emission control devices need to be evaluated at a fully operational facility. These include a bag house, and the use of a cyclone preceeding the electrostatic precipitator in the flue gas stream. A similar program, as outlined in Section 5.1.5, Mass Burning Steam Generator Research Programs, is recommended. Cost for experimental program development, testing, and data analysis would be about \$150,000, excluding pollution control equipment cost. Program duration would be 12 to 24 months, depending on equipment delivery.

Based on the results of the preceeding experimental programs, guidelines should be developed for the design of dedicated and retrofit boilers specific to co-firing RDF. Areas to be addressed are combustion chamber size and geometry, firing configuration, boiler tube configuration, grates and ash handling, and emission control.

Standard accounting procedures should be adopted for determining the true cost of co-firing RDF. Items to be considered are the capital cost for equipment and modifications, increase in operations and maintenance costs, and loss of boiler efficiency. The task would involve development of an accounting procedure, followed by application of the procedure to at least one operational facility. Cost of this analysis would be about \$35,000, with a four month duration.

5.3.2 Dedicated Boilers

5.3.2.1 Technology Description. Using preprocessed MSW as fuel in a dedicated (100 percent RDF) boiler offers definite

combustion advantages over mass burning. Because of the small particle size and relative homogeneity of the RDF:

- Less excess air is needed, reducing total blower power requirements and increasing ESP efficiencies
- Oxidizing atmosphere is more readily maintained, which reduces corrosion and particulate emissions
- A relatively constant heat content of fuel is produced, which facilitates load following.

The necessity to install and operate preprocessing and storage systems are the obvious disadvantages of the concept. Preprocessing complicates the relatively simple and reliable method of energy production by mass burning.

The facilities in Hamilton, Ontario and Hempstead, New York are the only dedicated boilers currently in operation. The Hamilton plant is a 460 tpd, spreader-stoker waterwall boiler, producing saturated steam from coarse-shred RDF. The Hempstead facility, presently in shakedown, will combust 1500 tpd of wet-pulped RDF to produce electricity. Descriptions of the processes are found in Section 4.1.1. The operation of the Hamilton plant was taken over by Tricil, Ltd., in February, 1978; since that time, the processing equipment has undergone extensive modification. Essentially, both Hempstead and Hamilton are in their shakedown phases.

The economics of the Hamilton operation are unknown because it has a blanket contract that includes the operation of landfills and transfer stations in the Hamilton-Wentworth Region in addition to the incinerator. The projected tipping fee for Hempstead is \$16/ton, with discounts anticipated for the sale of electricity and separated materials.

5.3.2.2 Research Needs for Prepared Fuel Firing in Dedicated Boilers.

• Conduct a detailed performance test at a fully operational facility. Facility evaluations should address:

- Capital and operating costs
- Energy and material balances
- System reliability
- Safety of process and working environment
- Air emissions and effectiveness of pollution control equipment
- Characteristics of residue.

A comparison of mass burning versus prepared fuel firing in terms of the above parameters is presently unavailable because of the lack of information on prepared fuel systems. A data base is needed for the different types of RDF.

5.3.2.3 Research Program for Prepared Co-Firing in Dedicated Boilers. Evaluation of the Hamilton, Ontario, or Hempstead, New York, facilities should be pursued; however, because of the proprietary nature, it is doubtful that an evaluation can be made of the Hempstead plant. Cost of a thorough evaluation would be about \$200,000 to \$300,000 over a 12-month period.

Additional information is also needed on boilers operating on 100 percent powdered or densified RDF as a fuel to determine whether advantages are gained by embrittlement or densification. Unfortunately, there are no facilities operating under these conditions, and even short term test burns would be very difficult to perform because of a lack of usable dedicated boilers. However, if available boilers can be located, tests should be encouraged.

5.4 Co-Disposal of MSW and Sewage Sludge

Non-thermal co-disposal techniques are discussed in Section 7, Bioconversion. The following discussion deals with thermal disposal of MSW and sewage sludge.

5.4.1 Technology Description

There are two basic approaches to thermal co-disposal. One method uses a solid waste fired combustor to burn sewage sludge and recover energy from both components. The other method uses solid waste as a fuel to combust sewage sludge in a sludge combustor.

In a refuse combustor, such as a waterwall furnace, the sewage sludge can either be predried before entering the furnace or it can be fed directly into the furnace as it is received, with only thickening or dewatering as pretreatment at the sewage treatment plant. Predrying of sludge can be achieved by direct or indirect drying using exhaust heat from the refuse combustor. Direct drying of the sludge can be achieved in rotary, spray, flash or fluid bed dryers. Off-gases from the dryer, which includes water vapor and volatiles from the sludge, are injected back into the refuse combustor above the grates to destroy odors. Indirect drying of the sludge can be performed in jacketed rotary dryers, wiped-surface evaporators or hollow flight screw dryers. Heat for these dryers is also obtained from the refuse combustor -- either in the form of hot flue gas or steam. The steam also can be used to heat a heat transfer fluid which is then used to indirectly dry the sludge in a heat exchanger.

Two methods have been tested for firing undried sewage sludge into refuse combustors. In one method, sludge cake (+20 percent solids) or low-solids sludge (5 percent) has been injected directly into the combustion zone of the furnace. The sludge burns both in suspension and on top of the burning refuse bed. The other method involves dumping dewatered sludge into the refuse pit and either mixing it with refuse, using a crane, before feeding it to the furnace or alternating furnace charges between refuse and sludge.

The alternative method of co-disposal is to use refuse as a fuel to combust the sewage sludge in a sludge combustor. Nearly all sludge combustors in this country are multi-hearth (MHF) or fluidized bed furnaces (FBF). For both the MHF and FBF applications, an RDF must be used as the fuel.

With a MHF, the RDF can either be premixed with the sludge and introduced onto the top hearth or the RDF can be added at a mid-hearth while the sludge is added to the top hearth. The MHF can be operated under either a combustion or pyrolysis mode. Off-gas from the pyrolysis mode is combusted in an afterburner. Heat can be recovered in either mode using a waste heat boiler.

In the FBF, with sand as the bed material, the sludge and RDF can either be introduced through the freeboard of the furnace or into the fluidized bed.

5.4.2 Technology Status

5.4.2.1 Technical. Co-disposal has been practiced in Europe and the U.S. with varying degrees of success. The Europeans are more experienced in this technology. They have operated both full-scale refuse combustors equipped for sludge disposal and sludge combustors fueled by MSW. Co-disposal experience in the U.S. is much more limited. Several full-scale refuse combustors have been modified to burn sludge, but the use of MSW as a fuel in sludge combustors has only been tested on a demonstration scale.

At present, the Harrisburg waterwall refuse combustor is the only fully operational facility in the U.S. that is co-disposing of MSW and sewage sludge. For the past 2-1/2 years, 17 tpd of dewatered sewage sludge (25 percent solids) has been dumped into the refuse pit, mixed, and fired with the raw refuse (450 tpd). An indirect-heated sludge predryer is now being installed. Some of the steam produced from combustion will be used to predry the sludge to about 40 to 50 percent solids. The dried sludge will then be injected into the furnace above the grates, and vapors from the dryer will be blown back into the furnace for odor control.

Eastman Kodak Company operates a combined industrial refuse and sludge combustor. The sludge is predried in a spray dryer and burned in suspension in an oil- and refuse-fired semisuspension boiler.

Two refractory wall, refuse combustion plants (Holyoke, Massachusetts and Ansonia, Connecticut) recently practiced co-disposal using combustor flue gas to predry the sludge. Both plants processed about 40 tpd of MSW. At the Holyoke plant, dewatered sludge was dried to 28 percent solids in a rotary dryer before being fired into the combustor. The Ansonia plant used a similar technique but dried the sludge with a spray dryer. Neither plant is now practicing co-disposal.

Co-disposal using a multihearth sludge combustor has been demonstrated at the Concord Wastewater Treatment Plant in Central Contra Costa County, California. An existing MHF was modified to accept RDF as a fuel. The MHF was operated in both the pyrolysis and combustion modes. The demonstration lasted two months with about 30 test runs, each lasting eight hours.

A demonstration project has been ongoing since 1971 in Franklin, Ohio where sludge and refuse are disposed of in a fluidized bed furnace. The FBF uses reject organics from a solid waste fiber recovery (hydropulping) operation as fuel. Black-Clawson, Inc., the facility's operator, shut down the plant in mid-1979 for economic reasons.

A 1350 tpd co-disposal facility is being planned for Wilmington, Delaware. Final design is underway for sewage sludge (350 tpd at 25 percent solids) and RDF (1000 tpd MSW) co-firing in a dedicated waterwall boiler. Capital cost of the facility is estimated at \$51 million.

A \$19 million, 740 tpd co-disposal plant is now under consideration in Duluth, Minnesota. A fluidized bed furnace will be used to combust 400 tpd of pre-processed MSW and 340 tpd of sewage sludge at 30 percent solids. The facility is scheduled to begin sludge test burns in October, 1979.

In Europe, there are five refuse combustion plants integrated with wastewater treatment plants for co-disposal. Three plants in France use steam recovered from the combustor to predry the sludge. The dried sludge is then injected into the furnace above the grates

and partially burned in suspension. The other two co-disposal plants are in West Germany. Here the sludge is predried with hot combustor flue gases in a flash dryer. The dried sludge is injected above the furnace grates and off-gas from the dryer is blown back into the furnace for odor destruction.

Co-disposal has not been practiced in starved air modular combustors with heat recovery. Occidental Research Corp. briefly evaluated co-disposal in their flash pyrolysis Garrett Process. However, because of poor overall system performance, no conclusions can be made regarding co-disposal in this process. Union Carbide Corp. also conducted co-disposal studies in their "Purox" system. The Purox system is viewed as being technically viable for co-disposal.

Co-Disposal in Refuse Combustors

Undried Sludge. Undried sludge can be disposed of in refuse combustors either by mixing it with refuse in the storage pit (as is now done at the Harrisburg facility) or by injecting or spraying it into the furnace above the grates.

The Harrisburg waterwall combustor has burned about 17 tpd of vacuum-filtered sewage sludge for the past 2-1/2 years. While the high variability of heat content of the refuse and sludge has caused some boiler operational problems, there has been a significant reduction in boiler tube corrosion. Battelle Columbus Labs evaluated the Harrisburg facility in mid-1978. The results (not yet published) show that tube corrosion decreased dramatically since co-disposal was initiated. Prior to sludge combustion, the superheater tubes failed after only 3000 hours of operation. With co-disposal they have not failed in 2-1/2 years.

Five reasons have been postulated to explain this. First, the superheater tube metal was changed to a two percent chrome alloy just prior to sludge combustion. However, it is generally agreed that this metal had little impact on the corrosion rate. Second, with the added moisture content of the sludge, the temperature in

the furnace was reduced. This could be partly responsible for a reduced corrosion rate. Third, while sewage has only a 0.5 percent sulfur content, sulfur has been shown to act as a corrosion inhibitor. Sulfur, which forms SO_2 upon combustion, reacts with metal chlorides in the furnace gas above the burning refuse bed and produces metal sulfates and hydrochloric acid. Both components are in the gas phase and are exhausted with the flue. Therefore, HCl forms in the gas phase rather than on the boiler tube metal, and corrosion is greatly reduced. Fourth, sludge has a high silica content and silicon oxide produced during combustion may be subsequently reduced to silicon in the upper zone of the furnace, forming a protective coating on the tubes. Finally, the soot blowers are only operated once per month instead of once per 8-hour shift as they originally were. This undoubtedly has reduced tube erosion at the expense of heat recovery efficiency, although until the recent development of a steam market this has been a very favorable procedure.

Stack emissions during the Battelle tests for SO_2 , HCl and NO_x averaged 135, 485 and 106 ppm, respectively, for refuse firing only and 240, 345 and 84 ppm, respectively, for refuse and sewage sludge. Particulate data were not available, but the combustor has not passed an emissions test. With the lower furnace temperature due to the high moisture content of the sludge (80 percent), boiler efficiency was slightly reduced.

Undried sludge has also been burned in refuse combustors in Europe. Two methods have been used. Dewatered sludge filter cake (25 to 30 percent solids) has been directly injected into the combustion zone of the furnace and dilute sludge (five percent solids) has been sprayed directly into the combustion chamber above the grates.

Direct firing of undried sludge offers potential capital cost savings over the predrying technique. However, problems with this method have limited its adoption in Europe. Sludge filter cake is

larger in size and heavier than refuse, and when it is direct-injected it moves faster than the refuse through the furnace. Thus burning time is reduced and combustion is not complete. A crust also forms on the cake, which hinders complete combustion.

Co-combustion experiments were conducted at the Gentofte and Bad Godesburg combustors in Denmark. Four methods of adding undried sludge to the furnaces were tested: 1) sludge continuously added to the refuse feed by a spreader, 2) sludge mixed with refuse in a trommel before feeding to the furnace, 3) a full bucket of sludge placed in the feed chute, and 4) sludge manually added by shovel to the feed chute. The major problem encountered was the formation of crust on the sludge cake, which inhibited its combustion. Alternative approaches that could be tested are mechanical size-reduction of the sludge cake and premixing of the sludge and refuse, possibly in a rotary drum or trommel.

Spray injecting of thickened sludge into the refuse combustor can reduce expense at the sewage treatment plant by eliminating the need for a mechanical dewatering step such as vacuum filtration. However, this technique requires that the combustor plant be located within pumping distance of the sewage treatment plant. This method is not attractive from an energy recovery standpoint, because of the water in the sludge that will have to be vaporized in the combustor.

European experience with this method of co-disposal has been unsuccessful. The major problem with this technique is to sufficiently atomize the sludge such that it will both dry and burn completely in the furnace. High pressure and small orifices are necessary for good atomization. Because sludge is fibrous, mechanical atomizers easily become plugged. Dual fluid spray nozzles using sludge and compressed air or steam have potential for sludge spray injection, but nozzle configuration, location and throughput rate must be determined.

Predried Sludge. All co-disposal refuse combustors presently operating in Europe predry the sewage sludge before combustion, as did the Ansonia, Connecticut and Holyoke, Massachusetts combustor plants. In all cases, sludge is predried in a separate unit. Heat for drying is obtained from either combustor flue gases or from the steam recovered by the combustor. The sludge may be dried directly or indirectly. This is the most widely used and successful co-disposal technique. One disadvantage of this method is the added capital and operating cost of the dryer.

As discussed in Section 5.4.1, "Technology Description," a variety of commercial dryers have been used to predry sludge. Indirect drying offers certain advantages over direct drying. System energy recovery efficiency is greater because heat transfer should be more efficient than direct drying and less ambient air is introduced into the system. Also, equipment should be smaller. However, the extent of required predrying as a function of boiler performance has not yet been quantitatively determined -- in fact, as a result of the co-disposal operation at the Harrisburg facility, the need for predrying is still in question.

The co-disposal refuse combustion plants now operating in France at Dieppe, Deauville, and Brive, and in West Germany at Krefeld and Ingolstadt have experienced good results, according to the literature [15]. However, DOE-funded case studies on several of these plants did not assess the technical impacts of co-disposal.

Co-Disposal in Sludge Combustors

There are approximately 200 municipal sewage sludge combustors in operation in the U.S. Nearly all these installations employ either a multi-hearth furnace (MHF) or fluidized bed furnace (FBF) for sludge combustion. Mechanically dewatered sludge (vacuum filtered) will typically have a solids content of 30 percent. However, solids content must usually be raised to above 35 percent for the sludge to burn autothermically. Therefore, fossil fuels are used as a heat source at sludge incineration plants.

The use of MSW as a fuel replacement in sludge combustors offers an attractive waste-disposal alternative and a significant savings in fossil fuel. Based on a national survey of municipal sludge combustor capacity for MSW, about 27,000 tpd of MSW could be used to fuel sludge combustors [16]. This equates to about 38,000 barrels/day of fuel oil.

Experiments in Europe have demonstrated that RDF rather than raw MSW must be used as the fuel source in sludge combustors. Based on per capita sludge and refuse-generation rates, there is sufficient MSW available in a city to more than replace the fossil fuel requirement of a municipal sewage sludge combustor.

MHF Applications

A demonstration program was conducted in mid-1976 in Concord, California, (Central Contra Costa County) to evaluate RDF as a fuel in an MHF sludge combustor. The test lasted for two months, with about 30 eight-hour runs. The MHF was modified to accept RDF as a fuel by either mixing it with sludge (16 percent solid content) and introducing it to the top hearth or by feeding the RDF directly into the third hearth. The system was also operated under pyrolysis and combustion modes by controlling the amount of combustion air added to the unit. Gas sampling, heat and material balances, and corrosion studies were performed.

An RDF-to-sludge ratio of 1:2 or higher on a wet solids feed basis was required for autothermic operation. However, the MHF could accommodate additional RDF for energy recovery.

The pyrolysis mode was easier to control than the combustion mode. Heating value of the pyrolysis off-gas was about 130 Btu/dscf. Gas composition analyses were performed, but a sampling error resulted in partial combustion of the gas samples. The data is thus of limited value. The pyrolysis mode was operated at 26 to 68 percent of stoichiometric air requirements. Using pyrolysis off-gas, an energy recovery efficiency of 72 percent is claimed for

the waste heat boiler. Furnace temperature in excess of 1800°F resulted in the formation of clinkers. The pyrolysis gas could be combusted at temperatures as high as 2500°F in the afterburner [17].

While the results of this demonstration were encouraging, the system's critical day-in-day-out operation has yet to be proved. Hearth and rabble arm erosion and corrosion of the internals need to be examined. The ash residue should be analyzed to determine ultimate disposal requirements. The quality of RDF and its impact on unit operation needs to be determined along with air emissions, particularly metals and hydrocarbons.

FBF Applications

Fluidized bed furnaces account for about 25 percent of the sludge combustors in the U.S. The Franklin, Ohio, demonstration project used an FBF to combust sewage sludge and used the organic residue from an MSW fiber recovery system as the fuel source. The residue, 20 percent solids, was blended with sludge at five percent solids and the mixture dewatered to 45 percent solids and injected into the FBF above the sand bed. Accumulation of coarse material from the refuse did not defluidize the bed. However, excess bed material had to be removed periodically. The FBF was 24 feet in diameter. The demonstration project is now terminated.

Earlier tests at the Lausanne, Switzerland FBF sludge combustor showed that premixed sludge and refuse could be successfully combusted [16]. In Thunder Bay, Ontario, an FBF bark boiler has burned MSW and sewage sludge [16].

Two FBFs are under construction in Duluth, Minnesota for co-disposal of MSW and sewage sludge. Plant start-up was scheduled for April 1979; 400 tpd of MSW and 340 tpd of sludge at 30 percent solids will be disposed of. The system will use waste heat boilers and the steam recovered will be used at the adjacent advanced wastewater treatment plant.

There are advantages and disadvantages of the FBF and MHF for co-disposal. Refuse must be reduced in size for both furnaces;

however, a greater size reduction is necessary in the FBF to prevent defluidizing. In the MHF, metal and wire must be removed to prevent binding of the rabble arms.

Because of the high gas velocities, greater particulate entrainment occurs in the FBF. Therefore, particulate loading to the air pollution control equipment will be greater. Freeboard injection of the RDF can result in blowout of unburned RDF from the FBF.

However, from a maintenance standpoint, the FBF is superior. Cool-down and heat-up time is much shorter for the FBF, and the FBF has no moving internal parts.

5.4.2.2 Economics. EPA has made an economic comparison of co-combustion and separate combustion of refuse and sewage sludge [16]. The analysis indicates that co-combustion is the least costly method. Disposal of sludge in a refuse combustor is less costly than using the refuse as a fuel in a sludge combustor (MHF), assuming that both facilities would have to be constructed. Direct predrying of the sludge before firing into the refuse furnace was less costly than indirect predrying. However, the EPA analysis has the major limitation that costs are not based on actual plant results. For example, annual maintenance is assumed to be 2.5 percent of direct capital cost. Energy revenues are also not included in the analysis, and these would vary depending on the technology used.

From a practical standpoint, use of existing refuse combustors provides the most immediate and lowest cost method of co-disposal. Direct burning of undried sludge in existing combustors is clearly the lowest capital cost approach. However, with the consideration of energy recovery and associated revenues, the added cost of sludge predrying may be offset by lower combustor maintenance cost and higher energy recovery.

Sludge combustors are also a market for MSW. However, RDF must be used, and this requires construction of a preprocessing plant. There is also the added capital cost of retrofitting the MHF

to accept RDF, and the cost of RDF storage facilities. Data on these costs are limited and retrofit and auxiliary equipment costs need to be more accurately determined.

Brown and Caldwell Consulting Engineers estimated the cost of co-disposal of RDF in MHFs at the new 45-mgd Central Contra Costa County Sanitary District water reclamation plant [17]. For total resource recovery, two additional MHF would be needed and a 1200 tpd MSW preprocessing plant. The system would provide 100 percent of the electric power and steam demand for the sewage treatment plant. A comparative analysis was also conducted without resource recovery. In this case, an additional MHF would have to be constructed to combust increased sludge quantities. All fuel to combust sludge and recalcine lime would have to be purchased along with electric power. The cost of the resource recovery option was estimated to be considerably lower than the non-resource recovery solution. However, the analysis was site-specific.

5.4.2.3 Environmental. Co-combustion of MSW and sewage sludge is not explicitly covered in the New Source Performance Standards, CRF 40, Part 60. The particulate standard for "municipal incinerators" (Subpart E, 0.08 gr/dscf at 12 percent CO₂) applies to facilities burning over 50 tpd of MSW. Subpart O, the particulate standard for "sewage sludge incinerators" (1.3 lb/dry ton sludge) applies to any size facility. An opacity limit of 20 percent also applies to "sludge incinerators". Table 5.4-I summarizes the rules that apply for co-combustion of MSW and sewage sludge.

Co-disposal in refuse or sludge combustors will result in an increase in uncontrolled particulate emissions. Where sludge is predried and burned in a refuse combustor, the resulting sludge ashes will be fine and fly ash entrainment can be expected. Likewise, in an MHF, the addition of RDF as a fuel will cause an increase in particulate emissions due to entrainment in the flue gas as it passes countercurrently across each hearth.

Table 5.4-I

Applicability of New Source Performance
Standards to Co-combustion of MSW
and Sewage Sludge

Sewage Sludge (percent)	Municipal Refuse (percent)	Combustor Charging Rate	Applicable Subpart (40 CFR 60)
51-100	0-49	>50 tpd Total Waste	Subpart 0 or Proration of 0 and E
0-50	50-100	>50 tpd Total Waste	Subpart E
0	100	≤50 tpd Municipal Refuse	None
100	0	Any Rate	Subpart 0
1-99	1-99	≤50 tpd Total Wastes, >1.1 Dry tph Sewage Sludge	Subpart 0
11-99	1-89	≤50 tpd Total Wastes, <1.1 Dry tph Sewage Sludge	Subpart 0
0-10	90-100	≤50 tpd Total Wastes, <1.1 Dry tph Sewage Sludge	None

Collection requirements on sludge combustors are stringent and 96 to 99 percent efficiency is necessary for pollution control equipment. With the addition of RDF as a fuel supplement, the increased loading will make it very difficult to comply with emission limits using existing pollution control equipment.

Uncontrolled particulate emissions were not reported by Brown and Caldwell for the Concord, California, MHF co-disposal demonstration [17]. However, limited data were presented for SO₂, SO₃, NO_x, H₂S and mercaptans. The study did recommend using a fabric filter followed by a venturi scrubber and wet impingement scrubber to meet air pollution requirements in a full-scale system for the Central Contra Costa County Sanitary District. This pollution control train is expected to reduce particulate emissions to 0.0045 gr/dscf. Heavy metal analyses were conducted on feed material and furnace ashes. Additional data on heavy metal and particulate emissions for MHF combustion of sludge and RDF should be determined, and the relationship between the quality of RDF and associated emissions must be established along with an acceptable pollution control system.

The data recently obtained by Battelle Columbus Labs at the Harrisburg facility provide a good baseline for emissions from refuse combustors burning undried sludge. A comparative analysis of this facility's emissions after installation of the sludge predryer would be useful to establish the environmental advantages or disadvantages of each method.

Only limited data are available on emissions (air, water, solid waste) from co-disposal facilities. Adoption of co-disposal practices at existing combustion facilities will probably result in an increase in particulate loading to pollution control equipment. In situations where emission violations will occur, the least expensive method of meeting pollution control standards must be determined. This could mean the addition of cyclones, scrubbers, bag filters or

electrostatic precipitators. However, before selection of appropriate control equipment can be made, a more thorough analysis of emissions must be conducted. This also applies to new co-disposal facilities, which must select appropriate air pollution control equipment.

With the possibility of future standards on heavy metals, hydrocarbons, and HCl emissions, consideration should be given now to techniques to control these pollutants.

5.4.3 Research Status

Battelle Columbus Labs was recently awarded a DOE contract to evaluate co-disposal of sludge and refuse in a fluidized bed. Sludge will be predried in an indirect-heated heat exchanger using the bed sand as the heat source. Sludge from the dryer will be pumped under pressure to a flash evaporator where the water will be flashed off as steam and the dried sludge will be fed to the FBF along with RDF. Steam from the evaporator, contaminated with organic vapors, will be used at a sewage treatment plant to raise the temperature of the incoming wastewater by about 10°F. The intent is to increase biological reaction rates in the activated sludge process and thus reduce sewage treatment plant overload conditions.

This concept's application is limited to sewage treatment plants experiencing overload conditions. The steam produced is contaminated with organic vapors and has limited use. The concept of heating sewage to increase biological activity as an alternative to plant expansion would appear to be a short-term solution. Technical questions arise concerning the energy balance of the process, that is, using sand as the heat source for sludge drying. Also, erosion in the sludge dryer and in the sand recirculation equipment can be expected to be severe. The more conventional predrying approach, using incinerator flue gas, would probably have fewer maintenance problems. No comparison has yet been made.

5.4.4 Research Needs for Co-Disposal

Technical research needs for co-disposal are presented in Table 5.4-II. A brief explanation of each need follows.

5.4.4.1 Refuse Combustors.

- Evaluate the economics of firing predried sewage sludge versus firing dewatered, undried sludge using existing design and cost data. While on the surface direct firing of undried sludge appears to be less costly than predrying, many factors must be considered. Capital cost for new and modified equipment, added maintenance and labor, additional ash disposal and air pollution control must all be considered.
- Evaluate firing predried sewage sludge versus firing dewatered, undried sludge on heat recovery efficiency, boiler corrosion, slagging, and air emissions at a fully operational facility. The Harrisburg facility has had reasonable success in direct firing dewatered sludge with refuse into the boiler. However, during this period, boiler performance was not of prime concern because the facility did not sell steam to an outside user. Boiler performance and energy recovery efficiency need to be determined for these two methods of sludge firing. Corrosion, slagging, and air emissions may also be affected by the degree of sludge predrying. Limits on the amount of sludge that can be burned by either method should also be examined.
- Evaluate the effects of co-disposal on long-term boiler corrosion at a fully operational facility. Battelle's work at the Harrisburg facility should be continued to establish long-term corrosion mechanisms and effects of co-disposal.
- Evaluate the technical and economic aspects of premixing sewage sludge in an RDF processing plant, and examine the combustion

Table 5.4-II

Co-Disposal Technical Research Needs

Refuse Combustors

- Evaluate the economics of firing predried sewage sludge versus firing dewatered, undried sludge using existing design and cost data.
- Evaluate firing predried sewage sludge versus firing dewatered, undried sludge on heat recovery efficiency, boiler corrosion, slagging, and air emissions at a fully operational facility.
- Evaluate the effects of co-disposal on long-term boiler corrosion at a fully operational facility.
- Evaluate the technical and economic aspects of premixing sewage sludge in an RDF processing plant, and examine the combustion properties of the RDF/sludge mixture through pilot- and full-scale evaluation.
- Characterize ash residue at a co-disposal facility to determine disposition requirements and end-use.

Sludge Combustors

- Develop costs to retrofit sludge combustors to handle RDF as a function of sludge combustor capacity and RDF availability.
- Evaluate technical and economic impact of RDF quality on MHF and FBF operations.
- Evaluate air emissions as a function of RDF quality for MHF and FBF at a fully operational facility, and specify the need for pollution control equipment.
- Evaluate RDF/sludge feed methods for a FBF at a fully operational facility.
- Characterize ash residue and determine disposition requirements and end-use.

properties of the RDF/sludge mixture through pilot- and full-scale evaluation. A homogeneous mixture of sludge and RDF will combust more efficiently in a refuse combustor. Blending sludge with MSW in the RDF plant could reduce shredder wear and power consumption (since the sludge acts as a lubricant), and might also inhibit shredder fires and improve air classifier performance. The effect on unit operations in the RDF plant should be determined. However, the cost of transporting the sludge to the RDF plant must be included in the overall analysis.

Subsequently, the effects of combusting the blended RDF/sludge mixture in a full-scale spreader stoker boiler should be evaluated.

- Characterize ash residue at a co-disposal facility to determine disposition requirements and end use. Disposition of the residue will depend on the degree of carbon burnout and the metal content of the ash residue. End use of the residue other than landfill will be determined by the residue composition.

5.4.4.2 Sludge Combustors.

- Develop costs to retrofit sludge combustors to handle RDF as a function of sludge combustor capacity and RDF availability. Depending on the size and location of the sludge combustor facility, using RDF may not be cost-effective. Economic analysis must determine retrofit cost as a function of sludge combustor capacity and type. This cost then needs to be linked with the cost of RDF production. Such analysis should be general and should cover several combustor size ranges, several city populations or population densities, and various transportation distances from the RDF plant to the sewage treatment plant. While Gordian Associates has partially addressed this subject, the work should be expanded.

- Evaluate technical and economic impact of RDF quality on MHF and FBF operations. While raw refuse cannot be fired in an MHF or FBF, it is necessary to determine the effect of the degree of

preprocessing on combustor performance. Requirements for a high quality RDF with little metals and glass will certainly add to the total system cost. The minimum degree of preprocessing should be established and the benefits of additional processing determined.

- Evaluate air emissions as a function of RDF quality for MHF and FBF at a fully operational facility, and specify the need for pollution control equipment. The degree of preprocessing of MSW may affect air emissions, especially with regard to particulate and metals emissions. With a higher gas velocity in an FBF, size distribution of the RDF could have a significant impact on particle elutriation. Presently, there is not enough data available to make any determination.

- Evaluate RDF/sludge feed methods for an FBF at an operational facility. Feeding RDF into the freeboard of the furnace may result in particle entrainment in the furnace off-gas. However, feeding directly into the bed causes feed problems and increases the possibility of bed defluidization and fouling of the distributor plate. While this is presently a research need, the testing at the Duluth facility should provide the proper information.

- Characterize ash residue and determine disposition requirements and end-use. This research need applies to co-disposal residues from sludge, as well as refuse combustors. A research program would address both types of facilities.

5.4.5 Research Programs for Co-Disposal

- 5.4.5.1 Refuse Combustors. Operational data is needed on co-combustion of sewage sludge in refuse combustors. The major issue is to compare firing predried sewage sludge versus firing dewatered, undried sludge on overall system performance. To address this issue, a paper study initially should be conducted to compare the economics of the two approaches. This study would develop conceptual designs for both sludge handling approaches at various refuse

combustor capacities and refuse/sludge ratios. For example, individual boiler capacities of 50, 500, and 1000 tpd of MSW could be evaluated. This tonnage range would cover the small, modular combustors, as well as the large waterwall boilers. The analysis would determine incremental capital and operating costs per unit of additional energy produced (\$/MM Btu). Only existing data and basic design principles would be used for the analysis. This approach would provide a fast turnaround time for a relatively low cost, i.e., about \$30,000, and would provide a clearer understanding of economics for the two sludge handling alternatives.

Simultaneous with the above study, a plant evaluation should be conducted to evaluate firing predried sewage sludge versus firing dewatered, undried sludge. This would be a comparative evaluation of the two sludge handling approaches. Information would be obtained on heat and material balances, energy recovery efficiency, boiler tube slagging and fouling, degree of sludge and refuse burnout, residue characterization, and air emissions. The Harrisburg mass burning facility would be an ideal candidate for evaluation, because it has burned dewatered, undried sludge for a period of time, and a new sludge predryer has been recently installed. Cost of the evaluation would be about \$200,000, extending for a period of 12 to 18 months. It is also recommended that when this analysis is completed, the data should be used to refine the economics of the initial paper study which examined the incremental cost per unit of additional energy produced for the two sludge handling approaches.

Because the need for sludge disposal also exists at the smaller community level, an evaluation of co-disposal should also be conducted at an operational controlled air, modular combustion facility. Firing predried sludge versus firing dewatered, undried sludge should be examined, using the same approach outlined above. Cost for this evaluation would be \$100,000 to \$150,000, with a 12 month duration. This does not include the cost of a sludge dryer, which may have to be purchased.

The present co-disposal work by Battelle on short-term boiler tube corrosion should be extended to examine long-term corrosion effects. Initial results at Harrisburg indicate that the presence of sulfur and silica in sewage sludge may reduce boiler tube corrosion rates. Ideally, this work should be performed at the same facility that conducts the large-scale sludge predrying evaluation. Cost of this study would be about \$100,000 over a 24 month period.

One final research program should examine the technical and economic aspects of premixing sewage sludge with MSW in an RDF processing plant. Potential advantages in shredding are reduced hammer wear, power consumption, and fires; improvement in air classifier performance is also a possibility. This evaluation should begin at the pilot scale, evaluating shredder and air classifier performance with and without sludge present in the raw MSW. Different sludge/MSW ratios should be examined. Combustion tests in a pilot-scale spreader stoker should be conducted on the blended RDF/sludge product. Existing pilot equipment should be used for this project. Cost of the preprocessing and combustion pilot program would be \$75,000 to \$100,000, with an 8 to 12 month project duration.

If the technical results of the pilot plant analysis indicate that premixing sludge does improve unit operation performance, then premixing should be evaluated at a fully operational RDF producing facility. Technical data from this evaluation should be used to determine the incremental processing cost or savings in premixing sewage sludge. The effect of sludge premixing on RDF storage should also be examined.

A second phase of this full-scale evaluation would be to examine the combustion characteristics of the blended RDF/sludge mixture in a dedicated, spreader stoker boiler.

5.4.5.2 Sludge Combustors. Research on co-disposal of RDF in sludge combustors is directed at determining retrofit and operating

costs, as well as developing data on system performance. Parallel studies should be conducted to address these needs.

Initially, a paper study should be performed to develop costs to retrofit sludge combustors to handle RDF. This analysis should take a general systems engineering approach, and should cover several MHF and FBF size ranges, several refuse and sewage sludge tonnage combinations, and various transportation distances from the RDF plant to the sewage treatment plant. Retrofit costs refer to those costs related to equipment modification; however, the cost of transporting RDF to the sludge handling facility should also be an integral part of the analysis. This study would be relatively low cost, i.e., \$50,000, with a duration of 6 months.

Parallel with the above study, a pilot-scale MHF and FBF should be evaluated for disposal of RDF and sewage sludge. In this evaluation, primary emphasis should be placed on examining the effect of the degree of MSW preprocessing on system performance. Coarse, fluff, powdered, and pelletized RDF should be examined. Several coarse and fluff RDFs could be produced for testing, using different process trains, e.g., with and without trommeling prior to primary shredding. These pilot plant tests should examine heat and material balances, flue gas emissions, material burnout, and fly ash and bottom ash characteristics. RDF for the tests would be produced by operational facilities and shipped to the pilot facility(s). A number of MHF and FBF pilot systems exist for this evaluation. Cost for both studies would be about \$100,000, over a 12 month period.

With the timely construction of the Duluth FBF co-disposal facility, results of the pilot plant tests should be validated at the Duluth facility or another fully operational facility. Tests should concentrate on evaluation of the most promising RDF types from the pilot plant evaluation. This effort may require some RDF processing equipment modifications or the import of RDF. In addition to the types of analyses conducted in the pilot plant evaluation, the full plant evaluation should also evaluate air emissions, boiler tube slagging and fouling, energy recovery efficiency, and

boiler tube corrosion and erosion. Cost of the evaluation test would be about \$200,000 to \$250,000, with a 12 to 18 month duration. EPA has recently awarded a \$200,000 contract for test and evaluation of the Duluth facility. This information should provide near-term data on FBF performance.

If a fully operational, MHF co-disposal facility comes on-line within the next three years, an evaluation similar to the above FBF evaluation should be conducted.

REFERENCES: SECTION 5 COMBUSTION SYSTEMS

1. Vaughan, D. A., et al., "Fireside Corrosion in Municipal Incineration versus PVC Content of Refuse," Proceedings of 1974 National Incinerator Conference, Miami, Florida, May 12-15, 1974.
2. Midwest Research Institute, "Environmental Assessment of Waste-to-Energy Process -Braintree Municipal Incinerator," EPA Contract No. 68-02-2166.
3. Krause, H. H. et al., "Corrosion and Deposits from Combustion of Solid Waste," Journal of Engineering for Power, Trans. ASME, Series A, Vol. 95, 1973.
4. Krause, H. H. et al., "Corrosion and Deposits from Combustion of Solid Waste. Part II: Chloride Effects on Boiler Tube and Scrubber Metals," ASME Winter Annual Meeting, Paper No. 73-WA/CD-4, 1973.
5. Krause, H. H. et al., "Corrosion and Deposits from Combustion of Solid Waste. Part III: Effects of Sulfur on Boiler Tube Metals," Journal of Engineering for Power, Trans. ASME, July, 1975.
6. Krause, H. H. et al., "Corrosion and Deposits from Combustion of Solid Waste. Part IV: Combined Firing of Refuse and Coal," Journal of Engineering for Power, Trans. ASME, July, 1976.
7. Krause, H. H. et al., "Corrosion and Deposits from Combustion of Solid Waste. Part V: Firing of Refuse with High Sulfur Coal", Journal of Engineering for Power, Trans. ASME, July, 1977.
8. Pavlovich, K. D. et al., "Installation of Incinerator Residue as Base-Course Paving Material in Washington, D.C.," Federal Highway Administration Offices of Research and Development, Report No. EHWA-RD-789-114, December, 1977.
9. Gorman, P.G., et al., "St. Louis Demonstration Final Report: Power Plant Equipment, Facilities and Environmental Evaluations," U.S. Environmental Protection Agency, EPA-600/2-77-155b, December, 1977.

10. Van Meter, D., et al., "Evaluation of the Ames Solid Waste Recovery System Part II," U.S. Environmental Protection Agency.
11. "Solid Waste Fuel Modifications, Second Series Burn Tests: Final Report," Sandwell, Inc. for the Eugene Water and Electric Board, Eugene, Oregon, December, 1974.
12. "Preliminary Findings: Use of d-RDF as a Stoker Coal Substitute Industrial Spreader Stoker," Systems Technology Corporation, June, 1977.
13. Don Riggs, Ames Municipal Electric System: personal communication.
14. Bud Fay, Wisconsin Electric Company: personal communication.
15. Sussman, D. B. and H. W. Hersham, "Thermal Methods for the Co-Disposal of Sludges and Municipal Residues", paper presented at the Fifth National Conference on Acceptable Sludge Disposal Techniques, Report No. SW-686, January 31 - February 2, 1978.
16. "A Review of Techniques for Incineration of Sewage Sludge with Solid Wastes", Roy F. Weston, Inc. for the U.S. Environmental Protection Agency, EPA Report No. 600/2-76-288, December, 1976.
17. "Solid Waste Resource Recovery Full Scale Test Report - Central Contra Costa Sanitary District", Brown and Caldwell Consulting Engineers, March, 1977.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SECTION 6

PYROLYSIS SYSTEMS

Pyrolysis is the destructive distillation of refuse, mainly the volatile fraction, through the application of heat in the absence or near absence of oxygen. There are three major methods for heating refuse to facilitate pyrolysis reactions --indirect-heating, direct-heating using oxygen, and direct-heating using air or steam. Most new, small-scale development work in the U. S. involves indirect-heated systems. Indirect- and direct-heated systems are discussed in detail later in this section.

There are many different types of pyrolysis systems, all with unique advantages and disadvantages. The major categories of pyrolysis systems are those that use vertical-shaft reactors (usually associated with fluidized bed and high temperature applications) and those that use horizontal reactors, with either stationary or mobile shells. The fluidized bed systems offer maximum heat-transfer characteristics. The high temperature systems offer reduction of the noncombustible fraction to a relatively inert, gritty residue that may be the most marketable of all refuse process residues. The horizontal reactors offer maximum control of material residence time, and have the potential to tailor fuel products (gas, liquid, and solid) for optimum market use.

Pyrolysis systems that combust either agriwaste or MSW yield three major products: char, oil, and gas. In the case of direct-heated systems, the char is either volatilized or combusted, or both, and oil or gas production is optimized. In the case of lower temperature (1200°F), indirect-heated systems, the quantities of the three major products can usually be controlled by varying residence time and temperature. Either oil or gas production is optimized, but a char residue (primarily carbon) remains. In the case of high-temperature pyrolysis (2500 - 3000°F), a brittle glossy frit remains from the rapid quenching of the molten slag generated in the process. The principal useful product is a medium-Btu gas.

Why Pyrolysis?

There is a significant segment of the solid waste processing community expending a sizable amount of time and money developing ingenious methods of applying pyrolysis to MSW. Most solid waste engineers agree that if pyrolysis can be shown to work economically -- at least at a cost comparable to or less than conventional combustion recovery systems -- it can be a significant advancement in the state of the art of solid waste processing. However, there have been several false starts, concepts that did not work, and concepts that worked but were not competitive with conventional refuse processing systems.

Why, then, pyrolysis? There are many residential, commercial, and industrial users of natural gas and fuel oil. With the predicted shortages of these fossil fuels and the difficulty of converting to coal-firing boilers, the potential demand for substitute gas and liquid fuels is great. Hence, the impetus behind developing coal gasification and liquefaction. Pyrolysis gas or oil offers the same substitute fuel advantage.

If the pyrolysis product is to be fired on-site in a boiler to produce steam and/or electric power, then why not simply combust the refuse material in the first place? The answer to this question often depends on site or locale. Some of the reasons why pyrolysis can be a preferred alternative follow.

- One of the most important points about pyrolysis is that the operation of systems with little or no combustion air and low-velocity gas movement requires little air pollution control equipment. The volume of gas requiring treatment is reduced by at least 50 percent from conventional systems -- in some cases more. Not only is there less volume to treat, but the lower velocities entrain significantly fewer particulates. Lack of production experience precludes a comparison of data, but the potential is clear.

- Pyrolysis can use less energy than other technologies, especially where off-gas is recycled for autogeneous process operation. Systems requiring front-end separation have the same energy cost as a similarly sized RDF system, but the pyrolysis equipment itself -- kilns, augers, oscillating conveyors -- have low energy requirements (3 to 7 kwh/ton of capacity). In high temperature systems producing a molten slag, minimal front-end separation is required.

- In gas-producing systems, a high stack is not required in most areas of the country. By shipping the gas to an existing plant, or by on-site combustion using a short exhaust stack (20 to 40 feet), visual aesthetics in areas with restrictive topography are not impaired.

- The beneficial effects of inert residue (as opposed to typical incinerator residue) on landfills, particularly regarding groundwater contaminant level, remain unexplored. Inert residue may mean reduced groundwater pollution, and possibly some increase in public acceptance of a pyrolysis dedicated landfill site.

- The lower temperature pyrolysis systems may have less corrosion potential because of the moderate temperatures (900° - 1200°F) at which they operate. Unfortunately, there is not much existing data on low-temperature gas pyrolysis. High-temperature chloride corrosion may be reduced or eliminated by these systems. Also, the high temperature systems tend to scrub much of the chloride out before gas firing. A report completed recently by Midwest Research Institute for U.S EPA [1] states that gas from the "Purox" process is low in HC and CO concentration; NO_x and SO₂ concentrations are greater than natural gas, but SO₂ concentrations are low; NO_x requires more testing; Hg and Cl concentrations are higher than natural gas (but not high enough, based on sludge facilities, for example, to warrant environmental concern); particulates are

low, most less than 1 micrometer in size, and all opacity readings are below 5 percent.

- Pyrolysis oil products in one case are very promising because they are comparable to No. 2 fuel oil. Depending on the area of the country and the market, production of oil using conventional transport methods could satisfy a particular local need, and eliminate the requirement that the facility be adjacent to the user.

- If the pyrolysis systems operate according to design, there could be a more complete volatilization of combustible material than with conventional combustion systems. Even where char is to be burned, the char by that time will be in a more consistent form.

- There is potential for pyrolysis systems of various sizes to produce 350 to 500 kwh/ton, which is comparable to the net electric energy from large-scale waterwall incinerator systems. Emphasis on new sources in the National Energy Act of 1978, as well as size flexibility of pyrolysis, could make this technology more desirable.

- The pyrolysis reactor vessel in most systems is more simply designed than conventional stoker/grate systems, and may need less maintenance overall.

6.1 Indirect-Heated Systems

6.1.1 Technology Description

Indirect-heated pyrolysis systems use heat generated outside the reactor vessel, which is then channeled to the refuse through the reactor vessel or by other means not indigenous to the material being pyrolyzed. The majority of indirect-heated systems use rear, horizontal retorts of varying design to distill-off the volatile products resulting from application of heat (see Figure 6.1-1). Designs incorporate a stationary shell, with an internal device such as an auger or oscillating conveyor used to move the refuse from the

Figure 6.1-1. Basic Moderate Temperature (1000°-1400°F)
Horizontal Retort Pyrolysis System

feed end to the discharge end. Heat is applied through the shell of steel-sided vessels, or internally by a radiant heat device projecting into the reactor -- this latter case is found in a stationary rectangular tunnel system where radiant heat tubes introduce heat into the reactor.

Both fixed and rotating horizontal retorts can be found in a refractory-lined firebox, which is much like an oven. Some fraction of the pyrolysis gas, once its production has begun, is fired inside the firebox but outside of the reactor shell. Resultant heat is applied to the refuse through the stainless steel shells of several units, both stationary and revolving.

Units that incorporate augers may be susceptible to inadequate heat distribution from the retort through the refuse. In at least one case, an attempt to hold a near-constant temperature gradient across the refuse has resulted in a hollow-shaft auger with heat supplied both to the auger shaft and the stationary retort shell.

The other predominant horizontal retort design incorporates a slowly rotating cylinder internally fitted with welded pins, fins or other protrusions to provide material turbulence. Generally, these retorts are slightly inclined, and move material from feed end to discharge end by gravity. In at least one case, however, the kiln is exactly horizontal. The refuse moves from feed end to discharge by reason of a decrease in its weight due to continuous distillation during the time it is inside the reactor, coupled with a reactor design that apparently uses some type of gently-angled interior blades to translate the refuse from feed end to discharge end.

6.1.2 Technology Status

6.1.2.1 Technical. Several indirect-heated units have been developed to the demonstration phase, and need funding for the last big step from the 2 to 10 tpd range up to the 50 to 150 tpd module range. Table 6.1-I summarizes the status of the technology.

Table 6.1-I

Status of Indirect-Heated Pyrolysis Systems

<u>Reactor Configuration</u>		<u>Products</u>		Next Stage of Development	Current Capacity (tpd)
General	Design	Principal	Secondary		
Near-Horizontal, Circular Cylinder	Stationary Retort - Auger	Oil Gas	Gas Oil Char	Engineering/ Demonstration	50
Horizontal Circular Cylinder	Rotating Kiln	Gas	Oil Char	Demonstration and Commercialization	50 to 2000
Vertical Circular Shaft	Co-injected char and organic material flash pyrolysis	Oil	Char	Demonstration Retrofit	200
Horizontal Rectangular	Stationary tunnel, oscillating conveyor	Gas	Char	Commercialization	100

Front-End Processing

Many potential problems associated with the systems cannot be addressed at the present small scale using waste other than MSW, but can be addressed when larger scale systems process the MSW. With few exceptions, indirect-heated technology requires excellent front-end separation, and preferably removal of all glass. Front-end processing research needs are covered elsewhere in this report. In discussing these pyrolysis systems, it is assumed that adequate front-end processing is available. At present, one- and two-inch nominal particle size is most common, but the maximum permissible particle size is not known. In all cases, the systems will operate better and maintenance costs will be lowered by 10 to 30 percent if all the glass is removed. Imbedding of glass in the combustibles, abrasion, slagging, plugging, and erosion are all problems resulting from glass entrainment.

Drying

In several horizontal systems, reactor temperature and residence time are critical. Time cannot be lost vaporizing excess water, and dryers must be placed upstream of the reactor. The benefits of combination dryer/trommels or dryer/shredder/trommels or shredder/dryers are unknown. At present, several systems reduce moisture to below 10 percent -- however, optimum permissible moisture level versus residence time and type of product is unknown.

Infeed Equipment

Air lock mechanisms are used on infeed equipment to minimize the introduction of air, reduce diluted off-gas, and prevent unnecessary heat loss. Systems operating at slightly greater than atmospheric pressure must keep in smoke and other partially combusted gases, and at lower than atmospheric pressure must keep air out. Operational performance of feedlock mechanisms on MSW containing tramp metals and other entrapped problem materials is unknown. One of the problems in Baltimore's Landgard system was jamming of the ram feedlock mechanism.

Feedlock mechanisms generally consist of graduated tiers of bomb bay doors, swinging hinged gate doors, piston-and-cylinder ram feeding devices and other mechanisms. The reliability and sealing efficiency of these configurations for operation on MSW are unknown.

Reactor Configuration

Different reactors offer distinct advantages and disadvantages. For almost all systems ready for demonstration-scale evaluation, the reactor sizing has been scaled up from the pilot-scale development. The optimum reactor configuration has not generally been explored beyond the basic design that was found to work for that system.

The operation of a reactor at different temperatures and pressures remains untested, as do parameters such as kiln or auger speed, gas flow and residual material handling.

Product Use

The use of product gas is constrained by its temperature, pressure, quantity of condensible oils, distance to the user, pipeline conditions, and other factors. The gas can be used, however, as a fossil fuel substitute by gas users located near the plant. Reluctance to use the gas off-site stems from lack of experience and burner equipment for optimum firing of this type of low-Btu gas. There is also a problem with gas product consistency, due mostly to the variation of the feedstock. At present, a more reliable use of the gas is on-site in a dedicated boiler for reactor heating or use in the dryer. An alternative use of the gas on-site is in a multi-or regenerative-cycle, gas/steam turbine. This option is still in the experimental stage.

The oil produced by various indirect-heated systems has exhibited some corrosive properties, but can be mixed and burned with various fuels, such as No. 6 oil. In particular, one system produces an oil very similar to No. 2 heating oil. Potential areas of

investigation for this material are consistency as produced, and stability of the oil both under static head and when stored for extended periods.

Residual Handling

Most indirect-heated facilities produce a char. The composition of the char depends on the composition of the feedstock from the front-end process. In many cases, the char can be combusted for further energy release. In other cases, the char is contaminated with tramp metals and other materials. If the char is fired on-site, the furnace used must be carefully designed to eliminate air pollution that might result from burning these contaminants along with the char. In other cases, the char is land-filled along with its contaminants and ash, but this represents a loss of potential heat. Good uses for the char remain unexplored.

6.1.2.2 Economic. The capital and operating cost of the indirect-heated systems vary significantly with the process, quantity of auxiliary fuel used (if required) and number of laborers and technical management personnel. Capital costs are projected at levels from \$20,000 to \$30,000/ton of daily rated capacity, depending upon the system proposed and the product desired. Operating costs vary from \$5 to \$10/ton, again depending on individual system requirements.

6.1.2.3 Environmental. One of the major advantages of pyrolysis, at least in theory, is mitigation of air pollution created by the facility. In many cases, particularly with demonstration-scale facilities in poor air-quality areas, such as in California, the big hurdle is obtaining an operating permit from the County or Regional Air Pollution Control Board. Limited air emission tests on the only indirect-heated pyrolysis pilot plants (4 tpd MSW in Upland, California and 50 tpd automobile fluff in Redwood City, California) showed particulate emissions below federal limits of 0.08 gr/dscf;

and the Upland, California, engineering-scale system has tested at 0.0198 gr/dscf and 0.0517 gr/dscf during two tests. Similar results have been experienced by other systems. Based on these limited data, almost all pyrolysis systems have been granted permits to operate in California. In most cases, the local air pollution boards have deemed combustion of the product gases with the relatively small-scale gas cleaning equipment to be acceptable. Gas combustion itself is not expected to have any problem with air emissions. Successful operation of the small system does not necessarily imply acceptable operation of a large-scale system, but does offer reason for optimism. If the char is burned on-site, the furnace configuration will be required to comply with emission requirements. Compliance could be costly.

Water pollution control will be required in those systems where a wet scrubber or residue quench is used. In some cases, there is a possibility that if the char and inerts are pure enough, a cooling screw conveyor will reduce the char well below ignition temperature and will permit the residuals to be handled in a dry state. There is some debate as to whether residue quenching would be required in some or all of these systems, and if required, the extent or type of quenching most appropriate. Also, a method of recycling the hot char for firing has not been developed, and even the desirability of such recycling has been questioned.

6.1.3 Research Status

Most of the research being performed by the various system developers is unique to the particular system they are developing. For systems near to being marketed commercially, developers have been reluctant to admit a necessity for any further research. Some of the systems obviously need further work before they will be commercially available. Units now in the exploratory or technology development phases are at the size where the parametric testing is being done.

Indirect-heated systems requiring work for MSW firing have been in development for some time, in one case since the early 1960's. Both Pan American Resources (Upland, California) and Pyro Sol Inc. (Redwood City, California) have done all development work on their respective systems. If the systems are commercialized, these firms will perform R&D as required to improve their existing systems. The Enterprise Company of Santa Ana, California has tested a hollow auger system -- now dismantled and reportedly enroute to a consortium of private haulers in Nassau County, New York. The Enterprise System is marketed east of the Mississippi River by B.W. Energy Systems, Inc. of New York City. B.W. reports that any R&D work for optimization will be performed on the system as required for each particular application.

It is difficult to determine to what extent these and other system suppliers are willing to participate in a DOE-funded project, and subject their systems to public testing and scrutiny while trying to optimize components of the various systems. There seems to be some desire to go to the next developmental step with Federal funds on the one hand, and a reluctance to tie up with a Federal R&D program on the other.

Before becoming commercially available, several promising systems should be tested at a scale where front-end requirements can be determined.

6.1.4 Research Needs for Indirect-Heated Pyrolysis Systems

Research needs for indirect-heated systems are presented below:

- Evaluate different heat-conducting materials for use in kilns or in externally heated equipment such as the rectangular tunnel's radiant heat tubes. Various systems depend on maximum heat transfer through the reactor shell, with emphasis on minimizing slagging, corrosion and erosion. Materials with high heat transfer and low slagging characteristics should be studied, since slag reduces heat transfer capability. Pyrolysis efficiency is directly proportional to high-efficiency heat exchange.

- Evaluate char furnace design and materials handling for return of char into the firing train, including a char/ash separation system. Char can account for 30 percent of the product (by heat content) extracted from dry feed. The ability to burn char would allow use of up to 30 percent more of the heat content of the material. For a 33 percent overall system efficiency (as with electricity production), a 10 percent increase in system efficiency could result from maximum char use, lowering disposal cost by \$1 to \$2/ton of refuse input. A char/ash separation system also needs to be developed.

- Develop uses for product char, creating a demand for up to 30 percent (by heat content) of the fuel produced by moderate-temperature pyrolysis. Using a typical proximate analysis of refuse, fixed carbon accounts for 6.6 percent by weight of refuse [2]. The char produced is essentially carbon, with some ash and inerts. In one pound of refuse (HHV = 4500 Btu/lb), 930 Btu is accounted for by fixed carbon, or the char. Based on the analysis used, fixed carbon can comprise up to 18 percent of the refuse weight as received [1], or 30 percent of heat content. If a good use for char can be found, it may not require on-site firing, although on-site firing takes advantage of the sensible heat of the char.

- Evaluate improved kiln configuration designs. At present, little is known about optimum kiln design. There is a need for design optimization concerning length, cross section, and heat transfer of materials used. No design equations exist for kiln or tunnel configurations.

6.2 Direct-Heated Systems

Vertical Shaft

Direct-heated systems are those systems that generate heat for the pyrolysis reaction within the reactor vessel -- either through combustion of a portion of the material, or application of heat

directly to the material. The more developed systems using this concept are vertical bed systems using three zones -- a combustion zone at the bottom of the shaft, a pyrolysis zone in the middle, and a drying zone at the top just below the infeed chute (see Figure 6.2-1). There are two full-scale designs. One design uses oxygen for combustion of the non-volatilized material which descends to the bottom; the other design uses air.

The oxygen- and air-fired systems operate at high temperatures (2200°F to 3000°F). Another system at the engineering development level, which was developed for parametric study of pyrolysis kinetics, uses a vertical shaft, fluidized bed reactor for rapid, almost instantaneous pyrolysis of the infeed material. The pebble fluidized bed is heated and suspended by natural gas and combustion air, resulting from an updraft through a distributor plate. Prepared refuse is injected into the fluidized bed (see Figure 6.2-2).

Still another vertical bed system uses seven percent of stoichiometric air to combust refuse and char at the very bottom of the vertical shaft, driving hot gases for volatilization up through the refuse plug flow [3]. Drying is done externally.

These systems have the advantage of total volatilization or combustion of all the combustible material, including the carbon fraction, which in a horizontal retort system usually remains as char. This eliminates the need for a secondary use for the char, and allows the heat release of char combustion within the reactor vessel. Inherent efficiencies are obvious, yet not enough data has been generated to analyze the efficiency derived from complete use of the char. Overall efficiencies claimed by the system developers show little difference in net energy produced.

Steam Gasification

There is at least one other direct-heated system. This system uses superheated steam for heat application within the refuse bed [4]. The reactor is actually a rotating autoclave using superheated

IA-54,722

Figure 6.2-1. Basic High Temperature Vertical Bed Pyrolysis Reactor

Figure 6.2-2. Typical Vertical Fluidized Bed Pyrolysis Reactor

steam (300 psi, 1100°F) for gasification of all the material, including the char fraction remaining after the other material is volatilized. The steam is heated externally, but the in-bed heat application and indigenous char volatilization classify this system as direct-fired.

6.2.1 Air-Fired, Direct-Heated Systems

While air-fired pyrolysis and starved air, modular incineration both use air to generate heat, there are fundamental differences between the two technologies which necessitate their separate evaluation. The principal intent of pyrolysis systems is to produce a low or medium-Btu gas which can be burned on-site or upgraded for off-site use. In contrast, starved air, modular incinerators are not designed or operated to produce a usable fuel product.

Air requirement in pyrolysis systems is only 10 percent of stoichiometric requirement. This low level is incorporated into the design to minimize combustion reactions and to produce a low-Btu off-gas. On the other hand, modular incinerators typically use 50 to 100 percent of stoichiometric air in the primary combustion chamber. Minimizing combustion reactions is not a concern, nor is the production of a usable fuel product. The air is used to control temperature in the primary combustion chamber.

6.2.1.1 Technology Description. The high temperature, air-fired system is essentially a blast furnace using extremely high temperature air (up to 3000°F) injected in the lowest portion of a vertical gasifier [5]. The refuse dries as it descends into the pyrolysis zone, then pyrolyzes, and the remaining portion is combusted with the hot air in the combustion zone. Oils formed during pyrolysis are cracked into lighter hydrocarbons that exit with product gas. The high temperature reduces the product residue to a molten slag, which is quenched to produce a black, glossy, sterile frit.

The vendor, Andco-Torrax, claims the system will drive off 90 percent of the available energy in the incoming refuse as gas exiting the gasifier. The air is preheated in regenerative towers, using either gas or oil, and recycled combustion heat. The preheated air exits both regenerative towers at about 2000°F. The preheat system is claimed to use 10 percent of the gas flow from the gasifier; the remaining 90 percent is directed to the energy-recovery waste heat boiler at 2100° to 2300°F, and exits the boiler at 550°F. Gas is exited to a conventional electrostatic precipitator.

Two other systems are a fluidized bed unit which volatilizes the organic fraction of the refuse and can be operated in a pyrolysis or combustion mode by varying inlet air rate, and a small-scale vertical bed reactor which receives refuse through a rotary air lock feeder on top of the shaft, and pyrolyzes the refuse into a hot gas, condensible oil, and a char. For the latter system, exit gases leave the vessel at about 400°F, and are cooled to 200°F in a scrubber-condenser particulate removal system. The system uses about seven percent stoichiometric air at the bottom of the vessel to create a continuous pyrolysis process.

6.2.1.2 Technology Status.

Technical

The high temperature, air-fired system has been developed at full-scale, and is either in operation or under construction in four locations in Europe. The system appears to be technically feasible and only requires system efficiency improvement. The use of supplementary fossil fuel at 0.1 MM Btu/ton is a drawback. Both fossil fuel usage and electrical consumption (80 kwh/ton) must be minimized.

The fluidized bed system has been tested and is ready for demonstration or commercial scale-up. Problems encountered are feed plugging, exit gas duct plugging from tars being transported, and general materials handling.

The vertical bed pyrolysis system has been tested and was ready for demonstration and introduction of sewage sludge, but funding could not be obtained. The future of simple, vertical bed, low temperature pyrolysis is uncertain.

Economic

The high temperature, air-fired system claims capital costs of \$19.80/ton (250 tpd) to \$11.50/ton (1500 tpd), and operating costs from \$16.60/ton (250 tpd) to \$9.40/ton (1500 tpd). Total plant costs range from \$36.40/ton to \$20.90/ton [5]. With an expected net steam production of 2.7 lb steam/lb refuse, revenues from steam sales are claimed to offset the cost significantly, reducing net disposal fees to \$8/ton (1500 tpd) up to \$23/ton. Experience with most large-scale energy recovery systems, particularly innovative technology, indicates that the tipping fee will be higher than initially estimated once the system is in full-scale operation.

The economics of the fluidized bed and the vertical shaft system are not yet sufficiently developed to assess, but are expected to be in line with the horizontal retort, indirect-fired unit costs (\$20,000 to \$40,000/ton of daily rated capacity, depending on size, and a proportional operating cost of \$7 to \$20/ton of material processed).

Environmental

There does not appear to be any significant environmental benefit from the high temperature system since state-of-the art air pollution control equipment must be used after combustion. The frit quench tanks will also require some treatment, although the requirements for cleaning frit quench water should be lower because of the sterile nature of the frit. The groundwater impacts from frit landfill, if frit cannot be sold, should be significantly less than from a standard combustion process residue.

There is not sufficient data to verify whether any environmental benefit can accrue from using this air-fired system. Although claims are made that the system can operate in compliance with current codes, and is reported to be doing so in Europe, its overall benefit is unknown. Some operational experience may provide concrete data for analysis of this system as well as for the systems whose descriptions follow.

At this time, insufficient data are available on air and water pollution, as well as on odors, noise and aesthetic degradation, to offer more than a qualitative discussion of benefits that could accrue from use of these systems. More technical operational data is required.

The environmental benefits of the fluidized bed are reduced velocity and volume of flue gas compared to stoichiometric firing, and reduced air pollution control requirements. The effect of a demonstration-scale fluidized bed pyrolyzer is unknown, but enough work has been done at the engineering level to indicate that the next scale will have some assurance of success.

The environmental benefits of the low temperature, vertical bed pyrolysis system are those inherent to pyrolysis. The fact that entrained particles can readily be scrubbed out of the gas stream by reusable process oils indicates that a rather clean gas product will result, and relatively clean combustion can be obtained.

6.2.1.3 Research Status. Research on the high temperature, air-fired system is continuing by the system developer. The goal is to reduce energy consumption in-plant. Each new design incorporates modifications for more efficient heat transfer in the regenerative towers. The system has great promise for unorthodox applications because of its use of air instead of pure oxygen, and its high temperatures. The system supplier currently has a contract with DOE to study possible thermal decomposition of transuranic, low level nuclear wastes.

The fluidized bed system has had significant engineering-level work, and has encouraged research into pyrolysis kinetics. The next step is demonstration-scale testing.

The vertical bed pyrolysis system requires exploration of methods for combined feed of refuse and sludge, variation of production of oil, gas and char; minimization of particulate carryover, allowable feedstock density, and modification of the oil scrubber and mechanical de-mister. Mechanical feeding problems were to be investigated by at least one supplier of this system.

6.2.1.4 Research Needs for Direct-Heated, Air-Fired Pyrolysis Systems. Research needs peculiar to direct-heated, air-fired systems follow.

- Improve feed mechanism for vertical bed systems. In high temperature systems, and in fluidized bed and vertical bed systems, there is an updraft of combustion and pyrolysis gases through the body of the descending refuse. It is necessary to plug the feed chute or feed device with a seal that will force the gases through the appropriate duct, all the while facilitating refuse infeed. Most system suppliers believe that the feed mechanisms they use are adequate but could use further refinement. Of particular interest is co-feeding of refuse and sludge. In discussing improvements, a suggestion emerged for pressurizing the vertical bed reactor greater than ambient. In that case, improvement of the vertical bed feed-lock mechanism becomes mandatory.

- Evaluate improved methods for handling entrained tars and particulates in fluidized bed systems. Fluidized bed systems experienced clogging and plugging of gas flow ducts by the tars and particulates agglomerating in the transfer lines and on the induced draft fan, which acts as a high-energy scrubber [6]. Tar is found in pyrolysis products as a vapor and a submicron-sized aerosol. These problems were overcome by moving the cyclone physically closer to

the reactor and maintaining temperatures of 800°F, and by using an oil-based scrubber. The scrubber may be replaced by an electrostatic precipitator. The experimental work in progress clearly illustrates the need for research into tar and particulate handling in all vertical bed systems.

Gas cleaning train improvement is needed, and various cyclone, scrubber, electrostatic precipitator and dry scrubber technologies should be examined. Cyclones, scrubbers, and electrostatic precipitators are well-established gas cleaning technologies. Dry scrubbers are new in concept, and employ a dry aluminum sulfate pellet (2 mm diameter) as the cleaning medium. The technology appears to be applicable to high temperature gases (2000°F range) and produces no sludge or wastewater. All pyrolysis systems need improved air pollution control systems, but particularly vertical and fluidized bed systems.

- Evaluate the effect of feedstock density on system performance. This R&D item should be investigated at the same time as the refuse-sludge handling and front-end processing items. Various feedstock densities affect both drying time and retention time in the pyrolysis chamber, and thus should be fine-tuned into the system. Feedstock densities also affect storage and feed systems, and their ability to accept various moisture levels in the sludge. The amount of sludge drying required may depend upon the feedstock density of the MSW. All these conditions can be optimized simultaneously, and will be applicable to various pyrolysis systems, but particularly to vertical bed systems.

- Determine maximum allowable moisture content when co-firing refuse and sewage sludge. Most systems require a moisture content less than or equal to 10 percent. However, modification of kiln configuration may allow higher levels of moisture.

6.2.2 Oxygen-Fired, Direct-Heated Systems

There has been one oxygen-fired unit, also vertical bed, that has received considerable attention -- the Purox system marketed by Union Carbide Corporation. This section concentrates on the development of Purox and the R&D areas that Union Carbide would like to explore next.

6.2.2.1 Technology Description. The heart of the Purox system is a vertical shaft furnace using three major zones in the reactor: a drying zone, a pyrolysis zone and a combustion zone (as shown in Figure 6.2-1). After front-end processing to a nominal 4 in. size, the refuse is introduced through a gravity feedlock mechanism, and descends through the vertical shaft. The refuse is dried to less than 10 percent moisture in the drying zone, and descends into the pyrolysis zone, where the combustible material is volatilized, with the exception of a char. The char and inerts then descend to the combustion zone where pure oxygen is injected at the bottom of the bed, causing high temperature combustion (3000°F). At this temperature, and with the introduction of the pure oxygen, nearly complete oxidation of the combustible fraction occurs. The inerts form a molten slag which is quenched and fractured into a fine, glassy frit that will not biodegrade any further.

The result is a low- to medium-Btu gas (about 300 Btu/scf) which, after cleaning, is ready for firing in an external combustion area. The plant requires a major supply of oxygen that can provide 0.2 lb O₂/lb. refuse fired. This usually means that an oxygen generating plant must be constructed adjacent to the Purox facility.

6.2.2.2 Technology Status.

Technical

The status of the Union Carbide technology is well-known in the resource recovery field. A 5-tpd facility was developed in Tarrytown, New York, in 1972. The facility was used to prove the

process, and subsequently a 200-tpd single reactor facility was built in South Charleston, West Virginia in 1975. Between 1975 and 1977, the facility clearly demonstrated that shredding is needed to eliminate voids in the refuse bed in the reactor, and also that technically, the oxygen-fired pyrolysis process works well. With some modification, the facility accomplished its design goals.

Economic

Up to this stage of development, Union Carbide is reported to have spent over \$10 million in internal research and development funds. Several proposals were submitted to various municipalities by the supplier, but the system was, for various reasons, (usually capital and operating cost) never selected. In Pinellas County, Florida, for example, the capital cost of a 1500-tpd facility was \$106 million, with a gross operating cost of over \$23.00/ton. Even so, Union Carbide has been the second choice in two recent proposals for municipalities in Florida. The company has run a 10-tpd pilot plant in Tonawanda, New York to test higher garbage fraction and higher moisture content refuse for design of a facility in Japan.

The company has temporarily retracted its marketing efforts while researching improvements in efficiency geared to reducing costs. Many of the R&D needs mentioned herein are being addressed under a \$1.4 million DOE grant to Dutchess County, New York, for study and preliminary design of a resource recovery system for that county. Union Carbide was a subcontractor to Charles O. Velzy Associates in the endeavor.

Environmental

The Purox system should be desirable to many communities. There are no tall stacks associated with the facility; the product is a clean fuel that can be fired without major changes to an existing facility. The frit residue has been seriously considered as an aggregate material for different construction applications, and

may be marketable. Even if it does not prove to be marketable, the frit residue could be used in landfill, and there should be a significant reduction in leachate potency from a frit landfill. Comparison of leachate from various landfills is a high-priority research need.

A detailed report on the environmental aspects of the Union Carbide Purox process, prepared for the U.S. Environmental Protection Agency by Midwest Research Institute, was released in November 1978 [7]. For this study, influent/effluent streams were sampled for an environmental impact assessment. The streams were: refuse; slag; scrubber water (river, scrubber effluent, and Unox waste-water treatment samples -- Unox is the trade name for Union Carbide's waste water treatment system); fuel gases (Purox and natural gas); and boiler stack effluent.

In regard to water effluents, the study concluded:

- Water discharged from the process will have to be treated, and phenols, total suspended solids (TSS), biochemical oxygen demand (BOD), dissolved oxygen (DO), and Cl may be of special concern. Certain metals (Pb, Fe, Mn, Zn, and Ba) may also be of concern.
- Unox treatment of water reduces most organics that will be of concern in the water effluent, but phenols may still be a problem.
- No pesticides were detected in the scrubber effluent.
- Analysis of water samples indicated predominance of polar organic compounds, leading to a suspicion that nonpolar organics may have been adsorbed by the char.

In regard to boiler stack gas emissions, the study concluded:

- Boiler stack emissions of HC and CO are low.
- NO_x and SO₂ emissions are higher when burning Purox gas than when burning natural gas, but SO₂ emissions are still low. The reasons for increased NO_x emissions when burning Purox gas should be investigated.
- Hg and Cl concentrations in the boiler stack are higher when burning Purox gas, but not to an extent that would cause environmental concern.
- Particulate emissions from the boiler are low when it is fired with Purox gas, and most particles are less than 1 micrometer in size.
- Polynuclear aromatic hydrocarbon (PAH) levels in the boiler stack emissions are generally low compared to conventional combustion sources.

6.2.2.3 Research Status. The technology status and research status of oxygen-fired, direct-heated systems go hand in hand. The research that should result from the Dutchess County work has already been explained. In addition, however, Union Carbide has identified certain items that may bear further exploration.

6.2.2.4 Research Needs for Oxygen-Fired, Direct-Heated Systems. Research needs associated with this system are listed below. Union Carbide indicates that most of these research needs either have been or will be addressed adequately in the Dutchess County work.

- Evaluate more economical methods of refuse infeed both for the present system (atmospheric pressure conditions) and for the reactor operating as a pressure vessel.

- Evaluate the effect of the degree of front-end processing on system performance. The question to be resolved is the maximum allowable particle size that would still provide a relatively homogeneous bed condition. Particle sizes from nominal 2 in. to over 12 in. should be examined. If a larger particle size could be used, 50 percent of the shredding cost could be saved, or about \$1/ton.

- Evaluate the advantages to be gained from operating the reactor at about 30 to 40 psi, instead of at atmospheric pressure. An elevated pressure could reduce both gas cleaning costs and compressor costs associated with gas delivery to the customer.

- Evaluate alternative methods of gas cleaning to reduce pressure drop and velocity of gas for increased efficiency of transport to users.

- Evaluate conditions for treatment of the wastewater which is condensed out of the gas stream. The wastewater has an extremely high BOD concentration. One new contemplated treatment may be a contained treatment plant using activated carbon. Other possibilities include area planning to incorporate Purox effluent into the anticipated loadings on a new secondary-level sewage treatment plant that may be planned or in the design stage.

Further investigation of the above work could be considered valid, particularly in the area of gas cleaning and elevated pressure reactor operation. These two particular research needs are generic to pyrolysis systems and would thus provide useful information to many system developers.

6.2.3 Steam Direct-Heated Systems

As explained in the introduction to direct-heated processes, this system uses steam generated in a boiler outside the reactor vessel. The vessel uses superheated steam injected into the refuse bed, which gasifies all but the inert components of the refuse. This system is promising because its design allows it to accept sewage sludge readily, without the need to pre-dry the sludge in an external dryer.

6.2.3.1 Technology Description. This technology injects superheated steam directly into the refuse bed in a pressure vessel, essentially a rotating autoclave, which gasifies all waste. The product liquids and tars steam-reform into additional gas, and the char is apparently subjected to steam gasification in the presence of a catalyst, sodium carbonate, yielding an additional gasified product.

The steam-laden, hot fuel gas is then routed under pressure to a combustion chamber where the gases are combusted and channeled (1980°F) through a regenerative cycle, gas/steam turbine that drives the compressor to feed combustion air to the combustion chamber, as well as to produce electricity. The spent flue gases are then channeled through a heat exchanger, where feedwater for the autoclave is heated to 900°F, and the cooled flue gases (250°F) are vented to the atmosphere through a stack. The steam generated in the heat exchanger is then channeled through a superheater (fired by pyrolytic gas) that superheats the steam and raises the temperature to 1200°F for introduction into the autoclave at 1100°F. Steam exiting the autoclave is channeled through a sludge preheater to assist gasification in the reactor. The system is designed for maximum reuse of heat wherever possible.

6.2.3.2 Technology Status. Steam direct-heated systems tested to this point have been at the bench-scale stage of development. The Wright-Malta Corp. of Ballston Spa, New York has conducted the

steam gasification testing described above. The work has been promising in that the wet system may be more readily adaptable to sludge. Also the catalyst used for char gasification may assist in scrubbing sulfur dioxide from the flue gases, yielding another environmental benefit.

Technical

A normal run of this autoclave consists of 10 lb. of coarsely shredded solid waste, two gallons of sludge and 1/2 lb. of sodium carbonate. Reaction time is on the order of one hour for PCB destruction and somewhat less for other material.

Steam gasification has also been performed in a biogasifier, using an auger for material transport. Temperatures vary from 100°F at the feed end to 1200°F at the discharge end.

Economic

At the bench-scale level, little information on the economics of a large-scale system is available. There are items consumed by the system, such as the sodium carbonate catalyst, which apparently amounts to five percent of the refuse feed by weight. Also, experience with the CPU-400 system tested by Combustion Power Company of Menlo Park, California attributed part of the system failure to fouling of the gas turbine/compressor by entrained particulates from the high pressure, fluidized bed reactor. The combustion gases were channeled through three separators before entering the turbine, and still severe turbine fouling occurred quickly.

The proposed steam gasification system does not show any gas cleaning train either before or after the combustion chamber prior to introduction to the steam/gas turbine. Based on the CPU-400 testing, turbine fouling is potentially a major problem with this system.

Environmental

Little entrainment of particulates is anticipated because of high humidity, relatively low gas velocity, and a gentle tumbling action of the refuse in the gasifier. The system has been operated at a scale too preliminary to project any real data on emissions.

The power plant does not require cooling water, nor processing of any liquid effluent. The expectation is for clean stack gases with minimal NO_x emission, because of lower combustion temperatures (reportedly 600°F cooler than normal combustion of hydrogen gas), due to the presence of steam. Chlorine is thought to be captured by the alkaline catalyst. The particulates must be contained to prevent turbine fouling.

It should be noted, however, that there is no provision for cleaning the gases. Previous experience with large systems (South Charleston, West Virginia, and Baltimore, Maryland) and the CPU-400 fluidized bed system has shown gas cleaning to be essential to system operation. In the CPU-400 system, even with three separators in series, the entrained particulates fouled the turbine. It appears that the system could require a gas cleaning function, which, depending on the technology chosen, could involve an effluent requiring treatment or disposal. The technology development stage -- the current level of this technology -- does not lend itself readily to determination of this need.

6.2.3.3 Research Status. Because the steam direct-heated system is still in the bench-scale development stage, its technology status and research status are interlocked. The system has great promise because of its ready adaptability to the introduction of sewage sludge. Provided the sludge is brought up to temperature, there is no need for the drying process that all other pyrolysis systems require. The presence of metals in the sludge raises the possibility of metallic aerosols becoming entrained and fouling the turbine. The current scale of development is too low to determine if these are valid concerns.

6.2.3.4 Research Needs for Steam Direct-Heated Systems. This system requires scale-up to the next level of normal development, which is the pilot plant stage. Only by scale-up to a pilot plant, and then to the demonstration phase, can the applicability of this system be tested, and the costs associated with its unique operating characteristics be assessed. Research needs are as follows:

- Evaluate different reactor vessel configurations to minimize steam/gas flow. The reactor vessel is essentially a rotating kiln with sealed ends which creates an autoclave and allows the system to run in its elevated pressure state of 300 psi. Volatilization and exit gas flow take place as a function of the quantity and pressure of the injected steam. The reactor has been designed as a pressure vessel, but no relationships among length, diameter, pitch, skin material, rotational speed and characteristic of infeed material have been established.

- Evaluate particulate entrainment levels. Nothing is known about particulate entrainment under various conditions of operation, or what the appropriate particulate level might be. Increasing the scale to the engineering development level may be required before any substantial data can be taken. Research into the appropriate types of air pollution control equipment is implicit in determining the allowable particulate level.

- Evaluate metallic aerosols concentrations in combustion gases. There has been no opportunity to study volatilization of sewage sludge, with resultant metallic aerosols, that may be a problem both within the system and as effluents. The following heavy metals concentrations (ppm) have been found: An - 228 to 6430; Cd - 0.6 to 970; Cu - 240 to 3490; Ni - 10 to 1260; and Pb - 52 to 4900 [8]. The implications and extent of volatilization and entrainment in this high temperature system are unknown.

- Evaluate gas/steam turbine design to optimize system. Presently, turbines are usually powered by either gas or steam, and there are many different designs for the particular gas application. In this case, the turbine is partially driven by the relatively high pressure steam which was used for volatilization, as well as by combustion gases resulting from oxidation of the volatile fraction and steam-gasified char. There appears to be no precedent for this particular turbine application, and extensive research and unique blade design (either in configuration or metallurgy) is anticipated.

- Determine sludge preheater location. As stated previously, the optimum location of the sludge preheater (in order to avail itself of maximum heat from the turbine, as well as minimum transport of heated sludge) is not known. There appears to be an optimum placement of equipment, which will depend on equipment size and allowable transport lines.

6.3 Other Systems

6.3.1 Description

There are several other pyrolysis systems in various stages of development, each based on the same concept as one of the systems previously described. One system in particular, a rotary-kiln, developed by Watson Energy Systems, Inc, utilizes several innovative applications of technology.

This 2,000-tpd rotary kiln process has been developed in California, and was scheduled for construction starting in June, 1979, with shakedown in June, 1981. The rotary kiln system acts as a large-scale, starved-air combustor. Refuse is front-end separated and shredded in a hot gas grinder, which acts as a combination shredder and dryer. The light fraction (60 percent) is pneumatically transported to storage; the heavy fraction (40 percent) is screened and separated. An unspecified quantity of heavy combustible material is recombined with the light fraction and fed into one

end of an inclined rotary kiln. The refuse progresses down approximately one third of the kiln's 96-foot length, where heated combustion air is added to the system and the material which has been volatilized is combusted together with the remaining material.

The hot combustion gases (2000°F) are channeled through a boiler, economizer and gas/air cooler. The boiler and economizer generate process steam for sale to a customer, reportedly Atlantic Richfield. The gas/air cooler cools gases for routing to the air pollution control equipment, and some of the cooled combustion gases are routed back through the shredder/dryer. The gases assist in drying the material in the shredding step, and act as an oxygen-free purge, thereby negating any oxygen-supported shredder explosions. The remainder of the flue gases are channeled through a bag house, I.D. fan, and water scrubber for secondary gas cleanup.

This application of pyrolysis mixes new ideas with proven technology. Although similar in many ways to the Baltimore City Landgard system -- including the rotary kiln afterburner --this system offers the advantages of concurrent gas flow, a more rigid kiln, and a more readily controlled combustion atmosphere. Several new ideas, such as shredder purge with flue gas, are interesting and could offer significant advancement to the state-of-the-art. Much of the technology has been tried before, however, and it is hoped this system will incorporate tried technology with the required evolutionary equipment changes. Two reputable engineering firms have reviewed the concept independently and found it to be technically sound.

At a rather ambitious 2000-tpd scale, many components of the system will be new and will be tried for the first time. The supplier will be performing research and development continuously on almost all system components, but has expressed little interest in any Federal participation.

Most research needs, other than the esoteric requirements of the particular system, have been identified under one or more of the pyrolysis systems analyzed earlier in this section.

6.4 Additional Uses for Pyrolytic Products

6.4.1 General

Considerable attention has been given to end-uses for pyrolysis products other than combustion -- either on- or off-site. Upgrading Purox gas (Union Carbide) into pipeline-quality gas, and transforming Purox gas into alcohol fuels, ammonia, and fertilizer have all been investigated. The City of Seattle considered the option of fertilizer production, but found the project unfeasible without a floor price guarantee for the fertilizer product.

Several proposals and studies have indicated that the capital cost of such a facility is in the range of \$70,000 to \$100,000/ton of daily rated capacity, depending on size and equipment redundancy. The relationship between tpd capacity and capital costs appears to be nearly linear, which indicates that product gas synthesis into other commodities is an extremely costly operation.

Recent work sponsored by EPA [9] has examined properties and composition of pyrolytic oil. Results indicate that the oil contains significant quantities of many valuable organic chemicals such as eugenol, isoeugenol and guaiacol. These results point out the possible potential for recovering chemicals from the oil rather than burning it as a replacement for fossil fuel. However, the economics of such a recovery process are unknown.

6.4.2 Application to This Analysis

Past pyrolysis product markets and technologies are not considered as a short-term R&D need because of the embryonic stage of pyrolysis in solid waste processing. The technology for producing useful products should be explored and evaluated first to see if the product can be produced with consistency by several systems. If

that is found to be the case, then application of a downstream technology for product optimization should be studied. It is conceivable that the market price of some of the secondary products may escalate to a point where the capital and operating costs are offset.

6.5 Summary of Pyrolysis Research Needs

Table 6.5-I presents a summary of technical research needs for pyrolysis. The research needs are divided into those that are applicable to pyrolysis systems in general, and those that are specific to indirect-heated and direct-heated systems. The research needs that are applicable to pyrolysis in general are discussed below.

6.5.1 Research Needs Applicable to Pyrolysis in General

- Survey all pyrolysis systems to determine the most promising systems for future work.

- Evaluate front-end processing trains specifically designed for pyrolysis. Front-end processing is required for almost all systems to reduce nominal particle size to less than 2 in. The most important requirement is complete removal of glass from the feed material. Elimination of glass abrasion, slagging and plugging would benefit all pyrolysis system suppliers and designers.

- Optimize design of air feedlock mechanism for both vertical gravity feed and ram feeder mechanisms. One of many problems experienced at the Baltimore Landgard facility was ram feeder jamming. The ram feeder was designed as an air feedlock, but continually jammed when high throughput rates (40 tons per hour range) were attempted. There is reason to doubt high rate operational performance of both vertical and ram feeder mechanisms. Since almost all pyrolysis systems require an air feedlock, these mechanisms should be tested extensively.

Table 6.5-I

Technical Research Needs for Pyrolysis

General

- Survey all pyrolysis systems to determine the most promising systems for future work. /
- Evaluate front-end processing trains specifically designed for pyrolysis.
- Optimize design of air feedlock mechanisms for both vertical gravity feed and ram feeder mechanisms.
- Evaluate various firing configurations for pyrolytic oil.
- Evaluate the cost of combined cycle, gas/steam turbine systems for electric power generation using pyrolysis gas.
- Conduct preliminary economic analyses of pyrolysis end-product conversion technologies.

Indirect-Heated

- Evaluate different heat-conducting materials for use in kilns or externally heated equipment.
- Evaluate char handling systems and char furnace design, including a char/ash separation system.
- Develop uses for product char.
- Evaluate improved kiln configuration designs.

Direct-Heated Systems

Air-Fired

- Improve feed mechanism for vertical bed systems.

Table 6.5-I (concluded)

- Evaluate improved methods for handling entrained tars and particulates in fluidized bed systems.
- Evaluate the effect of feedstock density on system performance.
- Determine maximum allowable moisture content of feed when co-firing refuse and sewage sludge.

Oxygen-Fired

- Evaluate more economical methods of refuse infeed.
- Evaluate the effect of the degree of front-end processing on system performance.
- Evaluate operation at elevated pressure (40 psig).
- Evaluate alternative methods of gas cleaning to reduce pressure drop and velocity of gas.
- Evaluate conditions for wastewater treatment.

Steam-Heated

- Evaluate different reactor vessel configurations to minimize steam/gas flow.
- Evaluate particulate entrainment levels.
- Evaluate metallic aerosol concentrations in the combustion gases.
- Evaluate gas/steam turbine design to optimize system.
- Determine sludge preheater location.

- Evaluate various firing configurations for pyrolytic oil.

Factors such as nozzle size, angle, the number of nozzles in a combustion area, gas swirl, and vortex burning have not been adequately investigated for use with pyrolytic oils of variable consistencies. Oil tests should analyze consistency and day-to-day stability versus time and varying static head conditions.

- Evaluate the cost of combined cycle, gas/steam turbine systems for electric power generation using pyrolysis gas. However, it is premature to address this research need until the technologies progress beyond the embryo stage of development.

6.6 Pyrolysis Research Program

The recommended research program for accelerating development and implementation of pyrolysis systems is directed at evaluation of technologies which have not reached the demonstration stage. The oxygen-fired, direct-heated Purox system is not included in this program, because the research needs of the system are presently being addressed by DOE in the demonstration grant to Dutchess County, New York.

For the pyrolysis research program, a technical and economic evaluation of indirect- and direct-heated pyrolysis systems should first be conducted. This analysis would only address systems which are not at demonstration stage. As a result of this analysis, one or two candidate systems should be selected for pilot plant evaluation. If not already available, pilot plants at 10 to 20 percent of full-scale module capacity should be constructed and experimental programs should be conducted that are consistent with the previously listed research needs. A schedule for completing this program is presented in Table 6.6-I. Cost of this three year program would be approximately \$2 million.

When the above program is completed, one system could be selected as a demonstration project, taking advantage of loan guarantees and/or price supports if necessary.

Table 6.6-I

Schedule for Pilot-Scale Evaluation of Pyrolysis Systems

<u>Work Item</u>	<u>Time</u>
Technical and Economic Evaluation	3 months
Selection of one or two candidate systems	1 month
Conceptual design of pilot plant(s)	2 months
Design of pilot plant(s)	3 months
Construction	9 months
Start-up	1 month
Testing of various components, data collection and analysis	6-18 months
TOTAL	25-37 months

NOTE: The evaluation only applies to technologies which have not reached the demonstration stage. Total pilot plant design and construction may not be required if equipment exists.

As a result of the present DOE demonstration grant to Dutchess County, New York, the Purox system may realize its first commercial operation. However, DOE loan guarantees and/or price supports may be necessary to make the system competitive with other technologies.

Only when pyrolysis processes advance to the demonstration stage should end-product conversion technologies be investigated. Such evaluations on upgrading and converting Purox gas have already been conducted. Investigations on pyrolytic oil are premature until the producing technologies are more fully developed.

REFERENCES: SECTION 6 PYROLYSIS SYSTEMS

1. "Environmental Assessment of Waste-to-Energy Process, Final Report, Union Carbide Purox System", Midwest Research Institute, for Industrial Environmental Research Laboratory of the U.S. Environmental Protection Agency, November, 1978.
2. "Municipal Refuse Disposal", APWA Institute for Solid Wastes, 1970.
3. M. D. Bowen, et al., "A Vertical Bed Pyrolysis System", presented at the symposium sponsored by the Division of Environmental Chemistry, 175th Meeting of the American Chemical Society, Anaheim, California, March, 1978.
4. J. A. Coffman, and R. H. Hooverman, "Power from Wastes via Steam Gasification", presented at a symposium sponsored by the Division of Environmental Chemistry, 175th Meeting of the American Chemical Society, Anaheim, California, March, 1978.
5. P. E. Davidson, and T. W. Lucas, "The Andco-Torrax High-Temperature Slagging Pyrolysis System", presented at a symposium sponsored by the Division of Environmental Chemistry, 175th Meeting of the American Chemical Society, Anaheim, California, March, 1978.
6. "Pilot Scale Pyrolytic Conversion of Mixed Wastes to Fuel, Volume 1", Energy Resources Company, Inc. for the U.S. Environmental Protection Agency, March, 1977.
7. "Lantz Converters for the Conversion of Combustible Material to Charcoal and Gas", Pan American Resources, Inc., unpublished report, 1978.
8. K. L. Chaney, S. B. Hornick and R. W. Simon, "Heavy Metal Relationship During Land Utilization of Sewage Sludge in the Northeast", U.S. Department of Agriculture, Agricultural Research Service, Biological Waste Management and Soil Nitrogen Laboratory, Beltsville, MD, 1976.

9. M. B. Polk, and M. Phingbodhipakkiya, "Stabilization and Characterization of Pyrolytic Oils". Presented at the U.S. EPA Solid and Hazardous Waste Research Division, Fifth Annual Research Symposium, Orlando, Florida, March 26-28, 1979.

SECTION 7

BIOCONVERSION PROCESSES

Biological processing techniques can be utilized in a variety of ways to convert the organic fraction of municipal solid waste to useful forms of energy and to recover materials in a manner which conserves fuels and energy. Bioconversion processing can be carried out using techniques which are inherently low in capital cost. On the other hand, quite sophisticated processing systems can be developed which accelerate the process and improve the yield. To provide a proper framework for the evaluation of bioconversion processes, technologies for the production of methane, alcohol, organic chemicals, and alkane were examined. Pretreatment technologies that improve the processibility of MSW and aid in the bioconversion processes were evaluated.

Conventional and novel methods of anaerobic digestion for methane production are discussed along with methane recovery from existing and enhanced landfills. Upgrading these gases to pipeline quality is also addressed. Alcohol production from both enzymatic and acid hydrolysis are considered, and novel methods of acetic acid, alkane, and other chemical production are described.

7.1 Pretreatment Technology

Municipal solid waste in its as-received form is a heterogeneous mixture of materials, only a fraction of which is potentially convertible to fuels and chemicals by biological means. The following sections address pretreatment technologies which may be used to accelerate and/or improve the yield of bioconversion processes.

7.1.1 Physical Pretreatment

7.1.1.1 Technology Status. Size reduction and physical separation of inorganic material are two important unit operations which impact the economics of most bioconversion processes. Municipal waste is typically non-homogeneous and is comprised of material

which is potentially two-thirds biodegradable and one-third inert on a solid basis. Separation of these inert materials from the feedstock can have significant benefits to the bioconversion process from the standpoint of energy consumption and capital and operating costs. Most mechanized separation processes require some degree of size reduction to break down the raw waste into its constituent parts. Further, size reduction has been shown to impact upon the biological process itself. Physical pretreatment is estimated to comprise 25 percent of the capital cost and 25 percent of the energy consumption of an anaerobic digestion facility. Physical pretreatment is essential to some bioconversion processes. In other cases, it can serve to enhance the process. In any event, physical pretreatment can have a significant impact upon the feasibility of bioconversion systems.

Size reduction serves several important roles in biological conversion processes. Among these are:

- Increased bulk density, reducing volume-related costs
- Increased biological conversion efficiencies, as a result of increased surface area, improved mixing, etc.
- Improved material handling characteristics (conveying, pumping, mixing, etc.)
- Improved separation efficiencies, reducing throughput related costs
- Improved plant operating factor.

Size reduction is common to most resource recovery systems, and the technology status has been previously addressed under Preprocessing.

Likewise, the efficiency of separation equipment can have a dramatic effect on the economics of biological conversion systems. By improving the separation of inorganics from the feedstock, one may:

- Reduce digester volume,
- Reduce pumping, mixing, and heating requirements,

- Reduce dewatering requirements,
- Reduce disposal costs,
- Reduce maintenance costs, increase equipment life.

The parametric sensitivity study carried out for the National Science Foundation on anaerobic digestion of MSW [1] showed that the separation efficiency of the pretreatment equipment was the most important processing performance variable to be considered.

7.1.1.2 Research Status. There are two key factors to be addressed with respect to size reduction, separation efficiency, and biological processing: the relationship between particle size and hydrolysis rate or solubilization, and the amount of size reduction and separation necessary to facilitate material handling/mixing of solid waste slurries in pipes and tanks. Several investigators are addressing aspects of these problems. The U.S. Army Natick Research Labs, among others, has shown that significant increases in available surface area, such as that achieved through ball milling, can enhance hydrolysis of cellulose. Waste Management, Inc., is investigating the effect of particle size and separation efficiency on material handling and mixing systems at the Pompano Beach pilot facility. The Institute of Gas Technology has evaluated the effect of particle size on methane production in conventional digestion.

7.1.1.3 Research Needs for Physical Pretreatment. It is evident from start-up problems encountered at Pompano Beach and at Recovery I in New Orleans, among other places, that although equipment is commercially available, sufficient operating experience has not been attained to permit confident design and prediction of operating performance of the size reduction and separation equipment.

The preliminary data available to date suggests that some degree of size reduction is desirable for most biological processes. The cost-effectiveness of various degrees of size reduction and separation efficiency for each type of biological process is not

well-known. Because of the high cost and energy requirements for size reduction, it is important that the planned experiments of Waste Management be carried out.

Research needs for physical pretreatment as it relates to bioconversion processes are as follows:

- Evaluate effect of dry and wet preprocessing of MSW on digester performance. Most bioconversion technologies require the solid waste to be in slurry form prior to biological attack. There may be advantages to hydropulped RDF versus dry RDF in terms of biodegradability and required residence time.

- Evaluate improved concepts for size reduction and separation that enhance biological processes. Most physical size reduction unit processes are, as the name implies, directed solely at reducing particle size of the MSW with no consideration of the effect on biodegradability. Development of new size reduction concepts should be encouraged as they relate to improving bioconversion of the organic fraction of the waste. These new concepts should reduce energy requirements and costs associated with available hardware, enhance biological activity, and improve mechanical operation. For example, roll milling should be investigated for enhancement of enzymatic hydrolysis.

- Evaluate extent of MSW preprocessing necessary for good slurry mixing. Results of tests at the Franklin, Ohio and Pompano Beach, Florida anaerobic digesters have indicated that slurrying and mixing RDF in a digester is a difficult task with severe operational problems in terms of matting on the surface, and stringers binding the shaft and impeller. Mixing of different RDF slurries (type and size of RDF versus percent solids) needs to be examined to determine what MSW preprocessing is required in order to achieve acceptable mixing.

7.1.1.4 Research Program for Physical Pretreatment. Despite research efforts at Franklin, Ohio and Pompano Beach, Florida, mixing of RDF slurries still remains a significant operational problem. While the experimental program at Pompano Beach is continuing, pilot-scale investigation of RDF slurry mixing should be pursued. Factors such as RDF size, RDF shape, impeller and reactor baffle design, shaft speed, and percent slurry solids should be examined. Prior to the study, a critical analysis of the Franklin, Ohio and Pompano Beach data should be conducted. Results of this pilot study could then be incorporated into the Pompano Beach program. This mixing study will cost about \$75,000 to \$125,000, with a duration of about 8 to 12 months.

The advantages of using a wet-pulped RDF versus a dry RDF as a feedstock to bioconversion processes needs to be examined. This should be a bench-scale study to determine the potential operational advantage of using a wet-pulped RDF as a feedstock for anaerobic digestion or hydrolysis processes. This study should be relatively low cost, i.e., about \$50,000, with a relatively short duration of about six months.

7.1.2 Alkali Pretreatment

7.1.2.1 Process Description. Alkali pretreatment may be employed before digestion to increase digestibility of lignocellulosic materials. The process involves soaking the substrate in a dilute solution (0.5 to two percent) of alkali at elevated temperatures (up to 480°F). Although sodium hydroxide is the most commonly used alkali, other alkalis such as gaseous and aqueous ammonia, sodium aluminate and ammonium bisulfate have also been effective in increasing digestibility, depending on the chemical composition of the feedstock and the type of reaction required.

7.1.2.2 Technology and Research Status. It is known that the mechanism by which alkali pretreatment increases digestibility involves a swelling of the substrate resulting in an increase in the

size of pore spaces. Lignin is solubilized to hydroxylated aromatics (phenols), thus isolating the carbohydrate fraction and allowing greater accessibility of enzymes. Elevated temperature and pressure aid in breaking down chemical bonds to yield a product which is more susceptible to hydrolytic activity during anaerobic digestion.

The value of alkali pretreatment before digestion is well-documented on a bench scale. Bioconversion rates have been reported from 15 percent [2] to 85 percent [3] greater for alkaline treated materials than for untreated materials digested in rumen fluid at 86°F or less. The degree of conversion efficiency depends upon the composition of the material being digested, but there seems to be an ultimate ceiling for digestion of alkaline-treated cellulose between 70 and 90 percent.

Research at Stanford University [4] on the biodegradability of chemical-heat-treated municipal refuse showed that peak biodegradability, measured by gas production, increased significantly at pH 13 and pH 1, progressively decreasing as the pH approached neutral. Biodegradability was greatest at pH 13 (392°F), reaching a maximum gas production of 151 ml STP gas/gCOD (volume of gas at standard conditions per gram of carbonaceous oxygen demand). These results were obtained from experiments on pretreated shredded municipal refuse at temperatures ranging from 77°F to 480°F and from pH 1 to pH 13. Maximum solubilization of organics was achieved with pH 13 pretreatment at 480°F. McCarty et al. [5] demonstrated that heat pretreatment of newspaper under alkaline conditions increased bioconversion to methane from 25 percent up to 47 percent. They predicted that the increased convertibility would reduce the weight of solids requiring subsequent disposal by about 30 percent. Some of the soluble products formed in McCarty's alkaline-heat treatment studies were found to be inhibitory to methane production. The inhibition occurred when the concentration of solubilized lignin (or phenolic residues) exceeded 1 to 2 g/l.

Economics

The economics of adding alkali pretreatment to anaerobic digestion have not been adequately determined for municipal refuse. An earlier evaluation [6] of municipal refuse indicated that the cost of methane would have to rise to \$4.00/MCF before alkali pretreatment would be economically attractive. Present residential retail price of natural gas is about \$3.50 to \$4.50/MCF, including fuel adjustment. Ensuing experimental work has led to identification of more attractive process operating conditions which should be evaluated in detail.

7.1.2.3 Research Needs for Alkali Pretreatment. The results of bench-scale experiments have indicated that alkali pretreatment at elevated temperature and pressure is an effective method to increase digestibility of urban refuse. An engineering investigation of alkali pretreatment is now needed to develop and evaluate design concepts for its use on a commercial scale. Research needs are as follows:

- Develop and evaluate design concepts for alkali pretreatment to determine cost-effective means of achieving high methane yields. Conceptual designs and preliminary engineering need to be developed for alkali pretreatment. The cost of this pretreatment should be compared with the potential increase in methane yield. Alternative, low cost sources of alkali also must be examined.

- Determine on a bench-scale the degree of lignin removal necessary for maximum production of methane with minimum phenol inhibition.

7.1.2.4 Research Program for Alkali Pretreatment. The primary work that needs to be done on alkali pretreatment is a conceptual process design with preliminary engineering and subsequent estimation of process capital and operating costs. This added cost then

should be compared with the increase in revenues associated with improved methane yield. This is a low cost paper study, i.e., \$25,000, with a four month duration.

Results of the above paper study should indicate the economic feasibility of alkali pretreatment. If results are favorable, bench-scale studies should be conducted to determine the degree of lignin removal necessary for maximum production of methane with minimal phenol inhibition. Cost of the study should initially be limited to about \$60,000, with a four month duration.

7.1.3 Temperature and Pressure Pretreatment

7.1.3.1 Process Description. By subjecting cellulosic materials to high and low temperatures, chemical bonds may be broken to yield a product which is more easily susceptible to hydrolytic activity during anaerobic digestion. High temperature pretreatment may be employed to increase digestibility by boiling or steaming at temperatures up to 480°F. Low temperature pretreatment employs repeated cycles of freezing and thawing of organic materials in water suspension to reduce both strength and degree of polymerization.

Pressure pretreatment is usually reported in conjunction with thermal pretreatment and hence, it is difficult to determine the magnitude of pressure-induced increases in biodegradability. A few reports of materials subjected to pressure treatment without thermal treatment have suggested that pressure plays an important role in the degradation process, however, presumably because of mass transfer augmentation.

7.1.3.2 Technology and Research Status. Bench-scale research on high temperature pretreatment has been conducted by boiling urban refuse [7-11] and by steaming other lignocellulosic substrates including straw [12-14] and wood [15-18]. The results indicated that the biodegradability of lignocellulosic materials increased with increased temperature to a maximum at 392°F. Treatment at a higher

temperature resulted in a decrease in biodegradability, presumably through the polymerization of heat treatment products and formation of humic materials.

Temperature and pressure pretreatment also is being studied as a method to shred refuse. In the process developed by Burke, Davoud, & Associates, unshredded municipal refuse is put into an 11 in. diameter cannon and subjected to steam treatment at 480°F and elevated pressure. When the door to the cannon is rapidly opened, the pressure is released and the municipal refuse explodes into small, puffed particles. Equipment to separate the puffed material has not yet been developed. Preliminary economic evaluations of this "steam gun" process compare favorably with shredding [19], according to its developers. Of particular significance to bio-conversion processing, the process appears to saccharize the cellulose, suggesting that improved biodegradability may result.

7.1.3.3 Research Needs for Temperature and Pressure Pretreatment. Research needs for temperature and pressure pretreatment are as follows:

- Conduct conceptual design and economic analyses on the "steam gun". Based on existing pilot-scale data, a conceptual design of a commercial-scale facility should be performed. The economics of this system should then be projected and independently reviewed.

- Evaluate the economic benefit of temperature pretreatment for improving methane yield. Based on bench-scale data, the economics of temperature pretreatment as a method of enhancing methane yield should be estimated.

7.1.3.4 Research Program for Temperature and Pressure Pretreatment. The near-term research program for temperature and pressure pretreatment centers on economic evaluation of present research

results. Of primary concern, a conceptual design for a commercial-scale "steam gun" should be developed. The capital and operating cost requirement of this unit operation should then be estimated and compared with a shredder that would produce approximately the same particle size reduction. The economic analysis should be reviewed by an independent party. If the results of the analysis appear favorable for the "steam gun", a bench-scale evaluation of the RDF product should be conducted to determine if biodegradability is enhanced. The conceptual design and economic analysis can be conducted for about \$30,000, including an independent economic review, and the study can be completed in about three months.

Temperature pretreatment has been experimented with on a bench-scale. A paper study needs to be conducted to assess the economic feasibility of temperature pretreatment as a method of enhancing methane yield. This study would develop order-of-magnitude estimates of temperature pretreatment capital and operating costs based on a simplified process design. This would be a low cost study, i.e., about \$15,000, with a two month duration. Analyses should likely be based on steaming the refuse rather than boiling in water as has previously been tested. Results of the study may warrant further bench-scale testing.

7.1.4 Acid Pretreatment

7.1.4.1 Process Description. Acid pretreatment is an effective method to hydrolyze the cellulose in lignocellulosic materials into simple sugars, leaving the lignin portion largely unaffected. Typically, the acid pretreatment process involves soaking the material in dilute mineral acid (e.g., 0.4 percent to 0.6 percent hydrochloric or sulfuric) at elevated temperature (466-500°F). The process must be closely controlled to prevent caramelizing of the cellulose, rendering it unsuitable for digestion. Further, since bacteria are inhibited by low pH, neutralization of the hydrolyzate is necessary before introduction into the digester.

A variation on acid pretreatment involves exposure of the lignocellulosic material to gaseous sulfur dioxide. Sulfur dioxide pretreatment breaks down the lignocellulosic complex into its constituent parts without altering either component significantly. Typically, the organic material is slurried in water and subject to initial sulfur dioxide treatment at 30 psi, 70°F followed by treatment at 250°F for several hours. After blowdown, the treated material may be neutralized with sodium hydroxide. This process is commonly used as a pretreatment for wood chips.

A more recent process development may be called autohydrolysis. Again based on pulp and paper technology, aqueous slurries of lignocellulosic material are subjected to air oxidation at temperatures from 320 to 420°F and pressures from 225 to 500 psig in staged reactors producing organic acids. A portion of this product is then recycled to promote hydrolysis in the first stage of the reactor [20-23]. Other processing concepts have somewhat more severe conditions (360 to 1110°F) [24-26]. In either case, the organic acids produced appear to be well-suited for anaerobic digestion to methane. Significantly, these processes do not appear to require the high corrosion-resistant materials of construction required for conventional acid pretreatment or the chemicals envisioned for acid and alkali pretreatment.

7.1.4.2 Technology and Research Status. Acid pretreatment followed by neutralization may be an effective method to increase conversion of cellulose to glucose, although it is presently not generally considered when methane is the desired end product. Because the process is selective in breaking down only the cellulose to sugars, it is often considered in ethanol production. An evaluation of methane yields resulting from pretreatments ranging from pH 1 to pH 13, however, favored alkali pretreatment [5]. Alkali pretreatment can also be carried out with less corrosion-resistant equipment and with less concern for process control than can acid pretreatment.

Gaseous sulfur dioxide pretreatment has been successfully used to increase the digestibility of lignocellulosic materials other than urban refuse. (There is no known experience with the latter, although it has been proposed.) At the U.S. Forest Products Laboratory, Millett et al. [27] reported that the digestibility of hardwoods pretreated with gaseous sulfur dioxide increased as much as 60 to 65 percent. Dunlap et al. [28] have suggested the following advantages of sulfur dioxide pretreatment over alkali pretreatment with sodium hydroxide:

- Sulfur dioxide is less expensive than sodium hydroxide.
- Sulfur dioxide gas can be removed easily and reused after treatment.
- Sulfur dioxide-treated material is in a solid form and solubilized materials can be removed by minimum liquid washing.
- Penetration of the cellulose structure by sulfur dioxide is rapid and complete.

If the concept was found to be cost-effective, the technology for utilizing gaseous sulfur dioxide pretreatment is readily available in the pulp and paper industry.

Although research on auto-hydrolysis has been conducted for many years, the application to wastes other than wood pulp is still in the early stage of development. McConnors, under NSF funding, has carried out experiments at the small pilot-scale level. He has recently begun a DOE-funded program to investigate autohydrolysis for application to woody biomass. McCarty is also pursuing auto-hydrolysis.

7.1.4.3 Research Needs for Acid Pretreatment. As noted above, research on mineral acid pretreatment has gravitated toward ethanol production from municipal solid waste. The research needs listed below are also directed toward ethanol production.

- Evaluate sulfur dioxide pretreatment and autohydrolysis of MSW on a bench-scale for enhanced ethanol production.

- Conduct economic evaluations of sulfur dioxide pretreatment and autohydrolysis of MSW based on results of bench-scale studies for enhanced ethanol production.

7.1.4.4 Research Program for Acid Pretreatment. Bench-scale studies should be conducted to evaluate the effect of sulfur dioxide pretreatment and autohydrolysis on ethanol production. This would be a two-phase program, first developing and experimenting with the pretreatment techniques and then determining their effect on ethanol production. Following this work, economic evaluations should be conducted on both pretreatments to determine their potential benefits to ethanol production.

To develop baseline data, the bench-scale studies should be limited to four to six months duration, at a cost of less than \$50,000 each. The economic analyses also should be of short duration, i.e., two months, at a cost of \$15,000 each.

It is considered that the above sulfur dioxide pretreatment efforts will not greatly reduce the cost of the mineral acid hydrolysis process which is now in the pilot stage of development. Therefore, efforts should now concentrate on the pilot-scale evaluation with mineral acid. If results are encouraging, then more extensive investigations of other acid pretreatments may be warranted.

For the autohydrolysis program, a minimal experimental effort on MSW is now proposed until the results of the DOE funded project on autohydrolysis of woody biomass is completed. Results of this study should reveal advantages of using MSW as a feedstock.

7.1.5 Irradiation Pretreatment

7.1.5.1 Process Description. Exposure of cellulosic materials to irradiation by gamma rays, high velocity electrons, or high intensity ultraviolet light results in a material with a lower degree

of polymerization, lower crystallinity, and higher moisture absorption capacity [29]. Consequently the cellulose is more accessible to hydrolysis during digestion.

7.1.5.2 Technology and Research Status. Highly significant improvements in digestibility of newspaper, straw, and wood substrates pretreated by irradiation have been obtained in bench-scale research. In a recent study, Brenner et al. [20] compared the effectiveness of various pretreatment processes on glucose yield from acid hydrolysis of newspaper. These pretreatments included Wiley mill grinding, industrial dry grinding, hydropulping, hydropulping with ferric ion/hydrogen peroxide presoak, and hydropulping followed by exposure to various dosages of ionizing radiation. Acid hydrolysis of newspaper pretreated by the latter process resulted in a peak glucose yield of about 48 percent, which was 12 to 14 percent higher than the other pretreatment processes.

Similarly, Saemen et al. [30] reported that irradiation pretreatment by electron bombardment resulted in a substantial increase in rate of hydrolysis and a maximum sugar yield at 5×10^8 rad. Peak digestibility was reached at 10^8 rad., at which dosage sugar yield was nearly three times that of the control and the rate of hydrolysis had increased seventeenfold.

Photodegradation has been reported to increase biodegradability of cellulosic materials fourfold after a 24-hour irradiation period [31]. The patented process [32] increases exposure of polysaccharides to high intensity ultraviolet light ($3650\text{\AA}$) in the presence of the photosensitizing agent, sodium nitrate.

Using wheat straw or various hardwoods as the feedstock, researchers have found that significant increases in digestibility occur at an irradiation pretreatment level of about 5×10^7 rad [33,34]. Millett et al. [27] have pointed out, however, that the degree of digestibility is highly species specific.

Several researchers have estimated the cost of irradiation as a pretreatment process. The cost of irradiation equipment, however,

is probably beyond the realm of commercial utilization. Millett et al. [27] estimated the cost of gamma and electron irradiation at well over \$100/ton of cellulose feedstock at a dosage level of 10^8 rad. Brenner et al. [29] conservatively estimated the combined costs of hydropulping and irradiation pretreatment at \$6 to \$22/ton of waste cellulose feedstock.

7.1.5.3 Research Needs for Irradiation Pretreatment. The effectiveness of irradiation to increase digestibility of cellulosic feedstocks is well-established. The downfall for commercial utilization of the process is the economics. Unless less expensive irradiation equipment can be developed, irradiation does not appear to be a viable pretreatment method.

7.1.6 Summary of Pretreatment Research Needs

Table 7.1-I presents a summary of pretreatment technology research needs.

7.1.7 General Research Approach for Pretreatment Technologies

There are many pretreatment techniques now being proposed and evaluated; however, efforts should be directed at selecting the most promising techniques for further development. After completion of experimental and economic evaluations of the various pretreatment techniques, a study should be conducted to compare these techniques and to select which are the most promising for subsequent bioconversion processes.

7.2 Methane Technology

Methane can be produced from MSW by anaerobic digestion in a processing facility, or it can be recovered from landfills. The following sections discuss conventional and novel methods of anaerobic digestion for methane production, and landfill gas recovery. Upgrading and end-use of the methane produced by these processes are also discussed.

Table 7.1-I

Summary of Research Needs for Pretreatment Technologies

Physical Pretreatment

- Evaluate effect of dry and wet preprocessing of MSW on digester performance.
- Evaluate improved concepts for size reduction and separation that enhance biological processes.
- Evaluate extent of MSW preprocessing necessary for good slurry mixing and handling.

Alkali Pretreatment

- Develop and evaluate design concepts for alkali pretreatment to determine cost effective means of achieving high methane yields.
- Determine on a bench-scale the degree of lignin removal for maximum production of methane with minimal phenol inhibition.

Temperature and Pressure Pretreatment

- Conduct conceptual design and economic analyses on the "steam gun".
- Evaluate the economic benefit of temperature pretreatment for improving methane yield.

Acid Pretreatment

- Evaluate sulfur dioxide pretreatment and autohydrolysis of MSW on a bench-scale.
- Conduct economic evaluations of sulfur dioxide pretreatment and autohydrolysis of MSW based on results of bench-scale studies.

7.2.1 Anaerobic Digestion

Anaerobic digestion of municipal solid waste for the production of methane involves four major elements: pretreatment, digestion, product recovery, and residue treatment. A flow diagram of the process is shown in Figure 7.2-1. Pretreatment of the solid waste is desirable to separate inorganic matter and materials which disrupt mechanical operation of the digester and to increase the biodegradability of the substrate. The digestion process results in the decomposition of organic matter and production of gas. The gas produced may undergo treatment for removal of carbon dioxide, leaving pipeline quality methane gas for the commercial market. A residue of undigested materials is dewatered and disposed of in a landfill or incinerator, or possibly used as a soil conditioner.

7.2.1.1 Conventional Digestion.

Process Description

A conceptual process design for an anaerobic digestion system was developed for the National Science Foundation during the period June, 1973 to January, 1975 [35]. This design is generally accepted as the baseline configuration for anaerobic digestion of municipal solid waste and sewage sludge to produce methane. The process illustrated in Figure 7.2-2 is described below.

Feed Preparation. The size reduction equipment fulfills two primary functions: it allows efficient separation of organic materials from the inorganic matter found in municipal waste, and it allows the feed to solubilize more readily during digestion. Both wet and dry separation schemes are being considered to provide a feedstock with a high concentration of digestible matter, relatively free of metals, glass and grit. The dry separation processes offer the advantage of flexibility in selecting the desired water content of the feed to the digesters. Wet separation processes necessarily operate at low solids concentrations in aqueous slurries, and hence have the disadvantage of requiring a dewatering step whenever a concentrated feed to the digesters is desired.

Figure 7.2-1. Flow diagram illustrating processes involved in the anaerobic digestion of municipal solid waste

Figure 7.2-2. Flow sheet of anaerobic digestion process for solid waste utilization used for Dynatech economic analysis [35]

Digestion. Before entering the digesters, the organic feed-stock is mixed with nutrients and control chemicals. The nutrients are supplied by raw sewage sludge. Lime and ferrous salts are added for pH and hydrogen sulfide control. Dilution water may also be added to facilitate mixing and pumping the slurry. Either raw water or recycled filtrate from the process may be used. The resulting mixture is then pumped into the digesters.

Each digester operates at mesophilic conditions and is of conventional high-rate design. The tank is stirred continuously by one or more digester mixing devices (gas recirculation, liquid recirculation, or mechanical agitation) and is equipped with a floating cover to maintain the system at constant pressure. The conversion occurs in two steps: solids are first solubilized or digested by enzymatic action; the soluble products are then fermented in a series of reactions producing methane and carbon dioxide.

The products of digestion consist of two streams. One stream, the gas stream, is composed of approximately equal volumes of methane and carbon dioxide. The second stream, the slurry stream, is composed of an aqueous suspension of undigested organic matter which must be disposed of appropriately.

Gas Treatment and Handling. The product gas from the digester contains methane, carbon dioxide and trace quantities of hydrogen sulfide. The two acid gases must be removed if the gas is to meet pipeline standards. A standard method of removing acid gases from natural gas is by absorption with monoethanolamine (MEA). The gas leaving such an absorber has essentially no residual carbon dioxide or hydrogen sulfide. The MEA is then regenerated and recirculated. Before the methane can be sold, it also must be dried. This may be accomplished by a glycol dehydration process in which the moisture is absorbed in dry glycol, which is regenerated and recirculated. If used off-site, the gas must be pressurized.

Effluent Handling and Disposal. During steady-state operation of the waste digestion system, it is necessary to bleed the system continuously. Water and non-digestible matter must be removed at a rate equal to their rate of feed. Because the digesters are reasonably well-stirred, the composition of the effluent is essentially the same as that of the contents. In addition to water and non-digestible matter, the effluent from the digesters contains undigested digestible solids, organic matter in solution, and a viable biological mass. The disposal of this slurry is best carried out by separating the solids from the liquid and either recycling the liquid or returning it to a sewage treatment plant for final disposal. The solids, in the form of a moist sludge or cake obtained from a filter or centrifuge, are then incinerated or sent to landfill.

Technology Status (Conventional Digestion)

Anaerobic digestion has been used as a means of treating sewage solids since the nineteenth century. Municipal facilities have been operated for many years, stabilizing sludge and producing a low-Btu gas used to provide a portion of heat and power requirements to the treatment plant. Some interest in anaerobic digestion as a means of solid waste disposal was shown in the early 1930's, but early experiments were not very successful.

In the late 1960's, renewed interest in anaerobic digestion technology was generated by the potential production of energy from the process. Golueke, Research Biologist at the University of California, Richmond Field Station, was the first of the most recent workers to study anaerobic digestion of solid waste. A five-year program under his direction examined the technical feasibility of digestion of municipal waste with large quantities of animal waste [36]. Further work at the University of Illinois under the direction of Pfeffer demonstrated the feasibility of methane production from municipal solid waste, with limited additions of sewage sludge [37]. This work included an evaluation of gas production as a function of pH, temperature, solids loading, retention time and slurry concentration, and an evaluation of the costs and net economic benefit of the system.

In 1969, an intensive laboratory and engineering evaluation of fuel gas production from municipal solid waste was initiated by Consolidated Natural Gas Service Company. Laboratory experiments reconfirmed the technical feasibility of utilizing the basic anaerobic digestion process to convert organic wastes to pipe-line quality fuel gas. A comprehensive model of a 1,000 ton per day municipal waste digestion system was developed for the National Science Foundation to evaluate economic feasibility.

In 1975, Waste Management, Inc. of Oak Brook, Illinois, was selected by ERDA to provide a complete program for full-scale production of methane gas from solid waste including design, construction and operation. Jacobs Constructors, Inc., Chicago, Illinois, has implemented design and construction of the facility at the Waste Management, Inc., Solid Waste Reduction Center in Pompano Beach, Florida. This process, now sponsored by DOE, is known as Refuse Conversion to Methane (RefCOM).

Design and construction phases of the Pompano Beach project are complete. The process design includes primary shredded refuse storage, magnetic separation, secondary shredding, air classification and pneumatic transport to the digester, anaerobic digestion, mixing of recycling digester gases, residue dewatering, nutrient addition, filtrate recycle and gas flaring. The digester design incorporates capabilities for investigation of thermophilic and mesophilic modes of anaerobic fermentation covering an average solids retention time span of 4 to 20 days [38].

Technical Status. The RefCOM facility is the only large MSW anaerobic digester soon to be in full operation in the U.S. The primary technical objective of this facility is to demonstrate long-term gas production at rates sufficiently high to result in attractive economics. At the present time, the RefCOM facility is operating at a ten percent feed solids concentration, two percent digester concentration with 20 to 30 day average solids retention

time. Significant improvements may be achieved during the ensuing experimental program, but the process is not economically attractive under these circumstances.

The RefCOM facility has experienced a variety of mechanical problems, some common to most resource recovery systems, some unique to anaerobic digestion. The former include failures in the size reduction and separation equipment. The air classification equipment has not performed as expected. Problems have arisen in pumping the slurry to the digester and in mixing the sewage solids and solid waste. Plastics and textiles have become entangled in impellers. As a result, the experimental program has lagged.

The experimental program was planned with the objective of establishing optimum operating criteria for the production of methane at the facility. Five goals of the proof-of-concept experiment have been defined [38]:

- To establish information concerning the gas product quantities and values,
- To evaluate process reliability and economics,
- To determine optimum design and operation parameter values for each process stage and method of operation,
- To establish a basis for comparing the process to other means of energy production and/or resource recovery from urban waste,
- To establish the technological and economic basis for commercial utilization of the process.

The experimental program at the RefCOM facility is divided into three phases including start-up, experimental program and steady-state operation at optimum conditions. The primary independent variables which need to be evaluated are temperature, solids loading,

feed slurry concentrations and solids size. As outlined by Waste Management [38], the range of variables to be investigated are as follows:

<u>Variable</u>	<u>Range</u>
Temperature	
mesophilic	(95-115°F) 35-46°C
thermophilic	(130-140°F) 54-60°C
Hydraulic Retention Time	5-30 days
Feed Slurry Concentration	8-20% dry solids
Loading Rate	(0.2-2.5 lb volatile solids/day/cu.ft.) (0.09-1.13 kg volatile solids/day/cu.ft.)
Filtrate (Centrate) Recycle	50-100%
pH	>6.8-7.0
Particle Size	1.5-3.0 in.
Nitrogen	300 mg/l
Phosphorus	60 mg/l

The material and energy balances for the RefCOM anaerobic digestion process are shown in Figure 7.2-3 and 7.2-4, respectively [35]. Assuming 6000 Btu/lb as the heating value of the input solid waste, the gross energy yield of the process is 34 percent. The net energy yield, allowing for electrical power and heat required, is 22 percent. It should be noted that this energy balance does not include the energy required to haul the residue to landfill or the energy required for incineration, if desired. Likewise, it does not include the energy required to process the wastewater effluent or a credit for energy saved by disposal of the sewage sludge. It should also be noted that the energy produced is in a storable form which may be converted efficiently to other uses.

Economics. A detailed economic analysis of anaerobic digestion of municipal solid waste was undertaken in 1974 [35]. The results

Figure 7.2-3. Material Balance for Waste Digestion Process [35]

Mass Units in Tons

Basis: 1,000 tpd MSW

Total Heat Required = 23,600,000 Btu/hr
 Time-Averaged Total Power Required = 2950 HP
 Methane Produced = 140,900,000 Btu/hr (net)

At 85% thermal energy recovered and 30% conversion to mechanical energy, ratio of energy required to drive the process to energy generated = 0.375.

*Note: Separators and shredders operate for 15 hours/day on a six-day/week basis. Power values shown here are averaged values for the sum of both lines.

Figure 7.2-4. Heat and Mechanical Power Requirements for the Waste Digestion Process [35]

Basis: 1,000 tpd MSW

of that analysis have been reviewed and updated in view of changing capital and operating costs. These costs are presented in Table 7.2-I. The analysis is based on the format and procedure outlined in Appendix A. Prior studies have arrived at a net gas cost by assuming a tipping fee, and other credits and penalties for input and effluent streams. While this is an appropriate method of analysis for comparing alternative energy production systems, municipalities that will contract for construction and/or operation of such facilities are primarily concerned with the disposal or tipping cost.

It should be noted that this cost analysis is highly sensitive to digester operating parameters, including feedstock composition, solids concentration, and retention time. It should also be noted that the capital cost does not include the cost of a disposal facility for the trommel screen unders, air classifier heavies, or the dewatered cake. However, disposal of these materials by landfill is included as Residue Disposal at \$10/wet ton. The costs presented include credits for sewage sludge input to the process and ferrous metal recovery. The analysis assumes a land requirement of 20 acres, two years for preconstruction planning and design, and a construction period of 22.5 months. Energy output is estimated at 3.72 MM Btu/ton MSW.

The analysis assumed a staff of 23 to operate the facility, excluding maintenance personnel. Despite operation of the front-end system only eight to 16 hours/day, five days/week as compared to around the clock operation of the digester, the number of employees would appear to be on the low side. In a recent proposal submitted by Combustion Engineering, Inc. for a 1500 tpd RDF facility with a dedicated boiler (128-West, Massachusetts), the manpower requirement excluding maintenance labor was 35 people. The front end system was considerably less complicated with only a flail mill, magnetic separator and trommel. A more realistic manpower requirement for the anaerobic digestion facility would be about 30 people. This would increase the tipping fee by about \$0.50/ton.

Table 7.2-I

Economic Analysis of Conventional Anaerobic Digestion
Basis: 364,000 tpy MSW Processed

		<u>Annual Income Statement (1980 Dollars)</u>	
<u>Capital Cost</u>		<u>Revenues</u>	
Land	\$ 200,000	Product Sales, Methane	\$ 2,301,936
Site Preparation	800,000	Ferrous	423,259
Installed Equipment Cost	17,289,780	Disposal Credit, Sewage Sludge	682,500
Construction	<u>2,074,770</u>	Tipping Fee	<u>5,682,850</u>
Installed Plant Cost	\$20,364,550	Total Annual Revenues	\$ 9,090,545
Design	\$ 1,221,870	<u>Expenses</u>	
Contingency	<u>4,072,910</u>	Annual Capital Cost	\$ 3,376,200
Total Plant Cost (1980)	\$25,659,330	Annual Operating Cost	
Escalated Total Plant Cost	\$32,168,240	Salaries and Benefits	575,000
		Fuel Oil	415,244
		Electricity	518,642
		Chemicals	12,014
		Water and Sewer	43,907
		Maintenance (Salaries and Supplies)	914,489
		Residue Disposal	2,211,215
		Taxes, Licenses, and Insurance	28,564
		Professional Services	47,400
		Net Profit	<u>947,870</u>
<u>Finance Costs</u>		Total Annual Operating Cost	<u>\$ 5,714,345</u>
Underwriters Fee	\$ 1,002,810	Total Annual Expenses	\$ 9,090,545
Bond Reserve Fund	4,085,550	NET DISPOSAL FEE (1980)	\$15.60/ton
Interest During Construction	850,160		
Start-up and Working Capital	<u>2,005,640</u>		
Total Bond Issue (1982)	\$40,112,400		
Present Value of Total Bond Issue (1980)	\$33,148,900		

An additional factor which should be noted in the NSF analysis, is that the electric power requirement for the front-end system was only 24 kwh/input ton of MSW. In contrast, the Ames, Iowa facility which has a similar front-end configuration has a direct power requirement of 36 kwh/input ton and an indirect requirement, i.e., conveyors, motors, ventilation, and lighting, excluding heat, of 14 kwh/input ton. A more appropriate value based on actual plant experience would be about 50 kwh/input ton. This would increase the presented tipping fee by about \$0.75/input ton.

The above processing scheme only achieves about a 50 percent solids reduction of the MSW. From a waste disposal standpoint this is not encouraging. Construction and operation of an incinerator with steam recovery to combust the process rejects would increase the tipping fee from \$15.60/ton (Table 7.2-I) to approximately \$19 to \$22/ton.

Environmental Impact. The potential environmental impact of anaerobic digestion of municipal solid waste has been evaluated at some length at the laboratory scale. There is little field data available at this time. The character of the filtrate/centrate produced during dewatering was documented by Pfeffer [39] and is presented in Table 7.2-II. Tests run with chemical coagulants indicated that a relatively pure supernatant could be produced. Concurrent tests of leachate produced when the dewatered residue was landfilled indicated that the quality of leachate was better than that found in conventional landfills. There are no known data available to characterize emissions from an incinerator processing the residual cake, but the chemical composition is expected to be no more objectionable than with any other solid waste system.

Present Status of Research and Development

The primary research and development effort centers around the RefCOM facility at Pompano Beach, Florida.

In addition to the work underway at the RefCOM facility, a variety of researchers are investigating specific unit operations in

Table 7.2-II

Filtrate-Centrates Characteristics [39]

	Recycle Ratio		
	0	0.5	0.8
Total solids - mg/l	8,350	10,507	19,366
Suspended solids - mg/l	4,600	5,930	11,625
Volatile solids - mg/l	4,340	6,093	10,789
COD - mg/l	7,057	18,053	24,650
Alkalinity as CaCO_3 - mg/l	1,100	1,500	2,000

Note: Experiments were run using various laboratory vacuum filtration and centrifugation equipment. Chemical coagulation was necessary to improve suspended solids levels to acceptable values.

the anaerobic digestion process. These are addressed in more detail in other sections.

Research Needs for Conventional Anaerobic Digestion

Any detailed evaluation of research needs is premature until the initial experimental program using the RefCOM facility is completed. The completion of this experimental program and thorough evaluation of the results, with the objective of establishing a state-of-the-art configuration, is essential to the determination of the technical and economic feasibility of the process.

Depending on the outcome of the present program, a number of research activities could be pursued at the RefCOM facility. Of primary importance should be an evaluation of alternative front-end processing schemes, particularly for removal of textiles and plastics which have caused serious problems with mixing in the digester. It may be that this type of experimenting will be incorporated into the present RefCOM evaluation. Cost of this type of evaluation would be about \$500,000, with a one year duration.

If the results of the recommended bench-scale pretreatment evaluation of wet versus dry refuse preprocessing indicate improved biodegradability for wet preprocessing, then full-scale testing of a wet-pulped RDF feedstock should be examined. Cost of this evaluation would be about \$500,000, with a one year duration.

7.2.1.2 High Solids Digestion. The continuous stirred tank reactor described in Section 7.2.1.1 is typical of anaerobic digestion systems used in the treatment of wastewater. Such systems have historically operated at low suspended solids concentrations and high retention times with the objective of stabilizing the sludge from wastewater treatment plants. The potential to easily achieve high solids concentration using municipal solid waste as a feedstock and the current primary interest in optimizing the process for economical energy production has resulted in the examination of a number of digestion concepts which offer significant improvements over

conventional technology. The following sections address major topics of on going study in new digestion technology.

Process Description

One of the most significant drawbacks to conventional anaerobic digestion of municipal solid waste is the large digester volume required. The concentration of solids fed to the digester is one of the most important design parameters from the standpoint of capital and operating costs, and the material and energy balance. Several concepts have been proposed to employ high solids concentrations in the digestion process, based upon packed and fluidized bed technology. This technology is a derivative of the anaerobic filter concepts formulated by Coulter [40], McCarty and Young [41, 42]. Anaerobic filters have been applied to wastewater treatment (e.g., the ANFLO process sponsored by DOE) and, more recently, packed and fluidized beds have been investigated for application to municipal solid waste and biomass. Shown conceptually in Figure 7.2-5, the packed bed digester is comprised of a containment vessel, inert bed material which supports biological growth, circulating fluid, substrate (e.g., municipal solid waste), pumping system and, in some cases, an extraction/purification system. The process has been used to produce methane, liquid fuels, and chemicals from organic waste materials. The fluidized bed system is similar in design, except that the inert bed material is fluidized by the substrate.

Under the baseline operating conditions described in the economic analysis of a conventional digestion system [35], the anaerobic digestion stage represented 28 percent of the process energy consumption and 35 percent of the capital cost of an anaerobic digestion system. Analysis has shown that digesters can be operated effectively at two to three times the solids concentration of conventional stirred tank reactors. Specific gas production, expressed as volumes of methane produced per volume of reactor per day (VVD), has been documented at 6.60 VVD, compared to one to two VVD for conventional systems [43]. It is reasonable to expect approximately a

SCHEMATIC DIAGRAM OF FIXED
PACKED BED FERMENTER

CONTINUOUS FLOW PACKED BED FERMENTER

Figure 7.2-5. Packed Bed Anaerobic Digester.

50 to 60 percent decrease in digester costs if a packed bed system were employed. In the case of methane production, the net gas cost is expected to decrease by at least 10 to 50 percent, and a 15 to 20 percent improvement in the energy balance of the system might be expected. Increases in total solids reduction and concurrent methane production can lead to even higher net energy yields from the system.

Technology and Research Status

Bioconversion systems employing fixed and fluidized bed techniques are still in the formative stages of development. Initial work employing municipal solid waste as a substrate was carried out in 55 gallon drums containing about 50 lbs. of material [44]. Methane was the primary end product. More recently experiments have been carried out on aquatic biomass to investigate production of liquid fuels and chemicals. These experiments have been carried out in batch fluidized bed reactors containing approximately 175 lbs. of material [45]. To date, results of these experimental programs show significant potential for reducing the cost of anaerobic digestion systems. Advantages of these systems include:

- reduced digester capital cost
- reduced water requirements
- reduced energy requirements for mixing, heating
- higher solids reduction/energy yield
- reduced residue disposal costs
- reduced wastewater treatment costs.

The packed and fluidized bed digestion technique has no additional adverse environmental impacts over conventional stirred tank reactor systems. On the contrary, it offers potential to reduce land requirements and it can significantly reduce residual disposal and wastewater treatment requirements.

Research Needs and Research Program for High Solid Digestion

Initial experiments with packed and fluidized bed digestion systems have shown that they offer considerable promise to improve the economics and energy yield of anaerobic digestion systems. There are no known systems operating today using MSW as a substrate. The advantages of these systems over conventional technology warrant further investigation in the laboratory. The programs to date have dealt only superficially with engineering design considerations. No detailed conceptual design or cost analysis of a large-scale bio-conversion facility employing these techniques is known to exist. The research need is to:

- Conduct bench-scale evaluations of fixed and fluidized bed digestion of MSW, and develop conceptual designs and cost estimates for a commercial-scale facility. The cost of each program would be about \$250,000, with a 12 to 24 month duration.

7.2.1.3 Multi-Stage Digestion

Two-Stage Digestion

Process Description. Two-stage digestion incorporates a combination of high-rate digestion and conventional unmixed digestion. The first stage is a continuously fed, completely mixed temperature controlled biological unit from which methane and carbon dioxide are collected. The second stage is a quiescent unit for solids separation and concentration. There is less gas production from the second stage than from the first.

Technology and Research. Two-stage digestion is currently common practice in municipal sewage treatment systems. The first digester functions to optimize conditions for maximum biological decomposition of the sludge and hence maximize gas production. Digested sewage sludge containing about five percent solids is then pumped into the second vessel where the solids settle to the bottom and a scum layer forms on the top. The supernatant is then easily removable.

The two-stage digester provides significant improvements over the high-rate digester and the unmixed digester individually. Most important is the reduction of retention time. Since mixing in high-rate digestion is not compatible with thickening, a 30 to 60 day retention time is needed for one-stage digestion, whereas in a two-stage system of sewage sludge, a 10 to 20 day retention time is needed for digestion and thickening [46-49].

Research Needs for Two-Stage Digestion. The technology for two-stage digestion is well-established on an industrial scale for sewage treatment. Since the function of the second stage is to facilitate solids separation and concentration, the process is applicable to any low solids feedstock. Addition of urban refuse in moderate amounts is not expected to alter operation of the system. Further research is not, therefore, considered necessary for commercialization of the process.

Two-Phase Digestion

Process Description. In contrast to two-stage digestion, two-phase digestion involves two biologically active digesters in series. Both digesters function to optimize conditions for active metabolism of microorganisms. In the first phase, complex organics such as fats, proteins, and carbohydrates are hydrolyzed, fermented, and biologically assimilated by facultative anaerobes and strict anaerobes. These bacteria are known collectively as acid-forming bacteria since the primary end products of the first-phase conversion are volatile fatty acids. During the second phase, organic acids are converted by several different obligate anaerobes, known collectively as methanogenic bacteria, to produce primarily the gaseous end products, methane and carbon dioxide.

Since the acid formers and the methane formers are different in terms of physiology, nutritional requirements, growth kinetic capabilities, and sensitivity to environmental stress, operation of each of the digesters is geared to meet the needs of the specific microorganisms. The parameters which can be controlled include temperature, nutrients, mixing, pH, and loading rates.

Technology and Research Status. Since the acids utilized by the methane formers are produced by the acid formers, the key to success of a two-phase system is obtaining a strict balance between the two groups of microorganisms. When the system is in balance, the methane bacteria use the acid intermediates as rapidly as they are produced by the acid bacteria. If the methane bacteria are not present in suitable numbers, or are slowed down due to unfavorable environmental conditions, the volatile acids will not be utilized. Therefore, successful application of this concept is dependent upon maintaining dominant cultures of acidogenic and methanogenic bacteria.

A number of methods to achieve two-phase separation have been attempted. These include: (1) membrane dialysis separation of the two groups of bacteria, (2) selective inhibition of methane bacteria in the acid digester, and (3) kinetic control of both groups of bacteria.

Membrane dialysis separation of acid and methane bacteria has proved successful in laboratory studies. Although the bacteria are physically separated, there is rapid interchange of nutrients and metabolic waste products throughout [50-52]. Due to operational difficulties with dialysis membranes, however, the potential for this method is limited for large-scale anaerobic digestion [53, 54].

Suppression of methane forming bacteria can be achieved by two types of inhibitors: (1) those that act as alternative acceptors of hydrogen, such as viologen dyes, long-chain fatty acids, propanediol, and sodium sulfate, and (2) chemicals that directly interfere in the metabolic pathway of methane formation such as methane analogues (i.e., the halogens, chloroform, carbon tetrachloride, bromochloromethane, chloralhydrate) and molecules resembling a coenzyme involved in methane formation (i.e., bromoethanesulfonic acid). Experimental studies in vitro and in vivo using cattle as a host have demonstrated that selective inhibition of methane formation is feasible. In a recent study at the University of Illinois, 100 percent suppression was obtained using bromoethanesulfonic acid [55]. Selective inhibitors of methane production in cattle which improve

feed efficiency are currently being developed by the pharmaceutical industry. There is little published research on the effectiveness of those methane suppressors for application in two-phase digestion. The drawback is that the inhibitor must be deactivated to enhance methane production in the second phase. Research funded by DOE on the suppression of methane for the production of alkanes is discussed in Section 7.4.

Kinetic control of the growth of acidogenic and methanogenic bacterial populations can be achieved by adjustment of dilution rate and cell mass recycling in both phases of the digestion process. This method of two-phase separation has been successfully applied to soluble and insoluble substrates at the Georgia Institute of Technology [56, 57] and at the Institute of Gas Technology (IGT), Chicago, Illinois. Research initiated in 1971 defined the kinetics of biological reactions in two-phase digestion using batch, semi-continuous or continuous culturing methods. The reactions studied included the production of acids from glucose, hydrolysis and acid production from activated sewage sludge, hydrolysis of cellulose, and production of methane from acetic acid. The feasibility of phase digestion by controlling kinetic parameters was demonstrated on a laboratory scale using two 10ℓ digesters [58]. The process has since been operated using a 100ℓ acid digester and a 400ℓ methane digester [59].

Based on the results of laboratory studies, projections of operating characteristics for two-phase digestion of urban refuse have been made [58]. With a feedstock of cellulose, the acid digester will require a retention time of one to two days. Longer retention times may be necessary, however, for the acidification of high-cellulose refuse feeds and with increasing cellulose particle size. The retention time for the methane digester is expected to be as high as five to eight days [60].

Several processes have been investigated with the intention of reducing the retention time required in the acid stage of urban refuse digestion. Klass, et al [61], patented a process involving

recycle of indigenous enzymes. The microbial cells within the system are ruptured so that enzymes are released. The enzymes then act to degrade untreated refuse, thus improving digestion efficiency and hence, methane yields. Methods of cell rupture cited in the patent include sonication, mechanical rupture by shearing and forcing refuse through orifices, and cycle pressurization-depressurization. The effectiveness of enzyme recycle on reducing detention time has not yet been reported.

Reduction in detention time of the acid phase has been attained using a plug flow system for hydrolysis and acid production of an urban refuse/sewage sludge feedstock [62]. Plug flow digestion was simulated by ten, 208ℓ steel reactors with a 2080ℓ total working volume for the acid phase. These reactors were maintained at 99°F with minimal mixing. Acidified refuse was pressed to separate residual solids and the liquid fraction was fed to the methane digester. The methane phase was operated using a 2270ℓ continuously stirred tank reactor (CSTR) unit maintained at 99°F. The system was operated at a retention time of 10 days and 15 days for the acid and methane phases, respectively. However, acid production levels in the plug flow systems tended to level off after five days and significant solubilization of the solid waste was obtained within three days. Other advantages of the plug flow system will be discussed subsequently.

Preliminary process design and mass and energy balances, in terms of daily solids loading, [58] have been developed for a hypothetical two-phase sludge digestion plant equivalent to the Stickney high-rate digestion plant of the Metropolitan Sanitary District of greater Chicago. Comparison of these results with the actual operating data from the Stickney plant indicate that a two-phase plant can produce up to 80 percent more methane than the conventional plant while the total digester volume for the two-phase system is only about 35 percent of the total volume of the high-rate digester. Similar engineering designs are not yet available for two-phase digestion of urban refuse. However, an engineering analysis is being undertaken for a system planned for the City of Pittsburgh [63].

The advantages of two-phase digestion over conventional high-rate digestion are:

- increased control of the growth of acidogenic and methanogenic bacteria populations
- substantial reduction in total reactor volume and hence, reduction in capital and operating costs
- decreased heat requirements and increased thermal efficiency
- higher rates of solids stabilization
- increased methane yield and higher percentage of methane in the product gases
- reduction of the nitrogen content of the system effluent by simultaneous liquefaction and denitrification of waste feeds in the acid digester.

The disadvantages of two-phase digestion are the necessity for skilled operators and increased instrumentation to monitor and control microbial population growth.

Research Needs for Two-Phase Digestion. The key to success of two-phase digestion is the optimization of acid and methane phases. Research emphasis should, therefore, be placed on economical methods to maintain high growth of uncontaminated cultures. Thus far, the most successful approach has been by control based on kinetics. The research need is to:

- Conduct a bench-scale evaluation on two-phase digestion of MSW to determine conditions for maintenance of microbial populations and maximum production of methane using kinetic control. Methods to reduce detention time by increasing biodegradation should be investigated. A detailed engineering and cost analysis of two-phase digestion of MSW should be completed. Cost of this program would be about \$250,000, with a 12 to 24 month duration.

Plug Flow Digestion

Process Description. The concept of a plug flow digestion system can be visualized as a conical cylinder lying on its side through which digester substrate continuously moves. Feedstock is continuously loaded from one end and effluent is continuously discharged from the other. There is virtually no blending or mixing of solids. Liquids trickle downward by gravitational forces, but essentially remain with the solids that were introduced at the same time as the liquid.

Technology and Research Status. Simple plug flow digesters operated with diluted and undiluted wastes, maintained at mesophilic temperatures without mixing, have proved to be effective and economical for production of methane from cattle and dairy farm wastes. Some commercial-scale systems have been developed, but there is little operational information available [64]. Two plug flow mesophilic, unmixed systems were designed and constructed under the supervision of Agricultural Energy Corporation, Luddington, Michigan. The more economical of the two systems, built in Custer, Michigan, is made of a fabric-reinforced "plastic" bag. The bag unit is supported by a V-shaped concrete-lined channel dug in the ground. The top of the bag is a flexible membrane which expands as biogas is produced. The digester is insulated with styrofoam sheets which float on the surface of the plastic material. The digester is claimed to be low in cost, easy to install, capable of withstanding low temperatures, and relatively trouble-free. The other plug flow system at Rice Lake, Michigan, is a galvanized metal tank laid in a trench and insulated on the top by soil. Fluid which accumulates in the bottom is pumped for recycle to the influent. Both the Custer and Rice Lake units are equipped with gas scrubbers. The gas produced is used to drive an engine/generator set and the waste heat from the generator unit provides heat for the digester [65].

Most of the operational information available on plug flow digesters has resulted from a three-year research program at Cornell University to develop improved low-cost anaerobic digestion technology for use on small farms in the United States. The feasibility

of maintaining high methane yields by plug flow digestion of dairy cow manure was demonstrated on a bench-scale using completely mixed fermenters in series. Optimum conditions for plug flow digestion have been identified using the bench-scale system and three pilot plants (5 cu. m. volume each). Variables being evaluated presently include: temperature of operation (77°F, 95°F), straw and sawdust bedding addition, intermittent feeding, mixing, and moisture content. A full-scale plug flow reactor (35 cu. m.) capable of handling wastes from 65 dairy cows when operated at a 10-day hydraulic retention time has been operated for one year. Preliminary analysis indicates more efficient solids conversion is attained with plug flow digestion than high-rate digestion. Under operating conditions of 95°F, 30 days hydraulic retention time and 10 to 12 percent total solids dairy manure feed, the full-scale reactor produces 1.26 cu. m. biogas/cu. m. reactor/day (980 cu. ft CH₄/day). The completely mixed control unit of similar size produces 1.13 cu. m. biogas/cu. m. reactor/day (820 cu. ft. CH₄/day) [43,66].

Research on plug flow digestion of dairy cow manure using the full-scale system will be complete in several months. At that time the economics of the system will be clearer. Several studies have indicated, however, that by reducing the cost of digesters by the bag-type design, substantial savings are realized [67, 68]. A recent evaluation of digestion concepts for digestion of biomass feedstocks showed plug flow digestion to be the most economical [68].

Application of plug flow digestion for methane generation from feedstocks with a higher solids content than manure is being investigated in a pilot-scale reactor at Cornell. Using wheat straw with a solids content of 30 percent, gas production was too low, but when water was added for a decrease in solids content to about 25 percent, an average gas production rate of 0.10 to 0.25 cu. m. biogas (50 percent CH₄)/cu. m. reactor volume/day was obtained over a four month period [66].

The feasibility of plug flow digestion of a mixture of urban refuse and sewage sludge has been demonstrated on a bench-scale.

The plug flow design was employed as the acid phase of a two-phase system. Acids extracted from the residue were then fed into a completely mixed reactor for the production of methane. The plug flow reactor was simulated using ten unmixed digesters. The results indicated that significant solubilization of solid waste occurred within three days retention time in the acid phase. Approximately one third of the total volatile solids introduced to the system was converted to biogas [62].

Research Needs for Plug Flow Digestion. Plug flow digestion appears to have been highly successful for methane production from manure due to reduction in capital and operating costs and higher gas yields when compared to high rate digestion.

- Conduct a bench-scale evaluation of plug flow digestion of MSW to determine the feasibility of one-phase digestion, and develop conceptual design and costs for a commercial facility. Cost of the study will be about \$125,000, with a 12 month duration.

7.2.1.4 Summary of Anaerobic Digestion Research Needs

Research needs for anaerobic digestion technology are summarized in Table 7.2-III. In all bench-scale evaluations, it is assumed that co-disposal of MSW and sewage sludge would also be evaluated.

7.2.2 Landfill Gas Recovery

7.2.2.1 Gas Extraction from Existing Landfills

Technology Status

The world's first commercial landfill methane recovery facility had its beginning in 1971 when the Los Angeles County Sanitation District constructed wells to prevent gas migration to adjacent residential properties at the Palos Verdes landfill in the city of Rolling Hills Estates. Since that time a number of facilities have sprung up, primarily in California, for the extraction of methane gas. A list of these facilities and operational information is summarized in Table 7.2-IV.

Table 7.2-III

Summary of Research Needs for Anaerobic Digestion Technology

Conventional Anaerobic Digestion

- Complete RefCOM experimental program.
- Evaluate alternative front-end processing schemes at RefCOM to improve digestability, particularly removal of textiles and plastics.
- Evaluate a wet-pulped RDF feedstock at RefCOM.

High Solids Digestion Technology

- Conduct bench-scale evaluations of fixed and fluidized bed digestion of MSW, and develop conceptual designs and cost estimates for a commercial-scale facility.

Multi-Stage Digestion

- Two-Stage Digestion
 - None
- Two-Phase Digestion
 - Conduct a bench-scale evaluation of two-phase digestion of MSW to determine conditions for maintenance of microbial populations and maximum production of methane using kinetic control.
 - Conduct detailed engineering/cost analysis of two-phase digestion system.

Plug Flow Digestion

- Conduct a bench-scale evaluation of plug flow digestion of MSW to develop kinetic data.
- Conduct detailed engineering/cost analysis of plug flow digestion system.

Table 7.2-IV

MAJOR LANDFILL GAS RECOVERY/PROCESSING/UTILIZATION PROJECTS IN THE UNITED STATES

Project Name	Location	Recovery System and Gas Rate	Processing System	Status and Utilization	Sponsors/Owners
Mountain View Landfill	Mountain View, Calif.	20 wells, average fill depth 40 ft, 1 million scf/D 700 cfm	Compression of 400 psig Triethylene Glycol water removal and Molecular Sieve carbon dioxide removal to produce 750 BTU/scf gas	Scheduled to begin operation by end of 1977 Gas to be introduced into PG&E natural gas transmission line resulting in 975 BTU/scf mixed gas	City of Mountain View, Pacific Gas & Electric Co. with EPA grant for partial funding
Palos Verdes Landfill (CA Class I)	Rolling Hills Estates, Calif. (Los Angeles Basin-coastal)	8 wells, average fill depth 120 ft, 2 million scf/D 2500 cfm	Triethylene Glycol water removal and Molecular Sieve carbon dioxide removal to produce 1000 BTU/scf gas	In operation since summer of 1975 Gas purchased by So. Calif. Gas Co. introduced into local transmission system	Reserve Synthetic Fuels Inc., Los Angeles County Sanitation Districts (LACSD), So. Calif. Gas Co.
Azusa-Western Landfill	Azusa, Calif.	11 wells, average fill depth 80 ft, 3.5 million scf/D 2400 cfm (designed for max. 3500 cfm)	Triethylene Glycol water removal providing 450 BTU/scf $\pm$ 10 percent gas	90 day shakedown completed August 1977, Commercial operations to begin Jan., 1978 Gas purchased by nearby chemical plant; potential for added industrial users	Azusa Land Reclamation Co. Southwestern Portland Cement parent Co. financed
Sheldon-Arleta Landfill	Sun Valley, Calif.	14 wells, average fill depth 130 ft, 3 million scf/D 2000 cfm	Water vapor removal to provide 450 BTU/scf gas	Recovery tests completed, collection and 1.5 mile pipeline under construction Gas to be used by LA DWP Valley Steam Plant as supplementary fuel	L. A. Dept. Water & Power, L. A. Bureau of Sanitation
North Valley (Sunshine) Landfill	Los Angeles, Calif.	Not available, average fill depth 175 ft, Not available	Triethylene Glycol water removal and Molecular Sieve carbon dioxide removal to produce 1000 BTU/scf gas	Gas production survey completed; design reported to be in progress; construction pending	Reserve Synthetic Fuels, Inc.

Table 7.2-IV (Continued)

Project Name	Location	Recovery System and Gas Rate	Processing System	Status and Utilization	Sponsors/Owners
62nd Street Landfill	Denver, Col.	15 wells, average fill depth 25 ft, 3 million scf/D 2000 cfm	Not available	Design status uncertain project apparently pending Gas to be sold to adjacent asphalt plant	Property Improvement Co.
Scholl Canyon Landfill	Glendale, Calif.	8 wells, average fill depth 100 ft, 1.7 million scf/D 1200 cfm	Not available	Analysis and survey completed; Design status not available; generate 3000 kW peaking power 8 hours per day using gas	City of Glendale, Calif.
BKK Landfill	West Covina, Calif.	Not available average fill depth 200 ft, 4000 cfm estimated	Ammonia synthesis planned	Gas production survey completed; feasibility study completed; project pending	BKK Landfills Inc, BKK Corp.
Ascon Landfill	Wilmington, Calif.	Not available average fill depth 65 ft, 800 cfm estimated	Probably water removal	Planning in progress; gas survey completed; project pending; Gas to be sold to nearby industry	Watson Industrial Properties
City of Industry Landfill	Industry, Calif.	Not available average fill depth 50 ft, 400 cfm estimated	Not available	Planning and gas survey underway; Gas to be used by nearby golf club for club house space heating and hot water	City of Industry
Pasqualletti Landfill	Phoenix, Ariz.	Not available average fill depth 35 ft, 1000 cfm estimated	No processing planned	Gas survey completed and planning reported to be in progress, implementation depends on sales contract to Phoenix Tallow Works	Reserve Synthetic Fuels
Puente Hills Landfill	Whittier, Calif.	Not available average fill depth 100 ft, 1500-3000 cfm estimated	Probably none but presently uncertain	In planning stage	LACSD

Table 7.2-IV (Concluded)

Project Name	Location	Recovery System and Gas Rate	Processing System	Status and Utilization	Sponsors/Owners
CID Landfill	Calumet, Ill.	Average depth 120 ft.	Not available	Gas survey completed; project pending	Reserve Synthetic Fuels
Lauer No. 1 Landfill	Menominee Falls, Wis.	Average depth 40 ft.	Not available	Gas survey completed; project pending	Reserve Synthetic Fuels
Mountain Gate Landfill	Los Angeles, Calif.	Average depth 100 ft.	Not available	Has migration system installed; gas survey completed	City of Los Angeles, LACSD
Holtsville Landfill	Brookhaven, L.I., N.Y.	Average depth 40-100 ft.	Not available	Survey and gas migration control system contract let; recovery system will follow if feasible	Brookhaven, L.I. N.Y. Reserve Landfill Dev. Co

$$m = 0.3048 \times ft$$

$$std \text{ cu m/min} = 19.652 \times MM \text{ scf/day}$$

$$cu \text{ m/min} = 0.02832 \times cfm$$

$$kJ/cu \text{ m} = 37.32 \times BTU/scf$$

The ultimate objective of gas extraction is to provide a renewable energy resource at a competitive price. The primary question which needs to be answered is, "From which existing landfills will the extraction of gas be profitable?" The answer depends on a number of technical and economic factors which influence the cost and potential success of the extraction process, including the location and composition of the landfill, the type of drilling and extraction equipment necessary, the gas production rate, local restrictions and regulations, gas processing and marketing. Few of these factors are adequately understood.

Technical. When the potential hazards of gas leakage from landfills were first realized, research centered on the identification of gas composition in relation to landfill age, and on gas movement through the landfill. This early research made an important contribution to present technology.

Based on the composition of sample gases, researchers can determine the stage of biogas production within a landfill. Therefore, before extensive gas extraction is undertaken, a test well and supporting wells are drilled and a series of tests are run to evaluate landfill pressure profiles, biogas composition and heating values, and stability of withdrawal rates [70, 71]. The results of these analyses are valuable in determining efficient operating parameters for the particular landfill, but it is still not possible to estimate the quantity of methane obtainable from the landfill.

It is well documented that gases move horizontally and vertically through the landfill at velocities of about 7 cm/day [72]. The rate may vary, however, depending on the landfill composition. Movement downwards results from molecular diffusion plus density differences, whereas movement to the sides and upward to the atmosphere results from diffusion alone [73]. Carbon dioxide can move into soil beneath a landfill, as well as upward, whereas methane tends to rise through the landfill and not dissolve into groundwater [74]. To determine the most efficient design of wells, a model is needed defining diffusion rates of gas through various soils and refuse substrates.

After drilling, the gas extraction wells are typically lined with a perforated casing and packed with sieved gravel. Collection manifolds connect the wells, bringing the biogas to a common collection site. This method has proved to be generally satisfactory, but other less expensive methods should be investigated. In early well systems, a differential settlement in the fill led to broken pipes and collapsed wells. Development of specialized drilling equipment may be necessary.

Removal of gases from existing landfills has been accomplished by the same principle that is involved in the extraction of groundwater. Pumps are manifolded to the wells, creating a pressure gradient within the landfill which draws the gas through the collection system. In some cases, sufficient negative pressure has developed in the fill so as to draw air into the fill. Oxygen can inhibit the anaerobic process while nitrogen can create nitrous oxides upon combustion of the fuel gas. Extensive experiments have been conducted at Palos Verdes and Mountain View, California, to develop optimum pumping rates for each fill. Another problem with the extraction system at Palos Verdes has been corrosion of pipes due to industrial wastes deposited in the landfill. Further investigation of corrosion problems and alternate extraction systems should be encouraged.

After extraction, the gas may be upgraded. A typical system consists of dehydration by compression and cooling, pretreatment for hydrogen sulfide and free water removal in molecular sieve towers, followed by another series of molecular sieve absorption towers to remove carbon dioxide. The resulting methane gas (950 Btu/cu.ft.) is pressurized (400 psig) and injected into a pipeline distribution system. Corrosion problems have been encountered in field installations. However, it is expected that corrosion can be eliminated with the injection of inhibitors into the biogas before processing [75].

Economics. Economic analyses have been made on the extraction of methane from existing landfills for the Mountain View Project

[75], the project at Palos Verdes [76], and by the Los Angeles Bureau of Sanitation [77]. Based on these studies, costs have been updated and are presented in Table 7.2-V.

A substantial portion of the cost is due to the low rate of methane production. Typical gas production from existing landfills is in the range of 120 to 460 cu. ft./year/ton of deposited waste, with a methane content above 50 percent [71]. The costs presented are based on a 20-year life of the gas produced in an existing landfill facility. It is also assumed that it will take 20 years for complete bioconversion of the waste substrate to a fuel gas. Thus, in this economic evaluation only 50 percent of the potential methane yield per ton of waste is recovered. In other words, at the end of the twentieth year, the first year's deposition is producing its last quantity of gas, while the twentieth year's of waste deposition has just started. The remaining 19 years of gas production are not considered for recovery in this evaluation. Thus, in this system, the gas production rate increases at a constant rate every year until the twentieth year, when the maximum production rate occurs for the entire facility, the end of the project life, after which gas production will decrease.

Costs are based on landfilling 364,000 tpy. The analysis assumes a land requirement of 180 acres, one year for pre-construction planning and design, and 0.6 years for construction. Energy output is estimated at 1 MM Btu/ton.

7.2.2.2 Methane Enhancement in Landfills

Technology and Research Status

There are several parameters which can be controlled during operation of a landfill which will enhance the production of methane. The landfill is treated like a large anaerobic digestion system into which urban refuse, nutrients, buffer, and inoculum are combined to sustain high reproduction rates of bacteria and hence, high methane yields. The nutrients, buffer, and inoculum may be provided either by chemicals, sewage sludge, or selected industrial

Table 7.2-V

Economic Analysis of Conventional Landfill Gas Recovery
Basis: 364,000 tpy MSW Landfilled

Annual Income Statement (1980 dollars)Capital Cost

Land	\$ 1,800,000
Site Preparation	1,800,000
Installed Equipment Cost	5,869,600
Construction	<u>704,350</u>

Installed Plant Cost \$10,173,950

Design	610,450
Contingency	<u>2,034,800</u>

Total Plant Cost (1980) \$12,819,200

Escalated Total Plant Cost \$14,168,100

Finance Costs

Underwriters Fee	\$ 433,900
Bond Reserve Fund	1,767,700
Interest During Construction	118,100
Start-up and Working Capital	<u>867,700</u>

Total Bond Issue (1981) \$17,355,500

Present Value of Total Bond Issue (1980) \$15,777,900

Revenues

Product Sales, Methane	\$ 618,800
Tipping Fee	<u>2,226,100</u>

Total Annual Revenues \$ 2,844,900

Expenses

Annual Capital Cost \$ 1,607,000

Annual Operating Cost

Salaries and Benefits	300,000
Fuel Oil	147,883
Electricity	8,649
Chemicals	N/A
Water and Sewer	N/A
Maintenance (Salaries and Supplies)	473,480
Residue Disposal	N/A
Taxes, Licenses, and Insurance	6,188
Professional Services	14,350
Net Profit	<u>287,350</u>

Total Annual Operating Cost \$ 1,237,900

Total Annual Expenses \$ 2,844,900

NET DISPOSAL FEE (1980) \$6.10/ton

N/A: Not Applicable

wastes which are mixed or layered with the MSW before deposition into the landfill, or by recycling leachate through the landfill, or by a combination of these methods. A landfill operated by one of the above methods is termed an enhanced landfill.

The landfill system may be provided with channels of high permeability material through which gases flow horizontally and vertically to collection points near the surface. These channels would be integrated into the construction of the newly formed landfill rather than drilled after the completion of the cell. Techniques similar to those described in the previous section would be employed for gas extraction and treatment. A cross-sectional view of a landfill designed to enhance methane generation is illustrated in Figure 7.2-6.

Without enhancement, a landfill undergoes active degradation over a period of many, many years, the time being primarily dependent on the moisture content of the fill. Thus, any problems associated with a given landfill (e.g., methane migration, ground water contamination) are likely to continue far beyond the termination of refuse placement, and indeed may not appear for some time after fill completion. Post-construction maintenance and monitoring of a completed landfill site, to assure that it maintains its integrity and does not become a source of pollution, can therefore be a long-term source of concern. Another disadvantage of slow degradation is the long period of time required for gas extraction and the low methane yields per ton of refuse on an annual basis. Significant cost savings could be realized by increasing the rate of degradation within existing landfills. Further, research to date has indicated that higher ultimate gas yields are possible in enhanced landfills.

Technical. Research on enhancement of methane production in landfills has been funded primarily by the EPA and several gas utilities. Results of experiments using test cells (Table 7.2-VI) have indicated that substantial increases in methane production can be achieved if conditions are favorable for mass transfer and for

SANITARY LANDFILL

Figure 7.2-6. A cross-sectional diagram of an enhanced sanitary landfill. Refuse cells are formed by compaction of the solid waste and daily cover with a layer of soil. A well is provided for monitoring leachate.

Table 7.2-VI

Research Projects on Enhanced Landfills

Location	System Design	Research Emphasis	Contact
Sonoma County, California	5 test cells - 18 m sq., 3 m deep, density 350 kg/m ³ . Water addition, sewage addition, leachate recycle.	Leachate treatment and methane production. One- time application of water and sewage vs. daily additions of water and leachate, vs. no additions.	
Pennsylvania A. W. Martin Assoc., Inc.	23 hectare landfill. 2 flow-through stabilization ponds. No sewage sludge.	Leachate treatment.	
Lycoming County	750,000 gal. lagoon for leachate treatment. Spray leachate on landfill.	Leachate treatment and disposal.	
North Hempstead	Leachate lagoons on landfill surface.	Leachate disposal. Landfill enrichment.	
Georgia Institute of Technology	4 test cells	Leachate recycle and methane production.	Frederick G Pohland
Mountain View, California		Sewage sludge and buffer addition. Leachate recycle.	Remedios, PG&E Buivid, Dynatech

methanogenic bacteria metabolism. Controllable parameters which affect the production of methane in landfills include refuse composition, refuse particle size, degree of compaction, nutrient concentration, pH, moisture content, and leachate recycle.

Composition of the refuse directly affects the rate of methane production and subsequently the ultimate methane yield. Urban refuse which is high in biodegradable materials such as food, garden wastes, and paper, decompose rapidly, releasing large amounts of methane. Sewage sludge mixed with the refuse increases the percentage of biodegradable materials in the landfill and, at relatively low concentrations (75 to 400 mg/l), stimulates gas production. At higher concentrations, however, inhibition may result [78]. Methane production may also be inhibited by industrial wastes containing high concentrations of sodium chloride, potassium, magnesium, calcium, ammonia, carbon tetrachloride, or chloroform.

Contradictory results have been obtained regarding the importance of particle size reduction for increasing methane production. Particle size reduction by shredding exposes more surface area for adhesion of nutrients and microorganisms. Research has indicated that particle size reduction increases methane production in laboratory digesters [79-81]. DeWall *et al.* [77] demonstrated that by reducing nominal particle size from 25 to 2.5 cm. through shredding and milling, gas production has increased by over a factor of four. Most of the gas produced, however, was carbon dioxide and not methane. In fact, the experimental system with the highest methane production was one with unshredded refuse.

The value of shredding urban refuse has not been accurately assessed by small-scale experimentation since reduction in particle size also affects the rate of oxygen depletion, density of the fill, and percolation of water, nutrients, and buffer into deeper layers. Due to the heterogeneous nature of the unshredded refuse, channels may form by infiltrating water, resulting in an uneven distribution of nutrients and buffer. On the other hand, shredded refuse covered daily with soil, compacts tighter than unshredded refuse and may

retard the percolation of water, nutrients, and buffer to deeper layers of the landfill. Recent laboratory work by Dynatech R&D Company, sponsored by Pacific Gas and Electric Company, has indicated that unshredded refuse produces more methane than shredded refuse.

As inferred above, refuse density affects mass transfer. Density also affects the onset of anaerobic conditions. Research on the effects of baling refuse is underway, but the optimum density for methane production has not yet been determined.

Nutrients to stimulate growth of bacteria within the landfill may be supplied by sewage addition, leachate recycle, or artificial means. Based on a bacterial cell formula of $C_5H_7NO_2$, approximately 12.4 percent by weight nitrogen is needed for cell growth, while one-fifth of that value of phosphorus is required [82]. The nutrient value of recycled leachate depends upon the landfill composition. Evidence suggests that leachate material could provide only a portion of the nutrient requirements; thus addition of sewage or artificial nutrients also may be necessary.

Since the bacteria which carry out the biodegradation process grow best within a narrow pH range, the pH within the landfill should be controlled. The optimal pH range of 6.25 to 7.5 has been controlled by the addition of calcium carbonate, a buffering agent [83], in simulated landfill cells.

Moisture content is the single most important parameter for enhancement of methane production within landfills. Small-scale studies have shown that the rate of refuse degradation and methane production increase with an increase in moisture content to an optimum of 75 to 85 percent moisture [84]. The moisture content of urban refuse as placed in a typical landfill is about 25 percent. Increases in moisture content can be provided by sewage sludge addition or by recycle of leachates (and rainwater). The sludge or leachate can be mixed with urban refuse upon deposition into the landfill or allowed to seep into the landfill periodically by spraying or upon completion of the landfill by lagooning. Dispersion of nutrients and inoculum into the fill are not a problem if the sludge is mixed before deposition.

Results of research projects (Table 7.2-VI) have indicated that leachate recycle increases methane production, increases the rate and predictability of biological stabilization, and reduces environmental pollution. Recycle with pH control and initial sewage sludge inoculation further enhances treatment efficiency and methane production.

Economics. Based on current capital and operating costs, the economics of methane recovery from enhanced landfills has been calculated. The costs are presented in Table 7.2-VII. The economics of the system are substantially better than those for "uncontrolled" conventional landfills due to higher methane production rates. It is estimated that 100 percent of the potential methane produced per ton of refuse is recoverable in one year. Therefore, the production rate from the entire landfill facility is assumed constant in this economic evaluation. In the enhanced landfill system, a gas production of 650 cu. ft./year/ton is assumed which represents a conservative rate as determined recently in test cells of municipal solid wastes [85]. The analysis assumes a land requirement of 180 acres, one year for pre-construction planning and design, and 0.8 years for construction. Energy output is estimated at 3.32 MM Btu/ton MSW.

7.2.2.3 Research Needs for Landfill Gas Recovery. Landfill gas recovery from existing landfills with no enhancement is commercially feasible using state-of-the-art techniques. Sufficient data has been developed on recovering gas from landfills such that systems can be implemented without further development work. However, Federal support is needed to increase technology transfer. To date, the concept of enhanced landfill for increased methane recovery is not ready to be commercialized.

The enhanced-gas-from-landfill concept has been shown on a laboratory scale to be a highly effective method to produce methane gas from MSW. Experimentation using laboratory test cells has provided a great deal of information on the effects of controlled conditions on methane production. Research has reached the point

Table 7.2-VII

Economic Analysis of Enhanced Landfill Gas Recovery
Basis: 364,000 tpy MSW Landfilled

292

Annual Income Statement (1980 Dollars)Capital Cost

Land	\$ 1,800,000
Site Preparation	3,150,000
Installed Equipment Cost	6,310,800
Construction	<u>757,200</u>

Total Installed Cost \$12,018,000

Design	\$ 721,100
Contingency	<u>2,403,600</u>

Total Plant Cost (1980) \$15,142,700

Escalated Plant Cost \$17,533,650

Finance Costs

Underwriters Fee	\$ 538,460
Bond Reserve Fund	2,193,750
Interest During Construction	195,740
Start-up and Working Capital	<u>1,076,900</u>

Total Bond Issue (1981) \$21,538,500

Present Value of Total Bond Issue (1980) \$19,580,600

Revenues

Product Sales, Methane	\$ 2,057,000
Disposal Credit, Sewage Sludge	1,055,600
Tipping Fee	<u>827,600</u>

Total Annual Revenues \$ 3,940,200

Expenses

Annual Capital Cost	\$ 1,994,300
Annual Operating Cost	
Salaries and Benefits	350,000
Fuel Oil	384,907
Electricity	31,484
Chemicals (CaCO ₃)	94,025
Water and Sewer (leachate treatment)	99,659
Maintenance (salaries and supplies)	563,040
Residue Disposal	N/A
Taxes, Licenses, and Insurance	9,715
Professional Services	19,670
Net Profit	<u>393,400</u>

Total Annual Operating Cost \$ 1,945,900

Total Annual Expenses \$ 3,940,200

NET DISPOSAL FEE (1980) \$2.30/ton

N/A: Not Applicable

where large-scale field studies are necessary to answer many of the remaining questions and to verify the application of results from laboratory studies to commercial use.

The following research needs are directed at evaluating enhanced landfill concepts and accelerating commercialization of landfill gas recovery. These needs are summarized in Table 7.2-VIII.

- Increase technology transfer of landfill gas recovery through Federally sponsored regional seminar programs. Many communities and engineering firms are unaware of the commercial readiness of landfill gas recovery. To accelerate implementation, regional seminars should be conducted to explain the technical, economic, and institutional aspects of landfill gas recovery. These seminars could be a joint DOE/EPA effort, similar to the present EPA regional seminars on resource recovery.

- Demonstrate enhanced methane recovery from landfills:

- Compare economics of enhanced landfill in initial sewage and buffer addition to landfill with leachate recycle
- Develop special drilling equipment, particularly for in situ distribution of water, buffer, and inoculum
- Develop more effective extraction systems, with particular emphasis on reducing the amount of air drawn into a landfill when gas is being withdrawn
- Prepare design and operating plan for a commercial-scale enhanced landfill.

- Evaluate health and environmental effects of enhanced landfill operation. The application of sewage sludge and recirculation of leachate on enhanced landfills is a potential health hazard for spreading bacteria and viruses, and a potential odor nuisance to nearby residents. The health and environmental effects of enhanced landfills need to be determined.

Table 7.2-VIII

Research Needs for Landfill Gas Technology

- Increase technology transfer of landfill gas recovery through Federally sponsored regional seminars.
- Demonstrate enhanced methane recovery from landfills.
- Evaluate health and environmental effects of enhanced landfill operation.
- Develop models for predicting potential methane production from existing and new landfills, with and without methane enhancement techniques.
- Evaluate utilization alternatives for landfill gas.
- Evaluate shredded versus conventional landfill for gas recovery.

indicate that conventional landfill is more effective for methane production. Further study on this subject is not warranted in the near term.

7.2.2.4 Research Program for Landfill Gas Recovery. Gas recovery from existing landfills is commercially ready; however, technology transfer to municipal officials and consulting engineers is lacking. A DOE/EPA sponsored regional seminar program should be conducted to explain the technical, economic, and institutional issues of landfill gas recovery. Cost to develop and coordinate such a seminar program would be about \$30,000 for three regional seminars, not including travel expenses for seminar attendees, which will be about \$50,000 to \$100,000, depending on the number of attendees.

The landfill gas recovery research program is directed at demonstration of enhanced landfill gas recovery. To achieve this goal, it is necessary to extend present work beyond the bench- or pilot-scale to field testing. Field testing should use a one-acre site divided into four test plots. A number of experiments would be conducted at the landfill to assess the viability of enhanced landfill operation. A comparison should be made between the effect of initial sewage and buffer addition, and leachate recycle, both as methods of enhancing methane production. Special drilling equipment also should be evaluated, particularly for injecting and evenly distributing water, buffer, and inoculum into the refuse layers of a landfill. A more effective gas extraction system should also be evaluated. For this work, the use of a plastic cover over the landfill to reduce the amount of air being drawn into the landfill should be tested. Based on this experimental program, a conceptual design and economic analysis should be developed for a commercial-scale enhanced landfill.

Cost of this research program would be about \$400,000, with a 12 to 18 month duration. This cost includes construction of the test landfill, experimentation, and conceptual design and economic analysis.

Subsequent to, or in the latter stages of the above field study, the health and environmental effects of enhanced landfill operation should be examined. This study would examine the potential health hazard of applying sewage or leachate to the landfill. Rodents, vectors, birds, bacteria, viruses, and odor would be monitored.

Another important research area that should be pursued is the development of models to predict potential methane recovery from existing or new landfills, with or without enhancement. The model will need to take into account geological and meteorological conditions, in-place refuse composition, landfill age, and operating conditions. Pacific Gas and Electric Company has been working with Dynatech R&D Company to develop such models. Based on the outcome of this initial work, additional Federal support may be warranted.

As indicated under Research Needs (Section 7.2.2.3), landfill gas utilization studies are now being conducted by Pacific Gas and Electric Company under DOE sponsorship. Additional research on gas utilization is not necessary at this time.

7.2.3 Methane End-Use Technology

7.2.3.1 Acid Gas Scrubbing.

Process Description

Anaerobic digestion processes, whether in the form of landfills or more sophisticated systems, are unique among solid waste processing techniques because they produce a gaseous product which can be 50 percent or more methane as it leaves the digester. This gas can either be utilized directly as a medium-Btu gas, with minimum clean-up, or can be readily upgraded to pipeline quality. In the latter case, acid gases--CO₂ and small amounts of H₂S--and moisture are removed before compression to 100 to 1000 psi and introduction into the gas pipeline. Methane has traditionally been viewed as a premium fuel because it is storable, clean-burning, has a high combustion efficiency, and can be distributed through an extensive pipeline network which is already in place. In addition to its heating

value, methane is used extensively as a chemical feedstock. The use of natural gas is high and collection systems are in place. Fuel-gas production from municipal solid waste, therefore, is an attractive process if it can be performed competitively.

Present Status of Technology

Various techniques for producing medium-Btu gas which can be utilized as-received from the digester or landfill have been described in previous sections. Large-scale experience with municipal solid waste in stirred tank digesters is very limited -- only preliminary data is available from the RefCOM facility at Pompano Beach where the gas is flared. On the other hand there is a large body of experience with digester gas from wastewater sludge. Experience with fuel gas production from novel systems such as plug flow or packed bed techniques is confined to small pilot-scale. Since 1972, experiments have been conducted to draw methane off of landfills, but again there is little commercial-scale experience with such systems. Most problems encountered to date in gas utilization have been with materials of construction.

A critical factor in evaluating the viability of fuel gas production from solid waste is the determination of the relative merits and the technical and economic feasibility of utilizing the gas as-received versus upgrading it to a high-Btu equivalent of pipeline quality. There are a number of commercial systems available to remove CO₂ and other possible contaminants from the digester or landfill gas. Purification experience with systems operating on solid waste gas is limited to a relatively few systems in California.

A recent review of available gas purification technologies [86] indicated that available methods for treatment of digester gas include physical absorption, chemical absorption, adsorption, and membrane separation processes. Capital, operating, and net gas costs for each system investigated are presented in Tables 7.2-IX and 7.2-X. Gas pressure of 125 psig is about equal to that found in a community distribution system, whereas 1000 psig is the typical

Table 7.2-IX
Cost Summary of Gas Purification Systems [86]
Delivery Pressure: 1000 psig

	Feed Rate MMSCFD	Total Capital Requirement (thousand \$)	Operating Costs (thousand \$)	Unit Gas Cost \$/MM Btu
WATER	0.1	172	18	1.94
	1.0	698	147	1.17
	3.0	1,439	288	0.78
SELEXOL (Dimethyl Ether of Polyethylene Glycol)	0.1	--	--	--
	1.0	1,195	224	1.87
	3.0	2,321	489	1.30
AMINE-GUARD (Monoethanol- amine)	0.1	358	40	4.23
	1.0	915	271	1.94
	3.0	1,802	645	1.46
BENFIELD (Potassium Carbonate)	0.1	--	--	--
	1.0	777	194	1.46
	3.0	1,601	426	1.05
CATACARB (Potassium Salt)	0.1	283	30	3.25
	1.0	893	226	1.69
	3.0	1,727	513	1.22
PHOSPHATE BUFFER	0.1	190	18	2.10
	1.0	724	146	1.18
	3.0	1,433	282	0.77
MARSCO (Molecular Sieve)	0.1	--	--	--
	1.0	--	--	--
	3.0	--	--	--
METHANE SEPARA- TION (General Elec- tric)	0.1	97	12	1.35
	1.0	432	128	1.04
	3.0	921	253	0.71

Table 7.2-X
Cost Summary of Gas Purification Systems [86]
Delivery Pressure: 125 psig

	Feed Rate MMSCFD	Total Capital Requirement (thousand \$)	Operating Costs (thousand \$)	Unit Gas Cost \$/MM Btu
WATER	0.1	171	19	1.98
	1.0	647	154	1.18
	3.0	1,273	314	0.79
SELEXOL (Dimethyl Ether of Polyethylene Glycol)	0.1	--	--	--
	1.0	1,322	242	2.03
	3.0	2,568	533	1.42
AMINE-GUARD (Monoethanol- amine)	0.1	373	42	4.43
	1.0	971	286	2.05
	3.0	1,931	688	1.56
BENFIELD (Potassium Carbonate)	0.1	--	--	--
	1.0	919	212	1.64
	3.0	1,883	474	1.18
CATACARB (Potassium Salt)	0.1	321	33	3.65
	1.0	1,070	248	1.91
	3.0	2,069	567	1.38
PHOSPHATE BUFFER	0.1	218	21	2.41
	1.0	811	163	1.32
	3.0	1,585	329	0.88
MARSCO (Molecular Sieve)	0.1	569	66	2.73
	1.0	1,175	242	1.95
	3.0	--	--	--
MEMBRANE SEPARA- TION (General Elec- tric)	0.1	123	14	1.67
	1.0	531	141	1.20
	3.0	1,112	287	0.82
FLUOR SOLVENT (Propylene Carbonate)	0.1	--	--	--
	1.0	525	124	0.95
	3.0	--	--	--

pressure found in interstate gas pipelines. Heat requirements for the gas cleanup systems are presented in Table 7.2-XI. Simple physical absorption water scrubbing and membrane separation were found to be most attractive based upon data available at the time. The membrane process may have important practical considerations which could rule in its favor, but there is little large-scale experience with this system. More experimental data is required on membrane and phosphate buffer systems, as well as a more careful analysis of CO₂ recovery proposals before a final selection can be made.

Research Needs for Acid Gas Scrubbing Technology

Ongoing and planned programs for digestion and landfill gas evaluation will produce much useful and necessary design data for gas purification systems. Based on the outcome of the landfill gas utilization research program (Section 7.2.2.4), further development of low cost gas purification systems could be warranted. Significant reductions in capital and operating costs, as well as improved energy balances, appear to be possible over the baseline design developed for the National Science Foundation in 1974.

7.2.3.2 Biomethanation of Synthesis Gases.

Process Description

Many processes, including municipal refuse pyrolysis, produce a gas with a low heating value consisting of methane, carbon dioxide, carbon monoxide, and hydrogen. Although there are many instances where this gas may be burned directly, there may be instances where it is economically justifiable to upgrade this gas to pipeline quality methane by shifting the CO to CO₂ and H₂, and methanating the resulting product. This upgrading may be accomplished either catalytically, as in coal gasification, or biologically. The latter process has been termed biomethanation.

In biomethanation, microorganisms can convert synthesis gas to methane as follows:

Table 7.2-XI

Heat Requirements for Selected Gas Purification Systems [86]

<u>Process</u>	<u>Heat Requirements (MMBtu/hr/MMSCFD)</u>
1. Membrane Separation	0
2. Water Scrubbing	0
3. Phosphate Buffer	<0.1
4. Benfield	1.83
5. Marsco	2.13
6. Selexol	2.4
7. Catacarb	2.65 for delivery pressure of 125 psia 2.14 for delivery pressure of 1000 psia
8. Amine-Guard	4.0

In the process, the gases from a pyrolysis unit, such as the Union Carbide PUROX System, are cooled to 120°F and then sparged into a pressurized fermentation vessel. The fermenter is filled with a broth containing nutrients, buffer, and the microorganisms which carry out the above conversions. A train of reactors is required to reduce carbon monoxide concentrations to pipeline standards. Because the carbon dioxide, which is usually present in excess, is more highly soluble in the broth than in the methane product, the fermenter also acts as an acid gas scrubbing system. An external recirculation loop is used to separate, concentrate, and recycle the microorganisms, and to flash desorb the carbon dioxide from the broth. The biomethanation concept is depicted in Figure 7.2-7.

Technology Status

The biomethanation concept has been evaluated experimentally at the bench-scale under ERDA funding as a process to upgrade coal gasification synthesis gas. Microorganisms were selected which carried out both the shift and methanation reactions. Operation at high conversions (280 VVD) and high pressure (400 psig) was demonstrated. The process was shown to be sulfur tolerant, unlike catalytic processes. An engineering analysis of the process to coal gasification projected that the process was more economical [88] when coupled with the water. More recently, a study has been carried out for the Urban Waste Technology Branch of DOE to evaluate the economic feasibility of applying biomethanation to the PUROX System. The unit gas cost for biomethanation, catalytic methanation, and conventional anaerobic digestion are compared in Figure 7.2-8. The costs presented are processing costs, exclusive of any revenues, and are calculated using the AGA gas cost routine [87]. The incremental cost for upgrading by biomethanation is approximately \$0.95/MMBtu. This is considerably less than catalytic methanation. Use of biomethanation to upgrade Purox gas would reduce the net tipping fee by about \$2 to \$10/ton depending on the scale.

Figure 7.2-7. Biological Shift Conversion and Methanation Flowsheet [87]

Figure 7.2-8. Unit Gas Cost for CH_4 Production from MSW including Effluent Disposal Costs [87]

Research Needs for Biomethanation of Synthesis Gas

As with acid gas scrubbing, the results of the landfill gas utilization study should be completed before further work on biomethanation is pursued. However, if a need for gas upgrading exists as a result of that study, then the following biomethanation research needs should be addressed. These needs are summarized in Table 7.2-XII.

- Evaluate sequential biological shift conversion and methanation at high pressure for upgrading Purox gas in bench-scale studies. This program would be conducted under thermophillic conditions at pressures up to 1000 psi, utilizing microorganism recycle to determine biological shift conversion and methanation. The program would also develop a conceptual design and economic estimates for a commercial gas upgrading system. Cost of this study would be about \$100,000, with a 12 month duration.

- Examine simultaneous biological shift conversions and methanation at moderate pressure for upgrading Purox gas in bench-scale studies. An experimental program is needed to develop compatible shift conversion and methanogenic microorganisms which are uninhibited by high concentrations of carbon monoxide, and are adaptable to thermophillic conditions and high pressure. The program would also develop a conceptual design and economic estimate of a commercial system. Cost of this study would be about \$100,000, with a 12 month duration.

If results of these experimental programs are favorable, construction of a pilot plant or demonstration facility based on experimental results could be undertaken, and this unit operated to determine actual performance data on biomethanation of pyrolysis gas produced from municipal solid waste.

Table 7.2-XII

Research Needs for Methane End-Use Technology

Acid Gas Scrubbing

- - Complete DOE RefCOM and landfill gas utilization evaluations to determine design data for gas purification systems.
- Develop lower cost gas scrubbing technology - e.g., water scrubbing, membrane processes.

Biomethanation of Synthesis Gases

- Evaluate sequential biological shift conversion and methanation at high pressure in bench-scale studies.
- Evaluate simultaneous biological shift conversion and methanation at moderate pressure in bench-scale studies.

7.3 Alcohol Technology

The following sections address two approaches to the production of alcohols from municipal solid waste: enzymatic hydrolysis and acid hydrolysis to produce ethanol.

7.3.1 Enzymatic Hydrolysis to Ethanol Technology

The enzymatic hydrolysis of cellulose to produce ethanol involves six major processing steps: pretreatment of the feedstock, production of the active enzyme (cellulase), utilization of the cellulase to saccharify the cellulose in the feedstock, conversion of the sugars produced to ethanol, product recovery, and residue treatment (Figure 7.3-1). The key feature of this process is the production of an enzyme which will break down the cellulose in municipal solid waste to fermentable sugars. Overall, the breakdown occurs as follows:

7.3.1.1 Process Description. Municipal solid waste is prepared by shredding or wet pulping followed by separation of the inorganic fraction. The resulting cellulose rich stream is slurried as appropriate, and a portion is diverted to the reactor in which the active enzyme is produced (Figure 7.3-2). In that reactor, a fungus (typically a mutant of Trichoderma reesei) is grown on a starved diet of the cellulosic wastes at 87°F at a pH from 3 to 4. The fungus produces enzymes which breakdown the cellulose molecules into soluble sugars, which are then partially consumed to sustain fungal growth. The broth produced is then filtered, with the filtrate containing the active enzymes being fed to the primary hydrolysis reactor (Figure 7.3-3). The remainder of the cellulose slurry is fed to the primary reactor where at 122°F and atmospheric pressure, the enzymes hydrolyze the cellulose to produce glucose. After

Figure 7.3-1. Enzymatic Hydrolysis to Ethanol - Flowsheet

Figure 7.3-2. Process design of pilot plant for cellulase production at U.S. Army Natick Research and Development Command, Natick, Massachusetts. From Spano [89]

Figure 7.3-3. Process design of pilot plant for hydrolysis of newspaper at U.S. Army Natick Research and Development Command, Natick, Massachusetts. From Spano [89]

a suitable period of time (up to 24 hours), the resulting syrup is harvested. The syrup may then be fermented anaerobically to produce ethanol. The ethanol may be purified and concentrated by standard distillation techniques.

7.3.1.2 Technology and Research Status.

Technical Status. Major contributions in the technology of enzymatic hydrolysis have been made at the U.S. Army Natick Research and Development Command in the past 10 years. A mutant of the fungus Trichoderma reesei (formerly T. viride) was developed at Natick to produce a cellulosic enzyme complex capable of converting cellulosic materials to glucose. Since 1970 there has been a 30-fold increase in the concentration of enzyme produced in fermentation broths and a 24-fold increase in productivity. Advances have also been made in development of improved mutants and optimization of fermentation conditions. Over 100 types of cellulosic wastes, including municipal solid wastes, have been tested using this fungus in the Natick system.

In 1973-74, pilot plants for cellulase production (Figure 7.3-2) and for hydrolysis (Figure 7.3-3) were set up at the Natick laboratory to establish the optimum conditions for commercial operation. Batch and continuous systems have been tested for both pilot plants.

For enzyme production, it has been possible to quadruple the enzyme productivity of T. reesei in the pilot plant by manipulating such variables as agitation speed, dissolved oxygen, nutrients, temperature, and acidity of the broth [89]. The conditions needed to produce the enzyme in quantity have been defined.

Further increases in cellulase activity appear possible through genetic manipulation of the fungus to create high yielding mutants. At Rutgers University, strides are being made to overcome the bottleneck in enzyme production by an intensive program of strain development. Montencourt and Eveleigh [90] have genetically selected hyperproducing cellulase mutants of T. reesei with a cellulase yield

15-fold greater than the wild strain. When the process improvements achieved at Natick are factored into the overall yield as reported by Montencourt, genetic manipulation would account for only a three-fold improvement over the wild strain. Several catabolite repression resistant strains have also been selected, allowing for the use of inexpensive culture medium components such as corn steep liquor, without reduction in cellulase yield. With the objective of reducing fermenter equipment costs, thermotolerant strains are being isolated as well. So far strains of T. reesei that grow well at 99°F have been isolated, but to date none show the hypercellulase yields of their parent strains. At Natick, parameters being optimized for the most economical production of fermentable sugars during the hydrolysis process include residence time, enzyme activity and characterization, operating temperature, acidity of reacting slurry, susceptibility of cellulosic feedstock to enzymatic hydrolysis, concentration of inerts in feedstocks, degree of agitation and mixing of the reacting slurry, and concentration of syrups in the reaction vessel. Developments in saccharification since 1973 as outlined by Mandels et al. [91] are presented in Table 7.3-I.

Under contract from the U.S. Department of Energy, researchers at Massachusetts Institute of Technology have been working on an extensive program on the degradation of cellulosic biomass for production of chemical feedstocks. The objective of the study is the direct conversion of cellulosic biomass to ethanol and/or soluble sugars by cellulolytic anaerobic microorganisms. Currently research focuses on the production of enzymes by Clostridium thermocellum and isolation and characterization of a new ethanol tolerant strain of that cellulolytic organism. Thermally exploded poplar, corn cob granules, corn stover and sugar cane bagasse are used as biomass substrates [92]. Similar investigations are underway at the General Electric Company, Schenectady, NY [93], and the University of Pennsylvania [94].

Pretreatment of the substrate to increase its susceptibility to hydrolysis is an important variable which affects the degree of

Table 7.3-I

Saccharification Developments at Natick Laboratory, 1973 - 1978 [91]

Date	Substrate	Filter Paper Cellulase, units/ml	R ₀ units/g	Conditions	hr.	Reducing Sugar		
						Conc g/l	Yield %	Productivity g/l/hr
1973	15% milled newspaper	1.3	12	1% stirred tank reactor 50°C, pH 4.8	4	60	40	15
					24	86	57	3.6
					48	100	67	2.1
1975	7.5% hydro- pulped waste	1.5	20	1% stirred tank reactor 50°C, pH 4.8	10	36	46	3.6
					22	46	59	2.1
1976	15% ball-milled pure cellulose pulp	2.0	13	1% stirred tank reactor 50°C, pH 4.8	8	43	29	5.4
					24	56	37	2.3
1977	15% ball-milled pure cellulose pulp	2.0 + 5.5 u/ml β glucosidase	13	shake flask 50°C, pH 4.8	4	50	33	12.5
					24	90	60	3.8
					48	110	73	2.3
1977	15% cellulose pulp - not pretreated	2.0	13	100% stirred tank reactor 45°C, pH 4.8	4	41	27	10.3
					25	60	40	2.4
					50	73	49	1.5
1978	15% cellulose pulp - not pretreated	2.0	13	100% stirred tank reactor 45°C, pH 4.8	4	36	24	9.0
					25	55	37	2.0
					50	66	44	1.3
1978	15% cellulose pulp - not pretreated	2.0 + 2.0 μ/ml β glucosidase	13	100% stirred tank reactor 45°C, pH 4.8	4	41	27	10.3
					25	84	56	3.3
					50	96	64	1.9
1978	25% cellulose pulp - not pretreated	3.0	12	100% stirred tank reactor 45°C, pH 4.8	4	65	26	16.3
					25	101	40	4.0
					50	110	44	2.2

R₀ = units cellulose/g substrate at t = 0).

saccharification and the economics of the process. Researchers at Natick are investigating a variety of pretreatment techniques including chemical pretreatment, physical pretreatment (roll milling, attritor milling), steam treatment, solvents, and hydropulping. The Black-Clawson fiber fraction separated from the hydropulping operation of municipal trash and the shredded cellulose fraction separated by air classification of municipal trash have proved to be good substrates for hydrolysis.

Gulf Oil Chemicals Company has been operating a 1 tpd enzymatic hydrolysis pilot plant since January, 1976. This effort has been achieved after eight years of process development. A number of potential feedstocks have been tested at the pilot plant. These include cotton gin trash, clarifier sludges, digester fines, digester rejects, straw, bagasse, and MSW. Physical pretreatments have used hammer mills, rod mills, roller mills, ball mills, and attritors. Chemical pretreatments tested include acid, base, cadmium oxide, dimethyl sulfoxide, ethylenediamine, and tartrate.

In the process, the cellulase enzyme is produced in 300 gal. reactors with a residence time of two days, using a mutant strain of T. reesei. In addition, a variety of yeasts have been screened for their compatibility with T. reesei for the fermentation of glucose to ethanol. A temperature of 104°F has been identified as optimum for combined cellulase and yeast systems.

A key feature of the process is the simultaneous saccharification and fermentation of cellulose to glucose to ethanol in the same reactor. This process scheme as compared with the more conventional conversion of cellulose to glucose in one reactor and then glucose to ethanol in another reactor has been shown to increase ethanol yield by 25 to 40 percent. Gulf Oil has recently donated the pilot plant to the University of Arkansas, along with a one-year operating grant of \$500,000.

Economic Status. A recent cost analysis of enzymatic fermentation of urban refuse by Spano et al. [95] has been reviewed. The analysis is based on a plant-scale operation with a production

capacity of 25×10^6 gallons of 95 percent ethanol per year from cellulosic material. The material balance for the system analyzed is presented in Figure 7.3-4. The overall yield on cellulase is shown to be 14 percent. In addition, additional material must be fed to the enzyme production system. Yield coefficients for cellulase production were not presented, but will further reduce the overall yield for this process.

The cost analysis has been reviewed and extended to include the enzymatic conversion beginning with raw refuse and concluding with the ethanol product, as illustrated in Figure 7.3-1. The results of the analysis are presented in Table 7.3-II. The front-end preprocessing system includes the same components as in the anaerobic digestion analysis (Figure 7.2-2). The analysis assumes a land requirement of 15 acres, 2 years for pre-construction planning and design, and a 2.5 year construction period. Energy output is estimated at 0.82 MM Btu/ton MSW, with an ethanol yield of 14.3 gal. (95%) per ton of MSW.

Based on an economic analysis conducted by Gulf Oil Chemicals Company, the capital cost of a 200 tpd (100 tpd MSW, 500 tpd mill waste, and 500 tpd pulp mill waste) commercial facility producing 50 million gallons of ethanol (95 percent) was estimated at \$112.2 million (1981 dollars). Assuming 80 percent revenue bond financing and 20 percent private equity financing, the projected selling price of ethanol was \$0.95 gal. in 1983.

Environmental Status. Wastes resulting from enzymatic hydrolysis include the filter cake and ultrafiltrate from the cellulase production stage and solids residue from the hydrolysis stage. The filter cake contains fungal mycelia which can be recycled to provide a protein source for enzyme production. However, research has been done on feeding this protein supplement to animals. Solids residues resulting from hydrolysis can be burned to generate process steam and power. Distillers yeast produced during the fermentation of sugars to ethanol can be used as a feed supplement for animals.

Figure 7.3-4. Material Balance for enzymatic production of 95% ethanol from cellulosic substrates. Values are given in amounts per year [95].

Table 7.3-II

Economic Analysis of Enzymatic Hydrolysis to Ethanol Production
Basis: 364,000 tpy MSW Processed

Annual Income Statement (1980 dollars)

Capital Cost

Land	\$ 150,000
Site Preparation	600,000
Installed Equipment Cost	25,056,500
Construction	<u>3,006,800</u>
Installed Plant Cost	\$28,813,300

Design	1,728,800
Contingency	<u>5,762,660</u>
Total Plant Cost (1980)	\$36,304,760
Escalated Total Plant Cost	\$46,621,950

Finance Costs

Underwriters Fee	\$ 1,466,360
Bond Reserve Fund	5,973,960
Interest During Construction	1,659,490
Start-Up and Working Capital	<u>2,932,720</u>
Total Bond Issue (1982)	\$58,654,480
Present Value of Total Bond Issue (1980)	\$48,472,000

Revenues

Product Sales, Ethanol	\$ 5,142,950
Ferrous	423,260
Cellular Biomass (yeast)	772,200
Tipping Fee	<u>4,858,830</u>
Total Annual Revenues	\$11,197,250

Expenses

Annual Capital Cost	\$ 4,936,900
Annual Operating Cost	
Salaries and Benefits	700,000
Utilities	1,000,000
Chemicals	993,312
Maintenance (Salaries and Supplies)	1,290,325
Residue Disposal	800,000
Taxes, Licenses and Insurance	39,903
Professional Services	68,400
Net Profit	<u>1,368,400</u>

Total Annual Operating Cost \$ 6,260,340

Total Annual Expenses \$11,197,250

NET DISPOSAL FEE (1980) \$13.35/ton

7.3.1.3 Research Needs for Enzymatic Hydrolysis. Enzymatic hydrolysis of urban waste to fermentable sugars has been demonstrated feasible on the pilot-scale (1 tpd). To prove economic viability for the production of ethyl alcohol fuel or chemical feedstock, a two-pronged approach is needed. First, the process should be scaled to a semi-works size, e.g., 50 tpd, prior to demonstration at a commercial-scale of 1000 to 2000 tpd. Both of these actions should be preceded by in-depth engineering analyses to assure that the final commercial-scale process will be cost-effective. Secondly, optimization of the process is needed. Efforts should be directed particularly toward cellulase production, pretreatment, and ethanol fermentation, according to the following:

- Continued selection of mutants which yield greater amounts of cellulase.
- Selection of mutants that are constitutive cellulase producers. The requirement for an insoluble cellulosic inducer substantially increases fermenter operation cost and complexity. The use of constitutive cellulase producers will circumvent the use of insoluble substrates and result in considerable savings.
- Selection of hypercellulolytic thermotolerant strains. Capital and operating cost savings will be realized if refrigeration is not required during enzyme concentration.
- Selection of end product resistant cellulases. Saccharification yields can be increased in enzymes which are resistant to end product inhibition.
- Selection of mutants which produce high quality enzymes.
- Selection of mutants which have a more favorable glucosidase to cellulase ratio.

- Investigation and development of combined saccharification-ethanol fermentation techniques.
- Develop commercially applicable techniques for processing residues for recycle and other applications.

A summary of enzymatic hydrolysis research needs is presented in Table 7.3-III.

7.3.1.4 Research Program for Enzymatic Hydrolysis. The objective of the enzymatic hydrolysis research program is to commercialize the process technology of converting MSW to liquid fuels, principally ethyl alcohol, and secondarily to a chemical feedstock. Enzymatic hydrolysis appears viable at the pilot-scale (up to 1 tpd). However, the process needs to be scaled-up to a semi-works scale, i.e., 50 tpd, before scale-up to commercial-scale, i.e., 1000 to 2000 tpd. Further bench- and pilot-scale development also is needed to optimize the process.

However, before any of the above programs are initiated, a conceptual design, preliminary engineering, and economic analysis of a commercial-scale system, i.e., 1000 to 2000 tpd, needs to be independently conducted to assess the cost-effectiveness of this technology. Cost of this study will be about \$75,000, with a duration of about six months.

Favorable process economics from the above study, as compared with a similar evaluation recommended for acid hydrolysis, may warrant construction and operation of a 50 tpd semi-works plant. Cost of this plant would be about \$4 to \$8 million. Operation of this plant likely would not begin until 1984.

If the preliminary design and economic analysis of a commercial-scale facility proves favorable, then bench- and pilot-scale experimentation should be continued to address the research needs presented in Section 7.3.1.3.

Table 7.3-III

Summary of Research Needs for Enzymatic Hydrolysis

- Conduct conceptual design and preliminary engineering of a commercial-scale enzymatic hydrolysis of MSW facility and perform an economic analysis to determine system feasibility.
- Demonstrate enzymatic hydrolysis of MSW to ethanol at a 50 tpd semi-works facility.
- Continue bench- and pilot-scale evaluations of enzymatic hydrolysis of MSW to optimize the process.

7.3.2 Acid Hydrolysis to Ethanol Technology

Acid hydrolysis differs from enzymatic hydrolysis for ethanol production principally in the manner by which the cellulosic fraction is hydrolyzed to produce glucose. The major processing steps include: pretreatment of the feedstock, slurring the feedstock with dilute mineral acid, hydrolysis to produce glucose, acid recovery, fermentation to produce ethanol, purification, and concentration of the ethanol product. Overall, the breakdown occurs as follows:

7.3.2.1 Process Description. Municipal solid waste is prepared by shredding and separation of the inorganic fraction by conventional dry or wet processing systems. Mineral acids such as hydrochloric and sulfuric can be used to hydrolyze cellulose to simple sugars as described in Section 7.1.4. Dilute acid treatment at elevated temperatures hydrolyze the cellulosic fraction leaving the lignin portion unaffected. Glucose and other fermentable materials are recovered from the hydrolysis unit. The acid is recovered and recycled to the front of the hydrolyzer. The soluble organics are fermented to produce ethanol, which is then purified and concentrated (Figure 7.3-5).

7.3.2.2 Technology Status. Based on economic analyses and bench-scale studies by Porteous [96], Saeman [97], and Fagen et al. [98], as well as the pilot-scale experiments of Brenner and Rugg [101], it is necessary to carry out the acid hydrolysis of cellulose in urban refuse in 0.4-0.6 percent mineral acid at 446 to 500°F with reactor residence times on the order of 5 to 30 seconds. A maximum sugar yield of 55 percent can be attained at 446°F with 0.4 percent acid.

Technical Status. A disadvantage of acid hydrolysis is the necessity to use corrosion resistant equipment. Severe corrosion

Figure 7.3-5. Acid Hydrolysis to Ethanol - Flowsheet

with dilute H_2SO_4 is a problem at high reactor temperatures. Rugg [107] has indicated in continuous acid hydrolysis experiments that proper materials of construction coupled with isolation of the acid to the reaction zone seems to alleviate this corrosion consideration. Additionally, lignin deposited on the reactor surfaces results in protection from corrosion as well as erosion in this severe environment.

Another technical problem with acid hydrolysis is that the temperature and acid concentration needed to achieve hydrolysis also may cause decomposition of the resulting sugars. Therefore, the process must be controlled so that this decomposition does not take place. Recent experiments carried out at NYU have shown that such reaction controls can be readily effected with commercially available equipment. These control systems are suitable for continuous hydrolysis operations.

Economic Status. The major parameters which affect the cost of glucose sugar production by acid hydrolysis are slurry concentration, sugar yield, residence time, degree of energy recovery and substrate cost. In the past, the single most important element affecting the manufacturing cost of sugar by acid hydrolysis has been the solid/liquid ratio. The primary reason is that the thermal energy requirement per pound of glucose produced increases with decreasing slurry concentration. Continuous acid hydrolysis experiments at NYU have achieved in situ reactor dewatering from initial input slurry concentrations of 10 percent up to 75 percent solids in the reaction zone. This results in a substantial reduction in the energy requirements for the reaction. Experiments are underway to optimize energy and materials recycle from the product stream. At NYU, cost data are currently being developed for a scaled-up continuous acid hydrolysis process.

The most recent cost analysis of acid hydrolysis [99] is based upon a bench-scale kinetic model and assumes a plant processing 322,000 tpy of newsprint. This is claimed to correspond to about 473,200 tpy of MSW. The results of that analysis have been reviewed

and updated in view of changing capital and operating costs. The results are presented in Table 7.3-IV. The analysis assumes a land requirement of 15 acres, two years for pre-construction planning and design, and two years for construction. Energy output is estimated at 1.16MM Btu/ton MSW.

Environmental Status. Fermentation of sugars by acid hydrolysis of refuse produces an effluent with BOD of 6,000 ppm. This waste material requires treatment before disposal.

7.3.2.3 Research Status. Currently, the acid hydrolysis process is being investigated at the Thayer School of Engineering at Dartmouth College, where, under the direction of Grethlein, researchers are trying to develop a method that is more economical than the semi-batch process. A continuous flow, bench-scale reactor has been built to provide isothermal reaction conditions for acid hydrolysis of pure cellulose (Solka Floc). The reactor can be adjusted to the following ranges: temperature 356°F to 464°F, sulfuric acid concentration 0.5 to two percent, cellulose slurry concentration 5 to 13 percent. Grethlein [100] has reported that with a reactor residence time of 0.22 minutes, the maximum yield of glucose reported as a percent of the potential glucan in the substrate is over 50 percent for 1 percent acid at 459°F. An economic comparison of this plug flow reactor with the semi-batch process has not been determined. Technical problems, which have arisen because of the high temperature and pressure and the difficulty of pumping a slurry at small flow rates, are still being resolved. In order to keep the pressure down, within the reactor and maintain low flow rates, a glass lined stainless steel capillary is used with a 0.27 inch I.D. This limits the particle size of the substrate that can be delivered to the reactor to a 1 percent or less slurry, an uneconomical slurry.

A continuous 1 tpd twin screw, hydrolysis reactor has been set up at the Antonio Ferri Laboratories of New York University to operate on hydropulped newsprint. At the present time, the researchers,

Table 7.3-IV

Economic Analysis of Acid Hydrolysis to Ethanol Production
Basis: 322,000 tpy Newsprint Processed

Annual Income Statement (1980 dollars)Capital Cost

Land	\$ 150,000
Site Preparation	600,000
Installed Equipment Cost	19,073,300
Construction	<u>2,288,800</u>

Installed Plant Cost \$22,112,100

Design	\$ 1,326,700
Contingency	<u>4,422,400</u>

Total Plant Cost (1980) \$27,861,200

Escalated Total Plant Cost \$35,097,000

Finance Costs

Underwriters Fee	\$ 1,096,050
Bond Reserve Fund	4,465,400
Interest During Construction	991,450
Start-Up and Working Capital	<u>2,192,100</u>

Total Bond Issue (1982) \$43,842,000

Present Value of Total Bond Issue (1980) \$36,231,000

Revenues

Product Sales, Ethanol	\$ 4,185,300
Ferrous	423,250
Cellular Biomass (yeast)	108,780
Tipping Fee	<u>4,551,970</u>
Total Annual Revenues	\$ 9,269,300

Expenses

Annual Capital Cost	\$ 3,690,100
Annual Operating Cost	
Salaries and Benefits	675,000
Utilities	1,329,637
Chemicals	267,471
Maintenance (Salaries and Supplies)	991,164
Residue Disposal	1,267,084
Taxes, Licenses and Insurance	27,944
Professional Services	48,600
Net Profit	<u>972,300</u>

Total Annual Operating Costs \$ 5,579,200

Total Annual Expenses \$ 9,269,300

NET DISPOSAL FEE (1980) \$14.15/ton

under the direction of Rugg and Brenner, have successfully developed a continuous process for the acid hydrolysis of this feedstock. The reaction conditions are 450°F to 500°F for 5 to 30 seconds, with acid concentration in the range of 0.1 to 1 percent. The twin screw reactor is a commercially available piece of equipment, which can be readily obtained in full-scale versions. Its unique in situ dewatering capability permits operation at exceptionally high solids content (up to 75 percent), resulting in substantial energy savings. Yields of more than 50 percent have been routinely obtained. Alternative RDFs are being evaluated as feedstock.

At Louisiana State University, Srinivasan [102] is working on the production of methane from acid hydrolysates of cellulose under contract from the U.S. Environmental Protection Agency. Reduced sugars obtained by acid hydrolysis of paper wastes are digested to produce methane. Current research focuses on optimization of environmental factors for methanogenesis from glucose and selection of a population of bacteria that will generate methane from glucose alone.

A variation of the acid hydrolysis process has been proposed by Tsao of Purdue University for the production of ethanol from plant biomass. The process is essentially a two-stage acid hydrolysis of the pentosans and hexosans, followed by conventional fermentation to ethanol of the C₆ sugar solution derived from the second stage hydrolysis of the crystalline alphacellulose. The importance of the Tsao-Purdue process lies in its potential for greatly increasing the yield of ethanol from the feedstock by increasing the reactivity of the cellulose. Currently the process is being investigated on a laboratory scale using corn stover as a substrate.

7.3.2.4 Research Needs for Acid Hydrolysis. Acid hydrolysis of cellulosic materials has proved to be an efficient method to produce ethanol on a bench-scale, and pilot-scale experiments are underway. However, there is a lack of a unified approach toward

development of this technology, which was operating at commercial-scale on wood feedstock as far back as the 1940s. There are presently at least four independent researchers conducting bench-scale experiments on acid hydrolysis of cellulosic material, and one research organization has reached the pilot-scale of development.

A valid research program should first assess the technical and economic feasibility of these competing alternatives, and select the most promising for further Federal support. If commercialization is the true objective, then efforts should concentrate on development of the most feasible approaches.

Research needs for acid hydrolysis are listed below, and summarized in Table 7.3-V.

- Perform conceptual design, preliminary engineering, and economic analysis of a commercial-scale acid hydrolysis plant, based on NYU pilot plant results. Results of this analysis should be compared with the enzymatic hydrolysis analysis.
- Evaluate technical and economic feasibility of ongoing bench-scale acid hydrolysis projects, and select most promising for further Federal support.
- Continue experimental programs of most promising acid hydrolysis approaches.

7.3.2.5 Research Program for Acid Hydrolysis. Presently, acid hydrolysis and enzymatic hydrolysis are competing technologies, both in terms of end-product (ethanol) and research money. The leading developers of each technology agree that it is time to reach a crossroad, and to select the most promising technology for commercial development. To achieve this goal, a detailed engineering evaluation of the two technologies is needed. This evaluation would include development of a conceptual design, preliminary engineering, and capital and operating cost estimates for a commercial-scale

Table 7.3-V

Research Needs for Acid Hydrolysis

- Perform conceptual design, preliminary engineering, and economic analysis of a commercial-scale acid hydrolysis plant, based on NYU pilot plant results.
- Evaluate technical and economic feasibility of ongoing bench-scale acid hydrolysis projects, and select most promising for further Federal support.
- Continue experimental programs of most promising acid hydrolysis approaches.

facility. Based on this evaluation, one technology should be selected for further development, as outlined in Section 7.3.1.4 and below.

For acid hydrolysis, the evaluation should be based on the pilot plant results from NYU. Care must be taken in the evaluations that both use the same assumptions and battery limits. Cost of each evaluation will be about \$75,000, with a six month duration.

If the results of this evaluation favor development of acid hydrolysis, then work at the 1 tpd continuous pilot plant should be supported. Successful completion of this work may warrant construction and operation of a 50 tpd semi-works facility.

Based on the merits of acid hydrolysis from the engineering evaluation, a study should be conducted to evaluate the technical and economic feasibility of ongoing bench-scale acid hydrolysis projects, and a selection of the most promising approaches for further Federal support should be made. Cost of this study will be about \$100,000, with an 8 to 12 month duration. The most promising bench-scale approaches should then be supported for further experimental work.

7.4 Organic Acid, Alkanes, and Other Chemical Production Technology

There are several incentives to investigate the production of chemicals from municipal solid waste. Most importantly, a wide variety of chemicals are produced today from methane. Alternative processes which could utilize wastes or renewable resources in a direct conversion process to chemicals could save natural gas for other purposes. Such processes could prove to be less energy intensive than available processes. Further, chemicals which use natural gas as a feedstock must inherently cost more than the raw material. Acetic acid, for example, which may be produced from natural gas, sells for \$0.16/lb. Natural gas at \$2.00/MCF has an equivalent price of \$0.045/lb. Alkanes, such as pentane, octane, decane can be burned in place of fuels such as gasoline and can be produced from MSW.

7.4.1 Process Descriptions

A process for production of organic acids from municipal solid waste can be achieved by preprocessing MSW and sludge and feeding this material to a packed or fluidized bed fermenter operating under thermophilic conditions. Liquid is continuously circulated, and organic acids are extracted outside the digester. If desired, methane production may be suppressed by any of a variety of alternative methods [102]. Acetic acid can be recovered by distillation or other appropriate means. Alternatively, a mixture of alkanes can be produced by passing the organic acid through a Kolbe electrolysis cell. Hydrogen and carbon dioxide are produced as by-products of electrolysis and the hydrogen could be oxidized in a fuel cell to produce electricity to run a portion of the process.

An alternative method of producing fuels and chemicals from MSW is by limited aerobic digestion. Although large-scale aerobic processing of sewage has been a well-developed technology in this country, this process has stressed conversion to CO_2 , not fuels and chemicals. Limited aerobic digestion may offer significant potential economic advantages over anaerobic digestion processes. Aerobic digestion proceeds at much higher rates than anaerobic digestion. This could result in much smaller digester volumes, with associated capital and operating cost reductions. On the other hand, aerobic digestion usually results in higher conversion of substrate to biological mass than does anaerobic digestion, with concurrent lower yields of fuels or chemicals. Further, mass transfer considerations usually result in higher energy requirements.

7.4.2 Technology and Research Status

The production of chemicals from cellulosic feedstocks has been carried out primarily in bench-scale equipment. The acetic acid process was first investigated at Dynatech R/D Company using municipal solid waste as a feedstock, and later was defined in more detail using marine biomass. Scientific feasibility is well established. Detailed conceptual process design and engineering analysis have not

been conducted. Other chemicals produced by various fermentation processes have included acetone-butanol (MIT, Penn, etc.) and acrylic acid (MIT). The former is a well-known fermentation typically applied to starches or molasses. There are no known applications to municipal solid waste. The latter is a recently identified fermentation using lactic/propionic acid as a feedstock [104]. These materials can be produced by fermentation of cellulosic feedstocks. There are no known economic evaluations of these processes as applied to municipal solid waste.

The scientific feasibility of the alkane process described above has been established in the laboratory at Dynatech R/D Company using aquatic biomass [105]. Work currently underway under DOE sponsorship is aimed at experimental optimization of the fermentation, extraction, and electrolysis using various biomass species. The fermenter operating conditions have resulted in high acid yields, e.g., 80 to 90 percent conversion of total carbon. A spectrum of acids is obtained, but a mixture containing 70 mole percent caproic acid has been shown to be readily converted to alkanes in the electrolytic cell. Power requirements in the Kolbe cell are claimed to be low, with a 7.1:1 net energy balance obtained for the aquatic biomass system shown in Figure 7.4-1. However, this net energy balance would be expected to drop to about 5 to 6:1 for MSW. This is lower, for example, than mass burning waterwall combustion, which has a net energy balance of about 7 to 9:1. A preliminary evaluation of the economics of alkane production from municipal solid waste is presented in Table 7.4-I. Alkane production from municipal solid waste could be an attractive proposition. It should be noted that the process offers significant potential for co-production of liquid and gaseous fuels by controlling the chemical regime in the packed bed fermenter. The analysis assumes a land requirement of 15 acres, two years for pre-construction planning and design, and a two-year construction period. Energy output of n-decane and hydrogen are estimated at 4.26 and 0.20 MM Btu/ton of MSW, respectively.

Figure 7.4-1. Process to Produce Liquid Hydrocarbon Fuels from Biomass

Table 7.4-I

Economic Analysis of Alkane Production from Municipal Solid Waste

Basis: 364,000 tpy MSW Processed

Annual Income Statement (1980 dollars)

Capital Cost

Land	\$ 150,000
Site Preparation	600,000
Installed Equipment Cost	15,806,800
Construction	<u>1,896,800</u>

Installed Plant Cost \$18,453,600

Design	1,107,200
Contingency	<u>3,690,700</u>

Total Plant Cost (1980) \$23,251,500

Escalated Total Plant Cost \$29,290,160

Finance Costs

Underwriters Fee	\$ 914,700
Bond Reserve Fund	3,726,600
Interest During Construction	827,390
Start-up and Working Capital	<u>1,829,400</u>

Total Bond Issue (1982) \$36,588,250

Present Value of Total Bond Issue (1980) \$30,236,500

Revenues

Product Sales, n-Decane	\$ 9,890,628
Ferrous	423,260
Hydrogen	182,464
Disposal Credit, Sewage Sludge	327,600
Tipping Fee (Credit)	<u>(2,777,652)</u>
Total Annual Revenues	\$ 8,046,300

Expenses

Annual Capital Cost	\$ 3,079,600
Annual Operating Cost	
Salaries and Benefits	750,000
Fuel Oil	156,369
Electricity	721,691
Chemicals	37,443
Water and Sewer	N/A
Maintenance (Salaries and Supplies)	827,840
Residue Disposal	1,563,744
Taxes, Licenses and Insurance	24,863
Professional Services	42,100
Net Profit	<u>842,650</u>

Total Annual Operating Cost \$ 4,966,700

Total Annual Expenses \$ 8,046,300

NET DISPOSAL CREDIT (1980) \$7.63 ton

N/A: Not Applicable

As with the anaerobic digestion analysis, the manpower and electricity requirement appear to be on the low side; however, adjustment of these costs will have a relatively small impact on tipping fee. A capital cost at about \$32,500/ton of installed daily capacity is presented. This is lower than the capital costs presented for enzymatic and acid hydrolysis, although all three systems utilize the same front-end processing sequence. A more detailed analysis needs to be conducted to more accurately determine capital cost.

The most important factor in the alkane cost analysis is the extremely high revenue obtained from n-decane, about \$30/input ton of MSW. With only bench-scale results on aquatic biomass available and the quality of the fuel product in terms of combustion performance yet undetermined, the value of the fuel product remains uncertain at this time. Nevertheless, if revenues were only half of that estimated, tipping fee would be quite low, at about \$5/ton.

There is a substantial background of research and development on aerobic fermentation technology in general, and on aerobic digestion of sewage sludge in particular. Examples of products produced by the former include acetic acid, citric acid, ethanol, and bio-synthetic products such as amino acids, vitamins, fats, oils, proteins, and carbohydrates [106]. None of these have been carried out using municipal solid waste as a feedstock.

7.4.3 Research Needs for Other Chemical Production Technologies

The production of chemicals from municipal solid waste is a relatively unexplored area. To the extent that energy intensive materials such as acetic acid can be competitively produced from municipal solid waste, the field is attractive. Alkane production also appears attractive. Research must concentrate on identification of those chemicals which provide significant energy conservation potential and which can be produced by fermentation of municipal solid waste. Experimental programs, coupled with engineering analysis, are necessary to determine yields and economic feasibility. Research needs are presented below and in Table 7.4-II.

Table 7.4-II

Summary of Research Needs for
Organic Acid, Alkanes, and Other Chemical Production Technologies

- Review prior work on aerobic and anaerobic digestion of biomass and sewage sludge, and identify product chemicals of interest.
- Conduct bench-scale studies on promising digestion techniques for chemicals production using an MSW feedstock.

- Review prior work on aerobic and anaerobic digestion of sewage sludge and other related organic biomass feedstocks, and identify product chemicals of interest. The existing literature should be examined to identify what potential energy conserving chemicals can be produced from sewage sludge and other cellulosic material. For certain attractive chemicals, a technical and economic assessment of the producing process should be made to determine the practicality for future commercial operation on MSW.

- Conduct bench-scale studies on promising digestion techniques for chemicals production using an MSW feedstock. Based on the above literature review, bench-scale experimentation using an MSW feedstock should be promoted for the most promising processes. At present, it appears that production of alkanes is an attractive route to evaluate with an MSW feedstock. Any work conducted in this area should build on previous biomass work, and should not duplicate effort.

7.4.4 Research Program for Other Chemical Production Technologies

The first stage of this research program is to critically evaluate present and past work on chemical production from biomass and sewage sludge, and to identify which processes produce the most desirable chemical products, are most amenable to an MSW feedstock, and appear commercially feasible from an economic standpoint. Cost of this study will be about \$50,000, with a six month duration.

Based on the above study, one or more technologies may warrant bench-scale evaluation using an MSW feedstock. At present, it would appear that alkane production is an attractive route for MSW utilization; however, results to date have only been on an aquatic plant feedstock. It is recommended that current biomass experimental programs be completed before initiating an MSW study in order to take maximum advantage of prior experimental knowledge.

For the DOE funded alkane production process, the present research using biomass will be completed within the next 12 months. If warranted, an MSW research program could be initiated once this first phase of biomass work is terminated.

REFERENCES: SECTION 7 BIOCONVERSION PROCESSES

1. Kispert, R.G., L.C. Anderson, D.H. Walker, S.E. Sadek, and D.L. Wise, Fuel Gas Production from Solid Waste, Dynatech Report No. 1207, NTIS No. PB 238068, 1974.
2. Wilson, R.K. and W.J. Pigden, "Effect of a Sodium Hydroxide Treatment on the Utilization of Wheat Straw and Poplar Wood by Rumen Microorganisms", Can. J. Animal Sci., 44 (1964), 122-123.
3. Dunlap, C.E., Jr., "Proteins from Waste Cellulose by Chemical-Microbial Processing", Diss. Louisiana State Univ., 1969.
4. Gossett, J., J. Healy, L. Young and P. McCarty, Heat Treatment of Refuse for Increasing Anaerobic Biodegradability, prepared for the National Science Foundation Report No. NSF/RANN/SE/GI-43504/PR/75/2, Stanford, CA: Stanford University Civil Engineering Dept., 1975.
5. McCarty, P.L., L.Y. Young, J.B. Healy, Jr., W.F. Owen, and D.C. Stuckey, Thermochemical Treatment of Lignocellulosic and Nitrogeneous Residuals for Increasing Anaerobic Biodegradability, IN: Proc. of 2nd annual Fuels from Biomass Symp., June 20-22, 1978. Troy, NY: Rennselaer Polytechnic Institute, 1978.
6. Quindry, G.E., J.C. Liebman, and J.T. Pfeffer, Biological Conversion of Organic Refuse to Methane, Vol. II, prepared for the National Science Foundation, Report No. NSF/RANN/SE/GI-39191/FR/76/4 Final Report, Urbana, IL: Univ. of Illinois Engineering Dept., 1976.
7. Gossett, J.M., J.B. Healy, Jr., D.C. Stuckey, L.Y. Young, and P.L. McCarty, Heat Treatment of Refuse for Increasing Anaerobic Biodegradability, Semi-Annual Progress Report (7/1/75-12/31/75) submitted to National Science Foundation under contract no. NSF/RANN/SE/GI-43504/PR/74/4, 1975.
8. Gossett, J.M., J.B. Healy, Jr., D.C. Stuckey, L.Y. Young, and P.L. McCarty, Heat Treatment of Refuse for Increasing Anaerobic Biodegradability, Semi-Annual Progress Report (7/1/75-12/31/75) submitted to National Science Foundation under contract no. NSF/RANN/AER74-17940-A01/PR/75/4, Report No. CE-TR-205, 1976.

9. Gossett, J.M., J.B. Healy, Jr., W.F. Owen, D.C. Stuckey, L.Y. Young, and P.L. McCarty, Heat Treatment of Refuse for Increasing Anaerobic Biodegradability, Final report (1/1/76-12/31/76) submitted to ERDA and National Science Foundation under contract no. NSF/AER-7417940-Aol/PR/76/2, 1976.
10. McCarty, P.L., L.Y. Young, J.G. Gossett, D.C. Stuckey, and J.B. Healy, Jr., "Heat Treatment for Increasing Methane Yields from Organic Materials", in Microbial Energy Conversion, H.G. Schleger and J.B. Barnes, eds. Gottingen, Germany: Erich Goltze KG, 1976, pp. 179-199.
11. Van Kampen, G.B., "Straw Cellulose", Chem. Weekbl., 16 (1919), 805.
12. Abele, W., "The Disintegration of Straw by Steaming", Zellst. Papier, 20 (1940), 67.
13. Panton, A.L., Food for Animals; Pulp, British Patent No. 480, 772, February 28, 1938, to The Straw Pulp & Fodder Co., Ltd.
14. Mangold, E., "Steam-Digested Straw as a Feedstuff (Digestion of Crude Fiber without Chemicals)", Wiss. Arch. Landwirt Abt. B. T.T.2 (1930), 585.
15. Kron, R., Fodder, Swiss Patent No. 76,805, June, 1918.
16. Schrame, A., Feed for Supplemental Substances in Dietetic Foods, German Patent No. 735,037, April 1, 1943.
17. Bender, F., D.P. Heaney, and A. Bowden, "Potential of Steamed Wood as a Feed for Ruminants", Forest Prod. J., 20 (1970), 36.
18. Heaney, D.P. and F. Bender, "Feeding Value of Steamed Aspen for Sheep", Forest Prod. J., 20 (1970), 98.
19. Burke, J. (of Burke, Davoud & Associates, Richmond Virginia), Personnel communication, 1979.
20. Merriman, M.M., H. Choulett, and D.L. Brink, TAPPI, 49 (1966), 34-39.
21. Bicho, J.G., E. Zavarin, and D.L. Brink, TAPPI, 49 (1966), 218-226.
22. Brink, D.L. Y.T. Wu, H.P. Naveau, J.G. Bicho, and M.M. Merriman, TAPPI, 55 (1972), 719-721.
23. Schaleger, L.L. and D.L. Brink, TAPPI, 61 (1978), 65-68.

24. Fang, P. and G.D. McGinnis. J. App. Pol. Sci., Sym. 28 (1975), 363-376.
25. Fang, P., G.D. McGinnis, and E.J. Parish. Wood Fiber, 7 (1975), 136-145.
26. Fang, P. and G.D. McGinnis. In: Uses and Properties of Carbohydrates and Lignins. New York: Academic Press, 1976, pp. 37-47.
27. Millett, M.A., A.J. Baker, and L.D. Satter. Pretreatments Enhance Chemical, Enzymatic, and Microbiological Attack of Cellulosic Materials. Biotechnol. and Bioeng. Symp. No. 5, 1975, pp. 193-219.
28. Dunlap, C.E., J. Thomson, and L. Chang-Chiang. Treatment Process to Increase Cellulose Microbial Digestibility. AIChE Symposium Series 158, Biochemical Engineering - Energy, Renewable Resources, and New Foods, No. 72, 1976, pp. 58-63.
29. Brenner, W., R. Barry, R. Stanton, P. Armstrong, A. Kuan-Ming, and C. Rogers. Development of Continuous Acid Hydrolysis Process for the Utilization of Waste Cellulose. Solid and Hazardous Waste Research Division 5th Annual Research Symposium, Municipal Solid Waste: Resource Recovery, March 26-28, 1979, Orlando. Fl.
30. Saeman, J.F., M.A. Millet, and E.J. Lawton. "Effect of High Energy Cathode Rays on Cellulose," Ind. Eng. Chem., 44 (1952), 2848.
31. Rogers, C.J., E. Coleman, D.F. Spino, T.C. Purcell, and P., V. Scarpino. "Production of Fungal Protein from Cellulose and Waste Cellulose," Envir. Sci. Technol. 6 (1972), 715.
32. Schwartz, A.M. and C.A. Rader, Nitrite-Photodegradation Process for Polysaccharides, U.S. Patent No. 3,352,773, Nov. 14, 1967, to Gillette Co.
33. Pritchard, G.I., W.J. Pigden, and D.L. Minson, "Effect of Radiation on the Utilization of Wheat Straw by Rumen Micro-organisms", Can. J. Animal Sci., 42 (1962), 215.

34. Huffman, J.G., W.D. Kitts, and C.R. Krishnamurti, "Effects of Alkali Treatment on Gamma Irradiation on the Chemical Composition and in vitro Rumen Digestibility of Certain Species of Wood", Can. J. Animal Sci., 51 (1971), 457.
35. Kispert, R.G., L.C. Anderson, D.H. Walker, S.E. Sadek, and D.L. Wise, Fuel Gas Production from Solid Waste, Dynatech Report No. 1207, NTIS No. PB 238068, 1974.
36. Golueke, C.J., Comprehensive Studies of Solid Waste Management, Third Annual Report, U.S. Environmental Protection Agency, 1971.
37. Quindry, G.E., J.C. Liebman, and J.T. Pfeffer, Biological Conversion of Organic Refuse to Methane, Vol. II, Prepared for the National Science Foundation, Report No. NSF/RANN/SE/GI-39191/FR/76/4 Final Report. Urbana, IL: University of Illinois Civil Engineering Department, 1976.
38. RefCOM Status Report, 8th Quarterly Coordination Meeting, 5/4/78, Conversion/Solar Energy Division, DOE, A.S.E.F. Solid Waste to Methane Gas, Waste Management, Inc., Ft. Lauderdale, FL, 1978.
39. Braun, J.W., J.T. Pfeffer, and J.C. Liebman, Biological Conversion of Organic Refuse to Methane, Final Report No. NSF/RANN/SE/GI-39191/FR-76/4.
40. Coulter, J.B., S. Sunede, and M.B. Ettinger, "Anaerobic Contact Process for Sewage Disposal", Sewage and Industrial Wastes, 29 (1957) 468-477.
41. Young, J.C. and P.L. McCarty, "The Anaerobic Filter for Water Treatment", J. Water Pollut. Contr. Fed., 41 (1969) 160-173.
42. McCarty, P.L., "Anaerobic Treatment of Soluble Wastes", Special lecture series on Advances in Water Quality Improvement, Austin, TX: The University of Texas, 1966.
43. Jewell, W.J., H.R. Capener, S. Dell'orto, K.J. Fanfoni, T.D. Hayes, A.P. Lenschner, T.L. Miller, D.F. Sherman, P.J. von Svest, M.J. Wolin, W.J. Wujcik, Anaerobic Fermentation of Agricultural Residues: Potential for Improvement and Implementation, preliminary draft of final report prepared for U.S. Dept. of Energy - Fuels from Biomass Report EY-76-S-02-2981-7, 1978.

44. Augenstein, D.C., D.L. Wise, and C.L. Cooney, Resource Recovery and Conservation, 2 (1977) 257-262.
45. Sanderson, J.E., D.L. Wise, and D.C. Augenstein, Organic Chemicals and Liquid Fuels from Algal Biomass. Paper presented at 1st symposium on Biotechnology in Energy Production and Conservation, Gattlinburg, TN, April, 1978.
46. Hammer, M.J., Water and Wastewater Technology, New York: John Wiley & Sons, Inc., 1975.
47. Willimon, E.P., Jr., and J.F. Andrews, "Multi-Stage Biological Processes for Waste Treatment", J. Water Pollut. Cont. Fed., 41 (1969), 99-112.
48. Report of the Workshop on Biogas and Other Rural Energy Resources, United Nations Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand, 1977.
49. Harrison, J.R., and J.B. Goodson, Process Design Manual for Sludge Treatment and Disposal. Manual prepared by Black, Crow and Eidsness for the U.S. Environmental Protection Agency, Technology Transfer EPA 625/1-74-006, 1974.
50. Gallup, D.M. and P. Gerhardt, "Dialysis Fermentor Systems for Concentrated Culture of Microorganisms", Applied Microbiology, 11 (1963), 506.
51. Hammer, M.S. and J.A. Borchardt, "Dialysis Separation of Sewage Sludge Digestion", J. San. Eng. Div., ASCE, 95 (1969), 907.
52. Schaumburg, F.D. and E.J. Kirsch, "A Multistage Fermentation System for Fundamental Anaerobic Digestion Research", Purdue Univ. Eng. Bull. Ext. Ser., 121 (1966), 368.
53. Geisser, H.R. and J.T. Pfeffer, Biological Conversion of Biomass to Methane: The Effect of Reactor Design on Kinetics. Report prepared for U.S. Dept. of Energy under contract no. EY-76-S-02-2917, report no. UILU-Eng-77-2019, 1977.
54. Pohland, F.G. and S. Ghosh, "Development in Anaerobic Stabilization or Organic Wastes: The Two-Phase Concept", Environmental Letters, 1 (1971), 225-266.

55. Balch, W.E. and R.S. Wolfe, "Transport of Coenzyme M(2-Mercaptoethanesulfonic acid) in *Methanobacterium ruminantium*", Journal of Bacteriology, 1 (1979), 264-273.
56. Pohland, F.G. and S. Ghosh, Environmental Letters, 1 (1979), 255.
57. Pohland, F.G. and S. Ghosh, Biotechnol. and Bioeng. Symp. Paper No. 2, pp. 85-106, 1970.
58. Ghosh, S. and D.L. Klass, "Two-Phase Anaerobic Digestion", Process Biochemistry, 4 (1978), 15-24.
59. Ghosh, S., Institute of Gas Technology, Chicago, IL. Personal communication, 1979.
60. Ghosh, S. and D.L. Klass, Two-Phase Anaerobic Digestion, U.S. Patent No. 4,022,6645, May 10, 1977.
61. Klass, D.L., S. Ghosh, and J.R. Conrad, Anaerobic Digestion with Liberated Enzyme Biomass Fractions, U.S. Patent No. 3,994,780, Nov. 30, 1976.
62. Wise, D.L., R.L. Wentworth, D.C. Augenstein, and C.L. Cooney, "Multi-Stage Digestion of Municipal Solid Waste to Fuel Gas", Resource Recovery and Conservation, 3 (1978), 41-59.
63. Klass, D.L., Institute of Gas Technology, Chicago, IL. Personal communication, 1979.
64. Abeles, T.P., Energy and Economic Assessment of Anaerobic Digesters for Rural Waste Management, Rice Lake, WI: Oasis 2000, 1978.
65. Abeles, T.P., D. Elsworth, and J.P. Genereaux, Anaerobic Digestion of Agricultural Residues: A Technology Assessment. Solid and Hazardous Waste Research Division 5th Annual Research Symposium, Municipal Solid Waste: Resource Recovery, March 26-28, 1979, Orlando, FL.
66. Jewell, W.J., Anaerobic Fermentation of Agricultural Residues: Potential for Improvement and Implementation. Eleventh Quarterly Progress Report (12/16/78 - 3/15/79), U.S. Dept. of Energy Report No. COO-EY-S-02-2981-11. Ithaca, NY: Cornell Univ., 1979.
67. Jewell, W.J., Small Farm Methane Generation Potential, Proc. 2nd Annual Symp. of Fuels from Biomass, June 20-22, 1978, Troy, NY: Rensselaer Polytechnic Inst., 1978.

68. Ashare, E. and E. Wilson, Analysis of Digester Design Concepts, Dynatech Report No. 1885, prepared for U.S. Dept. of Energy under contract no. EY-76-C-02-2991.*000, 1979.
69. Ham, R.K., K.K. Hekimian, S.L. Katten, W.J. Lockman, R.J. Lify, D.E. McFadden, and E.J. Daley, Recovery, Processing, and Utilization of Gas from Sanitary Landfills. Prepared for U.S. Environmental Protection Agency, report no. EPA-600/2-79-001. Monterey Park, CA: Lockman & Assoc., 1979.
70. Carlson, J.A., Recovery of Landfill Gas at Mountain View: Engineering Site Study. City of Mountain View Final Report for U.S. Environmental Protection Agency, grant no. S803396 01, 1977.
71. Boyle, W.C., "Energy Recovery from Sanitary Landfill: A Review", in Microbial Energy Conversion, H.G. Schlegel and J. Barnea, eds. NY: Pergamon Press, 1977, 119-138.
72. Bishop, W.D., R.C. Carter, and H.F. Ludwig, "Gas Movement in Landfilled Rubbish", Public Works, 96 (1965), 64-68.
73. Bishop, W.D., R.C. Carter, and H.F. Ludwig, "Water Pollution Hazards from Refuse-Produced Carbon Dioxide", J. Water Pollut. Cont. Fed., 38 (1966), 328-329.
74. In Situ Investigation of Movements of Gases Produced from Decomposing Refuse. California State Water Quality Control Board, final report no. 35, Sacramento, CA, 1967.
75. Blanchet, M., Start-up and Operation of the Landfill Gas Treatment Plant at Mountain View. Solid and Hazardous Waste Research Division 5th Annual Research Symposium, Municipal Solid Waste: Resource Recovery, March 26-28, 1979, Orlando, FL.
76. Bowerman, F.R., N.K. Rohatji, and K.Y. Chen, eds., A Case Study of the Los Angeles Sanitation Districts Palos Verdes Landfill Gas Development Project. U.S. Environmental Protection Agency, NERC Contract No. 68-03-2143, 1976.
77. DeWalle, F.B., E.S.K. Chian, and E. Hammerberg, "Gas Production from Solid Waste in Landfills", J. Envir. Engring. Div., 104 (1978), 415-432.

78. McCarty, P.L., "Anaerobic Waste Treatment Fundamentals", Public Works, 95 (1964), 9-12.
79. Klass, D.L. and S. Ghosh., SNG from Biogasification of Waste Materials, Institute of Gas Technology Paper presented at SNG Symposium I, March 12-16, Chicago, IL, 1973.
80. Millett, M.G., A.J. Baker, W.C. Feist, R.W. Mellenberger, and L.D. Satter, "Modifying Wood to Increase its in vivo Digestibility", J. Anim. Sci., 31 (1970), 781-788.
81. Mandels, M., L. Hantz, and J. Nystrom, "Enzymatic Hydrolysis of Waste Cellulose", Biotech. Bioeng., 16 (1974), 1471.
82. Emcon Associates, The State of the Art of Landfill Gas, preliminary draft, 1979.
83. Augenstein, D.C., D.L. Wise, R.L. Wentworth, and C.L. Cooney, "Fuel Gas Recovery from Controlled Landfilling of Municipal Wastes", Resource Recovery and Conservation, 2 (1976), 103-107.
84. Dynatech R/D Company, Unpublished results, 1979.
85. Buivid, M.G., Controlled Landfilling of Municipal Solid Waste, unpublished results, Dynatech R/D Company, Cambridge, MA, 1979.
86. Ashare, E., D.C. Augenstein, J.C. Young, R.J. Hossan, and G.L. Duret, Evaluation of Systems for Purification of Fuel Gas from Anaerobic Digestion, Dynatech Report No. 1628, submitted to U.S. Dept. of Energy under contract EY-76-C-02-2991.*000, July 30, 1978.
87. Ashare, E., A.C. Sharon, and S.R. White, Engineering Economic Analysis of Biomethanation of Pyrolysis Gas, Final Report on Contract EM-78-C-01-5154, Dynatech Report No. 1885, March, 1979.
88. Augenstein, D.C., D.L. Wise, R.L. Wentworth, P.M. Gallaher, and D.C. Lipp, Investigation of Converting the Product of Coal Gasification to Methane by the Action of Microorganisms, Final Report No. FE-2203-17 under contract no. E(49-18)-220, January, 1977.
89. Spano, L.L., Enzymatic Hydrolysis of Cellulosic Wastes to Fermentable Sugars for Alcohol Production, Clean Fuels from Biomass, Sewage, Urban Refuse, and Agricultural Wastes Symposium, Jan. 27-30, 1976, Orlando, FL.

90. Montenecourt, B.S. and D.E. Everleigh, Hypercellulolytic Mutants and Their Role in Saccharification, Proc. of Second Annual Symp. on Fuels from Biomass, June 20-22, 1978, Troy, NY: Rensselaer Polytechnic Inst., pp. 613-625, Vol. 2.
91. Mandels, M., S. Dorval, and J. Medeiros, Saccharification of Cellulose with Trichoderma Cellulase, Proc. of Second Annual Symp. of Fuels from Biomass, June 20-22, 1978, Troy, NY: Rensselaer Polytechnic Inst., pp. 627-669, Vol. 2.
92. Wang, D.I.C., C.L. Cooney, S. Wang, J. Gordon, and G.Y. Wang, Anaerobic Biomass Degradation to Produce Sugars, Fuels, and Chemicals. 2nd Annual Symp. on Fuels for Biomass, June 20-22, 1978. Rensselaer Polytechnic Institute, Troy, NY, pp. 537-570.
93. Brooks, R.E., W.D. Bellamy, and T. Su, Bioconversion of Plant Biomass to Ethanol. 2nd Annual Symp. on Fuels from Biomass, June 20-22, 1978, Rensselaer Polytechnic Institute, Troy, NY, pp. 511-536.
94. Pye, E.K., Thermophilic Degradation of Cellulose for Production of Liquid Fuels. 2nd Annual Symp. on Fuels from Biomass, June 20-22, 1978, Rensselaer Polytechnic Institute, Troy, NY, pp. 601-608.
95. Spano, L., A. Allen, T. Tassinari, M. Mandels, and D.D.Y. Ryu, Reassessment of Economics of Cellulase Process Technology: For Production of Ethanol from Cellulose, Proc. of Second Annual Symp. on Fuels from Biomass, June 20-22, 1978, Troy, NY: Rensselaer Polytechnic Inst., pp. 671-684, Vol. 2.
96. Porteous, A., Towards a Profitable Means of Municipal Refuse Disposal, ASME Publ. 67-WA PID-2.
97. Saeman, J., "Kinetics of Wood Hydrolysis - Decomposition of Sugars in Dilute Acid at High Temperature", Ind. Eng. Chem., 37 (1945), 43.
98. Fagan, R.D., H.E. Grethlein, A.O. Converse, and A. Porteous, "Kinetics of the Acid Hydrolysis of Cellulose Found in Paper Refuse", Envir. Sci. and Tech., 5 (1971), 545-547.
99. Grethlein, H.E., "A Comparison of the Economics of Acid and Enzymatic Hydrolysis of Newsprint", Biotechnol. and Bioeng., 20 (1978), 503.

100. Grethlein, H.E., Acid Hydrolysis of Cellulosic Biomass, Proc. of Second Annual Symp. on Fuels from Biomass, June 20-22, 1978, Troy, NY: Rensselaer Polytechnic Inst., pp. 461-479, Vol. 1.
101. Brenner, W., B. Rugg, R. Stanton, R. Armstrong, K-M Ang, and C. Rogers, Development of Continuous Acid Hydrolysis Process for the Utilization of Waste Cellulose. Presented at U.S. EPA 5th Annual Research Symp., Solid and Hazardous Waste Research Division, Orlando, FL, 1979.
102. Srinivasan, V.R., Production of Methane from Acid Hydrolysates of Cellulose Wastes. Presented at U.S. EPA 5th Annual Research Symposium, Solid and Hazardous Waste Research Division, Orlando, FL, 1979.
103. Sanderson, J.E. and D.L. Wise, Liquid Fuels from Biomass, Progress Report No. 5 on Contract EG-77-C-02-4388, Dynatech Report No. 1840, September, 1978.
104. Wang, D.I.C., C.L. Cooney, S. Wang, J. Gordon, and G.Y. Wang, Anaerobic Biomass Degradation to Produce Sugars, Fuels and Chemicals, Proc. of Second Annual Symp. on Fuels from Biomass, June 20-22, 1978.
105. Sanderson, J.E. and D.L. Wise, Liquid Fuels Production from Biomass, Progress Report No. 7 on Contract EG-77-C-02-4388, Dynatech Report No. 1889, April, 1979.
106. Taylor, D.M., G.R. Peterson, and B.G. Stokes, "Bioconversion of Biomass to Fuels and Chemicals" in Bioconversion Study Conducted by NASA Jet Propulsion Laboratory, November, 1978.
107. Rugg, B., New York University: personal communication.

SECTION 8

SOURCE SEPARATION

8.1 Technology Description

Source separation is a recycling process that commonly involves the public service sector and private citizens. Municipal officials ask members of a community to separate recyclable materials (either on a voluntary basis or as directed by ordinance) from their normally generated refuse. These recyclable materials usually include newspapers, bottles, and cans.

In some communities, citizens are instructed to separate clear and colored glass. Metal cans are often tolerated with either glass group because they are easily extracted through magnetic separation. The recyclable materials are frequently collected from homes by special crews and are either transferred or delivered directly to the materials purchaser.

An alternative to collection is the designation of special bins at the local landfill where glass, cans, and paper may be deposited. Recycling centers may be established where glass can be color-sorted, cans crushed, and newspapers baled prior to sale.

Among the benefits of source separation are an energy saving due to the displacement of raw materials that would otherwise be required for the manufacture of selected products; enhanced environmental preservation attributed to the reduced volume of solid waste requiring disposal; a potential economic benefit associated with revenues and waste volume reduction, and increased conservation of natural resources.

8.2 Technology Status

8.2.1 Technical

According to a draft of a recent EPA study [1], 218 municipal source separation programs were in operation in mid-summer 1978. Of this total, 14 percent collected metals and/or glass. Ninety-nine

percent recovered some form of wastepaper. The American Iron and Steel Institute projects that more than 50 billion steel cans per year will be magnetically extracted from residential waste by 1988. This reclamation would equal about 10,000 tons of steel per day. Recent attention has also been paid to collecting high-grade office paper and corrugated cardboard commonly present in commercial waste.

One of the most important features of a recycling program is the collection vehicle. Several designs and modifications are currently being used (some experimentally) across the country. Reducing vehicle manpower requirements and thereby cutting operating costs will make recycling more attractive. Many trucks now in operation require three-man crews -- one driver and two collectors. These vehicles are often too high to allow the driver to participate in the actual collection. Furthermore, inordinate vehicle height frequently causes interference with telephone and electrical wires by the hydraulic top-loading buckets.

A specially designed one-man truck has been developed by LoDal, Inc. in an effort to curb manpower requirements. This vehicle has a stand-up, optional side drive for added operator convenience. The truck is fitted with newspaper, can, and bottle storage as well as a rubbish hopper. One problem with this design is that the recycling capacity may be reached before the rubbish capacity, depending on the proportion of each group collected. This results in either the truck making trips to the transfer sites at less than full capacity, or in the routemen combining the recyclables with the rubbish until full capacity is reached. Both of these situations are undesirable.

Flat-bed trucks have been used in some communities solely for recycling. These vehicles are either open (for collection of one item, such as newsprint) or divided into compartments. High manpower demands (two to four men) and insufficient capacity are limitations associated with these arrangements.

Two other essential components of a recycling program are public awareness and community participation. These elements encompass a variety of considerations including degree of convenience,

extent of the publicity and education campaign, and reasons for participation.

In some communities, such as Nottingham, New Hampshire, private haulers or individuals deposit the recyclables at a recycling center. The participants must separate newspaper, glass, and cans. At the center, attendants stack newspaper, check bottles for caps and rings, and color-sort glass. A small magnetic separator extracts the ferrous cans from the aluminum prior to crushing. Glass is crushed, and newspaper is prepared in bales. A center such as this has the advantage that it requires little effort on the part of the residents and it provides a more desirable product to the markets. This kind of operation, however, can be expensive. The costs often exceed the market revenues due to the capital cost of the center and the high cost of labor to operate it.

In communities where recyclables are taken from the home or collection box directly to the marketplace, purchasers often demand that glass be color-sorted and caps and rings removed. These requirements are impossible to supervise and necessitate additional cooperation on the part of the consumer.

Special separation containers are available for use in the home. Many container designs consist of light, plastic, stackable compartments designed to save space and add convenience. The units can be easily identified by collection crews when placed at the curbside. Some programs have distributed the containers or have made them available to their participants (e.g., Santa Rosa, California, and Nottingham, New Hampshire) although they can be purchased by anyone.

In addition to convenience, community participation depends on an ongoing education and publicity program. Television and radio spots, newspaper articles, calendars, posters, logos, invitations, school visits, and pamphlets have all been used to "spread the word". Educational programs can provide citizens with reasons to participate. Even in communities where recycling is mandatory, participation may only be on the order of 40 to 60 percent.

8.2.2 Economic

The economic status of recycling programs depends on the availability and proximity of markets, individual program efficiency, and optimal use of manpower. Assessment of a program's economic effectiveness depends on whether or not the program is intended to be money-making or money-saving. Because several communities take aim at a profit-making plan, many programs are considered unsuccessful because they increase the total cost of waste collection and disposal. These judgements, however, do not take into account the potential energy savings and conservation of natural resources associated with a recycling program.

Although a program may not make money on a local level, there is an energy saving associated with using certain secondary materials. According to the Environmental Protection Agency [2], recycling aluminum requires less than 5 percent of the energy required to produce aluminum from ore. We must acknowledge, however, that in many recycling programs, recyclables are gathered by a separate collection, thus lowering the net energy savings achieved through use of secondary materials. This energy expense could be alleviated by simultaneous collection of rubbish and recyclables or by installing recycling bins at the local landfill for individual deposits. In the latter case, provided that residents must drive to the landfill for refuse disposal, a net energy saving can be achieved if recyclables are brought to the landfill on the same trip. If a recycling center is being operated apart from the landfill, however, the net energy saving of recycling is questionable considering the amount of gasoline used to drive to the center for the sole purpose of recycling.

Before a recycling plan can be implemented, markets for the recyclable materials must be established. Market proximity is essential because in many communities, transportation costs will exceed the revenues obtained from the sale of the recyclables. Because many towns are far away from potential markets (e.g., paper, steel,

and aluminum manufacturing plants), innovative uses for the recycled material must be developed. Examples of such uses include insulation and road construction material. Part of the success of the Marblehead, Massachusetts program can be attributed to the location of the markets in neighboring Salem.

Market prices are subject to extreme fluctuations (with the exception of aluminum, which has been increasing steadily in price since 1970). For example, newsprint prices dropped from a peak of \$38 to \$60/ton in the first part of 1974, to \$5 to \$25/ton six months later [3].

In the past, it has been extremely difficult to establish long-term contracts because of limited recycling experience. From the purchaser's point of view, consistency in supply and quality are of fundamental importance. A Miami-based paper recycler, Durbin Paper Stock Co., however, recently signed a 10-year self-renewing contract with Southeast Paper Manufacturing Co. to provide Southeast with up to 90,000 tons of waste newspaper per year. Durbin has signed long-term contracts with Miami-area municipalities in order to guarantee the supply. Southeast has agreed to construct a new paper manufacturing plant capable of using more than 80 percent secondary fibers. Southeast maintains that this plant will eliminate the large investment in forestland (on the order of \$50 million) necessary to build a paper plant feeding primarily on virgin materials. Furthermore, processing newsprint from old newspaper requires significantly less energy than making paper from virgin pulp. It is to be hoped that a trend change will result from this innovative arrangement and more cooperative efforts of this kind will be initiated.

8.2.3 Environmental

Source separation has a negligible effect on the environment. One possible environmental benefit could be realized if the recycling program were to result in a significant reduction in waste volume and weight. In this case, landfill requirements and environmental damage typically associated with land disposal methods

would be reduced. Although many recycling programs do not result in significant waste volume reductions (due in large part to poor community participation), with a participation rate of about 60 percent, Marblehead is able to recycle 25 percent by weight of its total residential waste stream. Off-site disposal of industrial waste which is not recycled, however, also must be considered in the overall waste disposal picture.

8.3 Research Status

The two most prominent demonstration recycling programs exist in Somerville and Marblehead, Massachusetts. Both communities received grants from the EPA. Somerville initiated source separation in December, 1975; Marblehead in January, 1976. Somerville's program is currently at a standstill. In the past, it could offer only intermittent service due to severe weather conditions and a strike. In May, 1978, the city was notified by their glass and can market that it would no longer purchase unsorted bottles and cans. Although paper collection continued, it too has been suspended because of a collapsed roof sustained by the paper buyer in a February, 1979 storm.

At its best, "Somerville Saves" had a participation rate of about 25 percent and was only able to recycle about 8 percent of the total residential waste stream. In 1977, as a result of a new disposal contract, Somerville's landfill costs decreased from \$14.95/ton to \$9.40/ton. For that same year, Somerville spent \$146,470 on source separation. With revenues received from the sale of recyclable materials (\$10,938) and credit accrued from the reduced waste volume (\$14,456), Somerville's program showed a net loss of \$121,076. On an actual cost basis (incremental cost to the community, excluding the cost of labor and equipment transferred from other waste-collection programs), the net loss sustained by the City was \$54,728 [3]. These figures correspond to a cost of approximately \$79/ton on a full cost basis and \$36/ton on an actual cost basis.

Difficulties with trucks spilling bottles and cans as the hydraulic bucket is tipped into the top-loading receptacle, interference of the rear door with the ground during dumping, subsequent breaking of the door hinges, and insufficient manpower and equipment (Somerville had to put one of its own trucks, with modifications, on the road) are among the problems encountered.

In contrast, Marblehead continues to operate a successful recycling program. As previously mentioned, Marblehead has enjoyed as high as 60-percent participation and has recycled as much as 25 percent of the total residential waste stream. For 1977, Marblehead's recyclables yielded \$25,540 in revenues. An additional \$41,084 in landfill costs were saved as a result of the reduced waste volume. On a full-cost basis, Marblehead experienced a net loss of \$23,760. On an actual-cost basis, however, the program yielded a net gain of \$16,788 [3]. These figures correspond to approximately \$11/ton expended (full cost) and \$8/ton saved (actual cost).

A history of recycling and the proximity of the markets are factors that have influenced the success of Marblehead's program. At one time, Marblehead collected rubbish twice each week. With the introduction of recycling, however, the town switched to separate collection of rubbish and recyclables each once per week, thus eliminating the cost of an additional collection for recycling. This kind of saving would not be realized by most communities Marblehead's size because normally, rubbish collection is performed only once per week.

In Santa Rosa, California, a pilot program funded by a \$45,000 grant from the California Solid Waste Management Board is under way. A continuing education and publicity campaign (assigned \$4,000 of grant money) is an important element of the program. Flyers, stickers, invitations, cards, pins, posters, and radio announcements are among the publicity tactics. Printing and distribution of promotional material comprises \$10,000 of the grant. City record-keeping is funded by a \$3000 allotment.

Standard compartmentalized containers have been purchased with \$28,000 in grant money and distributed to selected area households. The three stackable compartments house newspaper, glass, and cans, and can be wheeled to the curbside on collection days. With the containers, Santa Rosa has experienced more than 70-percent participation in the test areas. Specifically, 76 percent of the households on the test routes participated at least once during the test month. Approximately 17 percent participated every week.

Seven CETA employees staff the recycling program. Santa Rosa is currently using three 2-man, 3500-lb payload trucks. Each vehicle contains three open bins where glass, metal, and newspaper are deposited. The city is looking to a one-man 14,000-lb capacity truck to reduce manpower requirements and decrease the number of trips each truck must make each day (presently three to four).

In Davis, California, the Davis Waste Removal Co. will soon begin experimenting with an innovative recycling vehicle. Davis will use two Cushman motor scooters (with a dumpbox for newspapers) pulling tiny trailers capable of carrying four garbage cans for glass and metals. These vehicles will work full-time, servicing each of Davis' 8000 single-family homes, once each week. A mother trailer will be situated in a central location to the day's route where the Cushmans can deposit full garbage cans and pick up empties, and dump the newspaper. At the end of the day, the mother trailer will transport the recyclables to a processing facility. An arrangement such as this would not be suitable in areas of climate extremes (e.g., cold, snow, and ice). Furthermore, the four required transfers of material might constitute an unnecessary expenditure of time and effort.

The source separation program in Davis costs residents about \$5000 per month. The Davis Waste Removal Co. maintains that if the recyclables were treated as waste, disposal costs would still meet the \$5000 figure. Although the program is not profitable in a monetary sense, environmental benefits, conservation of resources, and improved attitudes towards wastes make source separation advantageous for Davis.

In April, 1979, Recycling and Conservation, Inc. began a 3-month test program with the "Separated Discards Carrier" (SDC) in Kittery, Maine. The SDC is a collection vehicle fitted for concurrent collection of rubbish and recyclables. The truck is equipped with a 15 cu. yd. rubbish receptacle, and gruncher (a continuously rotating auger that increases compaction and reduces collection time). Two bucket lifts are located in front of the gruncher. Bottles and cans are placed in the buckets and lifted to the top of the truck, where the bottom of the bucket drops out. Baffles installed in the receiving bins help to break the fall of materials. A three-man crew is required to operate the vehicle.

8.4 Research Needs for Source Separation

Over the past several years, numerous source separation programs have been initiated around the country. However, many of the programs which have been started have failed, due to lack of public participation or unexpected high costs. The high costs of certain types of source separation programs are often unanticipated because elected officials are unaware of the true costs involved in setting up a program and what realistic revenues will be.

It is widely recognized that public participation is a function of many factors, such as economic status, publicity effort, and community education. Methods to improve public participation have been developed and further work in this area is not necessary at this time. Research needs, therefore, are directed at improving the information transfer to elected officials on the technical and economic aspects of source separation.

It is also recognized that secondary material freight rates, collection vehicle design, container design, and uses of recycled materials all impact on the viability of source separation. However, research work on these areas is not essential to the implementation of source separation. What is needed, is for elected officials to have an understanding of the configurations and associated costs and revenues of various source separation systems.

The following is a list of source separation research needs, which are also presented in Table 8.4-I

- Develop a methodology for determining the net energy saving or expenditure (per ton of recycled material) associated with various source separation procedures. An analysis of the net energy saving or consumption needs to be conducted for various source separation alternatives. For example, curbside collection of recyclables by separate collection vehicles may consume more energy than is conserved by recycling. Likewise, hauling of recyclable materials by private citizens to local recycling centers may consume more energy in the form of gasoline than is saved by recycling.

- Develop a source separation implementation manual for municipal officials that can be used to calculate manpower and vehicle requirements, and realistic cost estimates. Although circumstances vary in each community, any level of standardization or establishment of criteria or guidelines will facilitate implementation of more efficient and effective recycling programs. This manual should also include a computer software package which could be used to determine the most economical method of recyclable collection, in terms of collection frequency, vehicle configuration, crew size, and route collection, given specific data describing the community.

8.5 Research Program for Source Separation

With source separation programs being initiated in many communities around the country, it is necessary to know the true impact these programs have on net energy savings or expenditures. A study should be conducted to develop a methodology to determine the net energy gained by a number of particular source separation programs. Net energy is considered to be not only the energy conserved by the reuse of materials, but also the energy expended to bring these recyclable materials to the reuse market. The energy expended includes the fossil fuel consumed in the haul of these recyclable materials from the home to a recycling center and/or market.

Table 8.4-I

Technical Research Needs for Source Separation

- Develop a methodology for determining the net energy savings or expenditure (per ton of recycled material) associated with various source separation procedures.
- Develop a source separation implementation manual for municipal officials that can be used to determine manpower and vehicle requirements and realistic program costs.

This study would address a number of general scenarios, and include variables such as:

- community size
- type and quantity of materials recycled
- frequency of collection
- method of collection and haul, i.e., curbside, pick-up or self-haul
- type of haul vehicle
- haul distance from source to final market.

The study would involve developing mathematical functions to describe energy consumption or conversion for various facets of a source separation program, such as Btus/mile for packer haul, transfer haul, and auto haul as a function of the amount of recyclables hauled.

The model would enable the user to determine what type of source separation program conserves the most energy and what the system configuration must be. For existing source separation programs, the model would be useful in calculating the net amount of energy gained or lost by the particular source separation program. This would be a valuable tool for Federal officials to use in directing the approach and progress of future source separation programs. Cost of this study would be about \$40,000 to \$50,000, with a six month duration.

A parallel effort should also be directed at developing a source separation manual for municipal officials, which can be used to estimate manpower and vehicle requirements, and realistic costs and revenues. As part of this study, a model should be developed to determine collection frequency, vehicle configuration, crew size, and route collection. The results of this model or the actual computer software should be part of the manual. In this manner, municipal officials will have a method for determining the frequency of recyclable collection, number and types of vehicles to use, and approximate costs and revenues. Cost of this study would be about \$100,000, with a 12 month duration.

REFERENCES: SECTION 8. SOURCE SEPARATION

1. D. M. Cohen, "Separate Collection Programs, A National Survey," Draft Report, U.S. Environmental Protection Agency, 1978.
2. U.S. Environmental Protection Agency, Fourth Report to Congress, Resource Recovery and Waste Reduction, prepared by the Office of Solid Waste, 1977.
3. Resource Planning Associates, "Solid Waste Recovery Programs in Somerville and Marblehead, Massachusetts," Monthly Reports: January, 1977 through December, 1977; January, 1978.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A
METHODOLOGY FOR RD&D PLAN DEVELOPMENT

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A

METHODOLOGY FOR RD&D PLAN DEVELOPMENT

A.1 Ranking of Technologies

The following methodology has been developed for ranking resource recovery technologies in terms of their near-term (less than five years) and longer-term (up to 15 years) commercialization potentials. Use of this procedure will provide a method for funding allocation to the various technologies. For example, if mass burning steam generation and refuse-derived fuel (RDF) processes ranked high in the near-term commercialization evaluation, and enzymatic hydrolysis ranked low but showed strong promise for longer-term commercialization, then near-term RD&D allocations should not only fund or be used for mass burning and RDF processes, but also for development of enzymatic hydrolysis. Development of promising longer-term technologies must begin now if their commercialization is to be realized in 10 to 15 years.

Table A.1-I shows the matrix for ranking technologies. A weight evaluation criteria method is used for the analysis. Rows identify the various resource recovery technologies, and columns represent the criterion applied to each technology. Each criterion is given a weight on a scale of 1 to 5. The methodology is flexible in that it enables someone to set his or her own priorities by placing different weights on each evaluation criterion.

The potential impact of a technology on an evaluation criterion is determined by the procedure which follows. The value that is obtained from this procedure is then multiplied by the criterion weight to obtain a total score for the impact of a technology on a criterion. The sum of the scores for a technology (in a row) for all the criteria gives the Merit Value. This measures the likelihood of widespread commercialization of the technology either in the near-or longer-term. An explanation of the evaluation criteria and the method of calculating a score for each is discussed below.

Table A.1-I

Evaluation of Resource Recovery Technologies

Technology	Criteria No.	1	2	3a	3b	4	5	6		
	Weighting	4	3	5		4	2	5		
		Net Tipping Fee	Potential Service Area	Energy	Material Product Value	Potential for Environmental Pollution	Waste Type Flexibility	Readiness for Commercialization	Merit Value	
									Near-Term 1-6	Long-Term 1-5
Mass Burning Steam Generation										
Controlled Air Modular Combustion										
RDF Co-Fired Utility/Industry Boiler										
RDF-Dedicated Boiler (100% RDF)										
Pyrolysis										
- indirect heated										
- air blown										
- oxygen blown										
Anaerobic Digestion										
- conventional										
- high solids										
Landfill Gas Recovery										
- existing landfills										
- enhanced landfills										
Ethanol Production										
- acid hydrolysis										
- enzymatic hydrolysis										
Alkane Production										
Acetic Acid Production										
In-Plant Materials Recovery										
Source Separation										

For weighting the criteria, Readiness for Commercialization, and Energy or Material Product Value are given weights of 5 which gives them the highest importance. Net Tipping Fee and Potential For Environmental Pollution are next in importance and are given a weight of 4. From a conceptual viewpoint, these two criteria are a measure of how widespread the implementation of a particular technology will be in the areas of the country where it is applicable. They therefore indicate how much of the potential shown in Readiness for Commercialization and Energy or Material Product Value can actually be realized.

How widespread the implementation of a technology will be is further determined by Potential Service Area. Thus, it is ranked next in importance with a weight of 3. Waste Type Flexibility, is considered least important and is ranked accordingly. The following sections describe how each criterion is evaluated.

A.1.1 Net Tipping Fee

Table A.1-II is the evaluation form used for Net Tipping Fee. Since some technologies under consideration are basically add-on features (material recovery, landfill gas recovery, source separation), they do not have a tipping fee associated with them.^A However, they do change the tipping fee of the system to which they are added. The lower portion of Table A.1-II is used for technologies with this add-on feature.

A.1.1.1 Weighting of Cost Components. Since operating costs are subject to inflation, a high operating cost was considered the worst condition and therefore given the lowest weight, and a low operating cost was given the highest weight.

Capital cost, on the other hand, becomes fixed at a point in time (once the plant is constructed and the capital amortized) and therefore, although a low capital cost is desirable, it is not as

Table A.1-II

Evaluation of Criterion 1 - Net Tipping Fee

			Cost Component			
			Capital ^a		Operating ^b	
			High	Low	High	Low
Weight			2	3	1	4
Estimated Net Tipping Fee ^c	Low	6				
	Medium Low	5				
	Medium High	4				
	High	3				
Estimated Change in Net Tipping Fee ^d	Large Reduction	3				
	Medium Reduction	2				
	Low Reduction	1				
	Increase	0				

^aCapital: High-Low dividing line = \$32,000 per daily ton of capacity.

^bOperating: High-Low dividing line = \$12/ton

^cEstimated Net Tipping Fee

Low	Less than \$8/ton
Medium Low	\$8-\$15/ton
Medium High	\$15-\$20/ton
High	Over \$20/ton

^dEstimated Change in Net Tipping Fee

Large	Greater than \$2/ton
Medium	\$1-\$2/ton
Small	Less than \$1/ton

NOTE: Normalizing Scale Factor = $\frac{5}{42}$

Example:

Estimated Net Tipping Fee = \$13/ton

Capital Cost = \$40,000/ton of daily capacity

Operating Cost = \$10.50/ton

Total Score = $\left[\frac{\text{Capital Cost}}{\text{Weight}} \times \text{Tipping Fee} \right] + \left[\frac{\text{Operating Cost}}{\text{Weight}} \times \text{Tipping Fee} \right]$

Total Score = $[2 \times 5] + [4 \times 5] = 30$

Normalized Score = Total Score x Scale Factor

Normalized Score = $30 \times \frac{5}{42} = 3.6$

advantageous as a low operating cost. Therefore, it is weighted one point lower. Similarly, a high capital cost is not as undesirable as a high operating cost and it is therefore weighted one point higher.

A.1.1.2 Weighting of Tipping Fee Ranges - For evaluation purposes, four ranges of tipping fees were established for technologies having a discrete tipping fee and four ranges for those which have only an incremental effect on tipping fee. These ranges are shown in Table A.1-II.

It is judged that a system with a high tipping fee should score equally with an add-on subsystem, i.e. materials recovery or source separation, that produces a large reduction in the tipping fee. From this point of agreement, the scores then get progressively higher as the tipping fee goes down, and progressively lower as the reduction in tipping fee gets smaller.

A.1.1.3 Calculation of Net Tipping Fee. Net tipping fee indicates the net cost of waste disposal including capital and operating costs, and revenues from the sale of energy and materials. For technologies that are operating at full-scale, actual cost data or recently submitted contractor proposals are used to estimate tipping fee. However, assumptions must be made in order to compare technologies on a common basis. Assumptions which are used in subsequent cost calculations are: full service operation of the resource recovery facility with 100 percent Pollution Control Revenue Bond financing for the life of the project, i.e. 20 years, with no equity participation.

For bioconversion technologies, tipping fee will be based on existing cost estimates if available. However, to be consistent with the above cost estimates, the accounting procedures outlined in Tables A.1-III and A.1-IV should be used. This analysis assumes that each technology will be operated under a full-service contract for 20 years, and that the facility will be completely financed by Pollution Control Revenue Bonds at an eight percent interest rate.

Table A.1-III

Capital Cost Calculation - Bioconversion Technologies
Basis: 1000 tpd MSW

Capital Cost

Land	\$10,000/acre
Site Preparation ^a	\$40,000/acre
Installed Equipment Cost	--
Construction	12% of installed equip- ment cost
Installed Plant Cost	--
Design	6% of installed plant cost
Contingency	20% of installed plant cost
Total Plant Cost	--

Finance Costs

Underwriters Fee	2.5% of bond issue
Bond Reserve Fund	1 year of debt service
Interest During Construction	8% inflation rate, 6% bank interest rate
Start-up and Working Capital	5% of bond issue
Total Bond Issue	--

^aSite preparation for landfill estimates: \$10,000/acre

Table A.1-IV

Net Tipping Fee Calculation
Bioconversion Technologies

Basis: 1000 tpd MSW

Annual Income Statement

Revenues

Product Sales ^a	--
Disposal Credits, Sewage Sludge	\$50/dry ton
Tipping Fee	--
Total Annual Revenues	--

Expenses

Annual Capital Cost	
CRF (8% int., 20 yrs.)	
x bond issue	--
Annual Operating Cost	
Salaries & benefits	\$25,000/person
Fuel oil	\$.32/gal. #6 oil
Electricity	3¢/kwh
Chemicals	Lime \$25/ton;
	Sulfuric Acid \$56/ton
Water & sewer	\$1/1000 gal.
Maintenance	5% of Total Installed Cost
Residue disposal	\$30/wet ton digester cake;
	\$10/ton other
Taxes, licenses & insurance	1/2% of Total Annual Operating Cost
Professional services	1/2% of Total Revenues
Net Profit	<u>10% of Total Revenues</u>
Total Annual Operating Cost	--
Total Annual Expenses	--

^a Methane - \$1.70/MM Btu
 Ferrous - \$17/ton
 Ethanol (95%) - \$0.99/gal.
 n-Decane - \$0.51/gal.
 Hydrogen - \$2.55/MM Btu
 Yeast - \$180/ton

Proceeds from the sale of the bonds are reinvested in a bank account at 6 percent interest. This account is then used to pay the underwriters fee and construction costs. Construction costs are paid in four equal installments, with the first on the date that the bond proceeds are received, and the last on the day construction is completed. This account is also drawn on to pay interest to bond holders during the construction period. At the end of the construction period, the money remaining in the account consists of working capital and bond reserve. Interest received from the bank is used to reduce the interest paid to bond holders during construction.

Battery limits for each technology are the delivery of MSW in packer or transfer trucks to the facility and the discharge of all treated effluent streams so that they meet all legal requirements. Energy and material products will be in their marketable form. Therefore, bioconversion technologies include an RDF processing plant along with the biological process equipment. Treatment of liquid effluent is also included.

Total plant cost is escalated at eight percent per year during the planning and design period, from January, 1980 to the beginning of construction. Total plant cost is also escalated at eight percent during construction, based on the assumption that the outstanding construction expenditures decrease linearly during the construction period, and that all expenditures escalate at the same inflation rate, i.e., 8 percent.

The Total Bond Issue is calculated based on Escalated Plant Cost. The present value of the Total Bond Issue (1980 dollars) is determined, using a discount rate of 10 percent. The Annual Income Statement is in 1980 dollars, with the Annual Capital Cost based on the present value of the Total Bond Issue. Costs are based on a facility with an annual MSW throughput of 364,000 tpy unless otherwise noted.

Tipping fee is calculated using an annual income statement format. Revenues result from product sales (energy or materials), disposal credits and tipping fee. Values assumed for the various revenue products are listed in Table A.1-IV. Ferrous at \$20/ton is the only material for which credit is given. Disposal credits are for sewage sludge at \$50/dry ton in co-disposal processes. Tipping Fee is back calculated through an iterative procedure using the format in Table A.1-IV. A net profit of 10 percent of Total Revenues is given to the facility operator. Unit costs for annual expenses are given in Table A.1-IV.

It must be stressed that the above costing procedures will only give a ballpark estimate of true system cost. In fact, most of the technologies are only at the bench-scale, and full-scale process flowsheets remain uncertain. Experience has shown that engineering estimates of embryo technologies have often overestimated revenues and underestimated capital and operating costs. This will likely be the case for the above analyses; however, they do serve as an initial screening tool for promising technologies.

For technologies that do not fall into the above two categories, tipping fees should be qualitatively estimated based on consideration of the type and value of the energy product, degree of system complexity, and level of capital intensity.

A.1.1.4 Evaluation of Net Tipping Fee Criterion. Once an estimated tipping fee or change in tipping fee is established, the evaluation matrix (Table A.1-II) is completed. Classification of capital and operating cost components are determined as high or low. The numerical weights of the two cost components are then individually multiplied by the numerical weight which corresponds to the value of the net tipping fee. These two values seem to obtain a total score for the technology. This score is then normalized on a scale of 0 to 5 by multiplying by a scale factor of 5/42. The denominator of this factor, 42, is the maximum score obtainable in the matrix, i.e., low capital and operating cost for a technology with a low (<\$8/ton) estimated tipping fee.

A.1.2 Potential Service Area

Table A.1-V is the evaluation form for Potential Service Area. Since DOE is interested in the energy aspects of resource recovery, more energy will be added or conserved by implementing systems in the highly populated areas, and therefore a system which is applicable in the urban environment receives the highest score. The other parameter considered is the technology's applicability to various parts of the country. For example, fluff RDF co-fired in a utility or industrial boiler has its greatest market in the Midwest where large amounts of coal are burned. However, it is quite limited in the East where most utilities burn oil. A technology that produces a liquid fuel would have relatively easy marketability throughout the country. A technology may also be limited in service area due to environmental restrictions. The technology with unlimited applicability receives the highest score which is four times higher than the most severely limited technology. A technology has either unlimited, moderately limited or severely limited application but it may be suitable for either one or all of the three service areas, i.e., urban, suburban and rural.

A.1.3 Energy Product Value

Table A.1-VI is the evaluation form for Energy Product Value. The horizontal axis, labeled Fuels Replaced, refers to the fossil fuels that will be replaced or not consumed with implementation of a particular resource recovery technology. Oil, gas and coal are considered to be the fuels that will be replaced.

On the vertical axis are the energy commodities produced from the various resource recovery technologies. A direct replacement fuel would be pyrolytic oil or gas, or methane from bioconversion processes. A limited replacement fuel is one that is co-fired with the primary fossil fuel. An example of this would be fluff RDF. The commodity, Chemicals, includes alcohols, acetic acid and other chemical feedstocks or products. All of the energy commodities are considered equally desirable except the limited replacement fuel which loses one point due to its limitations.

Table A.1-V

Evaluation of Potential Service Area

		Applicability to Various Parts of the County		
		Unlimited	Moderately Limited	Severely Limited
	Weight			
Urban	3			
Suburban	2			
Rural	1			

Normalizing Scale Factor = $\frac{5}{24}$

Example: Mass Burning Steam Generation

Applicability: moderately limited, e.g., unlikely in
California

Service Area: Urban, Suburban

Total Score - Applicability weight x Σ service area weights

Total Score - $2 \times [3 + 2] = 10$

Normalized Score = Total Score x Scale Factor

Normalized Score = $10 \times 5/24 = 2.08$

Table A.1-VI

Evaluation of Criterion 3a - Energy Product Value

Commodity Produced	Fuel Replaced				
	Oil		Gas	Coal	
	#2	#6		High Sulfur	Low Sulfur
Steam	5	5	4	3	4
Direct Replacement Fuel	5	5	4	3	4
Limited Replacement Fuel	4	4	3	2	3
Electricity	5	5	4	3	4
Chemicals	5	5	3	3	4

a = Weight

b = $\frac{\text{Commodity fuel equivalent (CFE)}}{10^6}$

c = Weighted Energy Value = (axb)

$$\text{Energy Replacement Figure of Merit} = \frac{\sum c}{\sum a}$$

Table for Determining CFE

Commodity	CFE Equals
Steam	$\frac{\text{lbs. steam}}{\text{ton MSW}} \times \frac{\text{Btu}}{\text{lb. steam}} \times \frac{1}{\text{boiler efficiency (E)}}$; where E=.82 oil .85 gas .78 coal
Direct & Limited Replacement Fuel	$\frac{\text{Btu of fuel}}{\text{ton of refuse}}$
Electricity	$\frac{\text{Kwh}}{\text{ton of refuse}} \times \frac{10^4 \text{ Btu}}{\text{Kwh}}$
Chemicals	$\frac{\text{lbs of chemical}}{\text{ton of refuse}} \times \frac{\text{Btu's of fuel feedstock}}{\text{lb of chemical}}$

A weight is given to each Fuel Replaced category based on the energy commodity produced. The highest weight is given to replacement of #2 and #6 oil. Low sulfur coal (since its replacement helps the switch to low sulfur fuels) and gas are next in importance. Replacing high sulfur coal is deemed least important.

For each technology, Table A.1-VI is filled in based on the energy commodity produced and the fuel replaced. A technology can replace more than one fuel and can produce more than one energy commodity. For example, a mass burning combustion system can produce steam and/or electricity, and its energy product would be capable of replacing oil, gas and coal. Alternatively, fluff RDF is only a limited replacement fuel and would only be used to replace high and low sulfur coal.

To fill in the appropriate boxes in Table A.1-VI, the weight of the fuel replaced is multiplied by a commodity fuel equivalent (CFE) factor to obtain a weighted energy value. The CFE factor is defined as the amount of fuel replaced per ton of refuse, taking into account fossil fuel boiler efficiencies. The table at the bottom of Table A.1-VI shows how the CFE is calculated for each commodity. For scaling purposes, the CFE is divided by 10^6 .

The sum of all the weighted energy values is divided by the sum of the weights to obtain an Energy Replacement Figure of Merit for each technology. This method eliminates a bias for technologies that will replace more than one fossil fuel.

A.1.4 Material Product Value

Table A.1-VII is the evaluation form for Material Product Value. Due to the marketing advantages that a high quality product has, it is weighted twice as much as a low quality product. If the technology produces an unuseable product, it is given a score of zero.

Because of conflicting attributes of ferrous and aluminum recovery, they were both weighted equally. That is, production of aluminum is more energy intensive than ferrous, but the percentage of ferrous in refuse is much higher than aluminum. However, both were given twice the score of recovering glass and paper.

Table A.1-VII

Evaluation of Criterion 3b - Material Product Value

Grade	Weight	Material			
		Ferrous	Aluminum	Glass	Paper
		2	2	1	1
High Quality Scrap or Cullet	2				
Low Quality Scrap or Cullet	1				
Unmarketable	0				

$$\text{Normalizing Scale Factor} = \frac{5}{12}$$

A.1.5 Potential for Enviromental Pollution

Table A.1-VIII is the evaluation form for Potential for Environmental Pollution. A technology having a high potential for pollution is given the lowest score. Having a medium potential is three times as good as a high potential, and having a low potential is six times as good as a high potential but only twice as good as a medium potential.

A.1.6 Waste Type Flexibility

The evaluation form for Waste Type Flexibility is given in Table A.1-IX. If a technology requires that normal packer truck waste be presorted it receives a score which is half that of a technology that does not. If the technolgy has the capability of accepting special wastes, it is rated twice as good as one which only processes packer truck waste. A special waste, for example, would be sewage sludge.

A.1.7 Readiness for Commercialization

Table A.1-X is the evaluation form for Readiness for Commercialization. Technologies which have operational facilities processing MSW at production-scale on a day-to-day basis were rated highest. Technologies that have been demonstrated at production-scale but do not have a production facility on-line were rated slightly less. If the technology has only been demonstrated at a pilot-scale, it is rated half that of one that has a production-scale demonstration, and twice as good as one that has only been demonstrated at a bench-scale.

A.2 Summary of RD&D Plan Development Methodology

The preceding evaluation techniques are used to determine which technologies offer the greatest potential for wide-scale commercialization. Merit Values correlate directly to how widespread commercialization of a technology will be in the near- and longer-term based on present status.

Table A.1-VIII

Evaluation of Criterion 4--Potential for Environmental Pollution

		Low	Medium	High
	Weight	6	3	1
Air	6			
Water	5			
Land	4			

Normalizing Scale Factor = $\frac{5}{90}$

Table A.1-IX

Evaluation of Criterion 5-Waste Type Flexibility

Score	Description
1	Requires presorting
3	All packer truck waste
6	Accepts sewage sludge, tires, wood waste, agricultural waste.

$$\text{Normalizing Scale Factor} = \frac{5}{6}$$

Table A.1-X

Evaluation of Criterion 6--Readiness for Commercialization

Existing Status	Score
Demonstrated At Bench Scale	1
Demonstrated at Pilot Scale	2
Demonstrated at Production Scale	4
Operational Facility	5

Normalizing Scale Factor = 1

The methodology is flexible in that different weights can be placed on the criteria based on personal preferences or positions. In fact, alternate technology hierarchies can be developed, depending on the importance placed on different criteria.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX B

FACILITIES VISITED DURING RD&D PLAN PREPARATION

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX B

FACILITIES VISITED DURING RD&D PLAN PREPARATION

Akron, Ohio

Ames, Iowa

Baltimore County, Maryland

Bridgeport, Connecticut

Bureau of Mines, Avondale Metallurgy Research Center, Avondale, Maryland

Chicago Southwest Fuel Supplementary Plant, Chicago, Illinois

Chicago Northwest Incinerator, Chicago, Illinois

Combustion Power Co., Menlo Park, California

East Bridgewater, Massachusetts

Franklin, Ohio

Harrisburg, Pennsylvania

Hempstead, New York

Lane County, Oregon

Milwaukee, Wisconsin

Monroe County, New York

Mountain View, California

North Little Rock, Arkansas

Pan American Resources, Upland, California

Pompano Beach, Florida

Pyro-Sol, Inc., Redwood City, California

Recovery I, New Orleans, Louisiana

Hooker Energy Corporation, Niagara Falls, New York

RESCO, Saugus, Massachusetts

SWARU, Hamilton, Ontario

Tacoma, Washington

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX C

LIST OF WORKSHOP ATTENDEES FOR DOE RD&D PLAN REVIEW

June 12 and 13, 1979

Colonial Hilton, Wakefield, Massachusetts

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX C

LIST OF WORKSHOP ATTENDEES FOR DOE RD&D PLAN REVIEW

Harvey Alter
Director of Research Programs
National Center for Resource
Recovery
1211 Connecticut Avenue
Washington, DC 20036

John Basic
Basic Engineering
21 West 161 Hill Avenue
Glen Ellyn, IL 60137

Joseph Berke
Manager, Resource Recovery
Program
Office of Recycled Materials
Bureau of Standards
Physics Building, B-326
Washington, DC 20234

Max Blanchet
245 Market Street
Pacific Gas & Electric Company
San Francisco, CA 94134

Alan S. Cohen
CSI Resource Recovery Systems
55 Union Street
Boston, MA 02108

Peter Donnelly
Energy and Environmental Systems
Division
Argonne National Laboratory
Argonne, IL 60439

John C. Ellis
Plant Manager
Department of Streets and
Sanitation
Bureau of Sanitation
3757 West 34th Street
Chicago, IL 60623

Chris Ganotis
Wheelabrator-Frye, Inc.
Liberty Lane
Hampton, NH 03842

Jerry Hagenbach
Union Carbide Corporation
Linde Division
P. O. Box 44
Tonawanda, NY 14150

Floyd Hasselris
Manager of Technical Services
CEA, Inc.
555 Madison Avenue
New York, NY 10022

Norman L. Hecht
Research Scientist
Office of the Associate Director
University of Dayton, Research
Institute
Dayton, OH 45469

Roger Hecklinger
Charles R. Velzy Associates, Inc.
355 Main Street
Armonk, NY 10504

Arthur Helmstetter
Manager, Technical Implementation
Systems Technology Corporation
245 North Valley Road
Xenia, OH 45385

George Huff
Gulf Oil Chemical Company
Biochemical Technology
P. O. Box 2900
Shawnee Mission, KS 66201

Carroll Hughes
President
Consumat Systems, Inc.
P. O. Box 9579
Richmond, VA 23228

Ronald Isaacson
Energy and Environmental
Systems Division
Argonne National Laboratory
Argonne, IL 60439

Herbert M. Kosstrin
Principal Scientist
Energy Resources Co., Inc.
185 Alewife Brook Parkway
Cambridge, MA 02138

John Pacey
EMCON Associates
1420 Koll Circle
San Jose, CA 95112

Robert J. Petersdorf
Wisconsin Electric & Power Co.
231 West Michigan Avenue
Milwaukee, WI 53203

Barry Rugg
Department of Applied Science
New York University
26 Stuyvesant Street
New York, NY 10003

Bruce Simister
Research Engineer
Midwest Research Institute
425 Valker Boulevard
Kansas City, MO 64110

Leo Spano
U.S. Army Natick R&D Command
Kansas Street
Natick, MA 01760

David Spencer
Raytheon Service Company
Spencer Laboratory
2 Wayside Road
Burlington, MA 01803

David B. Sussman
Environmental Engineer
U.S. Environmental Protection
Agency
Resource Recovery Division
401 M Street, SW
Washington, DC 20460

George Trezek
Professor of Mechanical Engineering
University of California
Etcheverry Hall
Berkeley, CA 94720

Peter Ware
Waste Management, Inc.
900 Jorie Boulevard
Oakbrook, IL 60521

Michael L. Wilkey
Energy and Environmental Systems
Division
Argonne National Laboratory
Argonne, IL 60439

R. Eric Zimmerman
ESCOR, Inc.
820 Davis Street
Suite 400
Evanston, IL 60201

APPENDIX D

MEMBERS OF PANEL ON URBAN WASTE, URBAN RESEARCH COUNCIL

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX D

MEMBERS OF PANEL ON URBAN WASTE, URBAN RESEARCH COUNCIL

James G. Abert - Chairman
Vice President - Research and Development
National Center for Resource Recovery
1211 Connecticut Avenue, N.W.
Washington, DC 20036

Blair T. Bower
Consultant
3718 25th Street, North
Arlington, VA 22207

William E. Franklin
Franklin Associates, Limited
9340 Mission Road, Suite 101
Prairie Village, KS 66206

Donald F. Othmer
Polytechnic Institute
333 Jay Street
Brooklyn, NY 11201

James R. Smith
Building Research Advisory Board
National Academy of Sciences
2101 Connecticut Avenue, N.W.
Washington, DC 20418

S. Russell Stearns
Thayer School of Engineering
Dartmouth College
Hanover, NH 03755

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

GLOSSARY

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

GLOSSARY

Abbreviations

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
DOC	Department of Commerce
DOE	Department of Energy
EPA	Environmental Protection Agency
MRI	Midwest Research Institute
MSW	Municipal Solid Waste
NBS	National Bureau of Standards
NCRR	National Center for Resource Recovery
d-RDF	Densified Refuse Derived Fuel
RDF	Refuse Derived Fuel
RD&D	Research, Development, and Demonstration

Symbols

Btu/lb	Btu per pound
cfm	cubic feet per minute
cu.ft.	cubic feet
dscf	dry standard cubic feet
gal.	gallons
gpd	gallons per day
gr/dscf	grains per dry standard cubic foot
KW	kilowatts
kwh	kilowatt hours
lbs.	pounds
lb/hr	pounds per hour
MCF	thousand cubic feet
M lbs.	thousand pounds

MM Btu	million Btu
psig	pounds per square inch, gage
scfm	standard cubic feet per minute
sq.ft.	square feet
tpd	tons per day
tph	tons per hour
tpy	tons per year

*U.S. GOVERNMENT PRINTING OFFICE : 1960 O-311-119/107