August 1992 • NREL/TP-431-4982

# RD&D Priorities for Energy Production and Resource Conservation from Municipal Solid Waste

*Prepared by*
*ICF Incorporated*
*Fairfax, Virginia*

National Renewable Energy Laboratory
A Division of Midwest Research Institute
Operated for the U.S. Department of Energy
Under contract No. DE-AC02-83CH10093

NREL/TP-431-4982 • UC Category: 249 • DE92016406

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A Division of Midwest Research Institute
Operated for the U.S. Department of Energy
Under contract No. DE-AC02-83CH10093

Prepared under Subcontract No. CJ-1-11167-1

August 1992

**On September 16, 1991, the Solar Energy Research Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory.**

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Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A13

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

# PREFACE

This report was produced by ICF Incorporated under a subcontract to the National Renewable Energy Laboratory (NREL), located in Golden, Colorado. ICF and the study participants produced, reviewed, and edited the report; therefore, the views and positions espoused within, except those found on the errata sheet, do not represent the positions held by NREL and the Department of Energy (DOE). Any inconsistencies within the study report are a reflection of the participants' diverse backgrounds and opinions.

Several public interest and environmental groups were invited to participate in this study; all but one declined and that one attended only the first meeting.

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# EXECUTIVE SUMMARY

## Purpose

This report identifies research, development, and demonstration (RD&D) needs and priorities associated with municipal solid waste (MSW) management technologies that conserve or produce energy or resources. This assessment of RD&D needs and priorities was prepared for the National Renewable Energy Laboratory (NREL) of the United States Department of Energy (DOE) in recognition of the many changes that have occurred in the nature of MSW management over the past decade. For example:

- Recycling programs are being widely established to address certain components of the MSW stream;
- New, more stringent regulations that have been imposed on MSW management technologies to protect human health and the environment will significantly increase the cost of waste management;
- Existing landfill capacity is rapidly declining, while local communities are generally reluctant to support the development of new landfills; and
- The public often does not view waste-to-energy plants as environmentally safe waste management alternatives.

The changing character of MSW waste management and the public's heightened awareness of its real and perceived benefits and costs creates opportunities for RD&D in MSW technologies. Increased recycling, for example, creates new opportunities for energy, chemicals, and materials recovery. New technologies to control and monitor emissions from MSW combustion facilities are available for further improvement or application. Furthermore, emerging waste-to-energy technologies may offer environmental, economic, and other advantages.

Given these developments, DOE identified a need to assess the RD&D needs and priorities and carefully target RD&D efforts to help solve the nation's waste management problem and further the National Energy Strategy. This report presents such an assessment. It identifies and documents RD&D needs and priorities in the broad area of MSW resource recovery, focusing on efforts to make MSW management technologies commercially viable or to improve their commercial deployment over a 5 to 10 year period. Panels of technical experts identified 279 RD&D needs in 12 technology areas, ranking about one-fifth of these needs as priorities. A "Peer Review Group" identified mass-burn combustion, "systems studies," landfill gas, and ash utilization and disposal as high priority areas for RD&D based on cost and the impacts of further RD&D.

The results of this assessment are intended to provide guidance to DOE concerning possible future RD&D projects. Factors in addition to this assessment, however, will also be important to DOE funding decisions.

## Results

Based on the aggregate impact and cost scores from the Peer Review Group, the technology areas were classified as being rated high, moderate, or low for further RD&D. The basis for each technology's classification by the Peer Review Group is summarized below along with the RD&D projects given the highest priority by the technical panels.

### 1. Areas Rated High for Further RD&D

Four technology areas received from the Peer Review Group both high relative impact and low relative cost ratings.

- **Mass-burn combustion** is expected to be the least expensive area for further RD&D because the RD&D needs focus on increasing the technology's social and institutional acceptability, rather than developing, building, or operating expensive facilities. The panel of technical experts for this technology identified the following high priority RD&D projects:

  -- Estimating and comparing the health risks of mass-burn combustion with other MSW management technologies;

  -- Investigating methods to reduce the cost of acid gas air control pollution devices (e.g., lime substitutes); and

  -- Developing mass-burn combustion systems that generate steam at a higher temperature and pressure.

- **Systems studies** were identified as an RD&D area by the Peer Review Group and the technical panels; systems studies were not included in the initial list of 12 technology areas. System studies can be conducted to compare the performance and impacts of alternative technologies and to facilitate the design of optimal MSW management systems. The Peer Review Group supported system studies as a relatively low cost area of RD&D that could be a means of:

  -- Identifying what is known and unknown about various technologies and their impacts;

  -- Facilitating the development of optimal MSW management systems by examining when, where, and how various technologies can be used in combination; and

  -- Decreasing reliance by public officials and the general public on information published by proponents and opponents of various technologies by providing objective and

comprehensive information that is tailored to the audience's needs and background.

- **Landfill gas** received a high impact score from the Peer Review Group because further RD&D may facilitate gas collection from a large number of existing landfills; reduce the potential impact of landfill gas releases on human health and the environment; and reduce the unit cost of landfill gas. The technical panel of landfill gas experts identified the following as high priority RD&D needs:

  -- Determining optimal MSW management techniques considering both energy potential and environmental impacts (e.g., landfilling and landfill gas recovery versus recycling or versus combustion);

  -- Demonstrating leachate recirculation techniques for enhancing landfill gas generation;

  -- Determining how waste stream composition affects gas generation potential; and

  -- Developing field techniques to estimate gas generation and the portion that is recoverable.

- **Ash utilization and disposal** received favorable scores from the Peer Review Group because better management methods could improve the negative public image of ash and MSW combustion technologies that generate residuals. In addition, reducing the cost of ash management could significantly decrease the cost of producing energy through MSW combustion. The technical panel identified three categories of high priority projects:

  -- Developing tools for public education about ash disposal and utilization;

  -- Studying the utilization of ash in structural/non-structural fill, landfills, concrete, asphalt, road base, and ceramic applications; and

  -- Conducting fundamental research on the following: bottom rejects, fly, scrubber, and utilization by-products; the factors that affect combustion ash quality and quantity; the relationship of the binding states of metals within MSW combustion ash to leachability; trends and changes in monofills; environmental fate models; and risk assessment models.

## 2. Areas Rated Moderate for Further RD&D

The Peer Review Group assigned eight technology areas moderate relative cost and moderate relative impact scores.

- **Material recovery facilities** (MRFs) are centralized facilities where recyclable materials are recovered from MSW or some portion of the MSW stream and prepared for marketing. The panel of technical experts assigned the highest ratings to the following RD&D areas:

  - Improving the flexibility of technologies to utilize recovered materials;

  - Defining separation requirements for new materials processed by MRFs;

  - Developing an efficient automated system to sort bags or other containers of pre-separated wastes; and

  - Improving automated systems to break open bags of waste at facilities that accept mixed waste.

- **RDF production and dedicated combustion**, for purposes of this project, refers to mechanical processing of MSW to produce a more homogeneous fuel that is used as the sole fuel source for a "dedicated" RDF combustor. The panel of technical experts for this technology area identified RD&D priorities that dealt primarily with environmental concerns. Specifically, their high priorities were:

  - Developing technologies for proactive control of regulated heavy metals;

  - Identifying components of MSW that contribute to combustion and environmental concerns;

  - Evaluating methods and technologies to remove toxic constituents from MSW; and

  - Designing boilers that allow higher temperature and pressure steam generation for RDF and that utilize corrosion-resistant materials.

- **Source reduction** involves the design, manufacture, acquisition, and reuse of materials so as to minimize the quantity and/or toxicity of waste produced. The Peer Review Group did not identify specific RD&D projects for source reduction. It did, however, note that such efforts may significantly affect the waste stream

managed by other MSW management technologies, but will not obviate the need to implement other MSW technologies.

- **Source separation and collection** refers to the process through which members of a community separate recyclable material from MSW and the separated materials are collected for recycling. The panel of technical experts identified several high priority RD&D needs, including:

  -- Assessing the impact of source separation on the suitability of downstream MSW management technologies;

  -- Studying the energy consumption impacts of recycling;

  -- Comparing the efficiency of co-collecting source separated recyclables materials and solid waste in the same truck versus in a dedicated truck for recyclables;

  -- Evaluating current and potential glass recycling practices;

  -- Studying the energy impacts of alternative collection programs; and

  -- Studying the environmental impacts of recycling.

- **Modular mass-burn combustion** facilities differ from other types of mass-burn technologies in that they use a system of two refractory-lined combustion chambers, rather than a waterwall combustion chamber, and tend to be prefabricated, smaller capacity units. The panel of technical experts on MSW combustion assigned the highest scores to the following RD&D needs for modular combustion:

  -- Estimating the health risks of modular combustion and comparing them to the risks of other MSW management technologies;

  -- Evaluating the impact of source separation on the economics of modular units; and

  -- Determining the relationships among combustion chamber design, operating conditions, and air emissions.

- **Composting** is a microbially-mediated process through which organic material decomposes into a humus-like substance. The panel of technical experts rated four RD&D needs as having a high priority:

- -- Examining the conflict between DOE's emphasis on energy recovery and EPA's encouragement of composting in its waste management hierarchy;

- -- Determining whether government policies reflect the comparative economic, public health, and environmental effects of composting and other MSW technologies;

- -- Shortening the length of time needed to compost MSW while minimizing space and energy requirements by maximizing the rate of microbial activity; and

- -- Conducting a detailed health and environmental risk assessment of composting.

- **RDF production and co-fired combustion**, for purposes of the RD&D assessment, focuses on the use of densified RDF in existing coal-fired (or oil- or wood-fired) boilers, in combination with the primary fuel. The panel of technical experts identified two RD&D needs as essential:

  - -- Investigating slagging and fouling and the impact of RDF on the removal of inert fines; and

  - -- Optimizing methods for removing elemental heavy metals and other waste stream constituents.

  The panel identified five other areas as high priority RD&D needs:

  - -- Developing better real-time indicators and demonstrating real-time continuous monitoring;

  - -- Studying the properties of co-fired bottom and fly ash;

  - -- Investigating the effects of varying blends of RDF and coal and burn rates on boiler performance, availability, and capacity;

  - -- Studying furnace injection velocity and geometry position in the various types of boilers; and

  - -- Studying the effects of RDF additives (e.g., lime).

- **Anaerobic digestion** is the process by which solid wastes and sewage sludge are converted through decomposition by anaerobic microorganisms to produce biogas and carbon dioxide. The panel of technical experts recommended a commercial scale demonstration project to overcome public apprehension to anaerobic digestion. Panel members felt that a demonstration project would also provide valuable information to fulfill many of the following high priority RD&D needs:

  -- Developing a better understanding of methano-acetogenesis;

  -- Studying the physiological requirements and status of microbes;

  -- Evaluating the role of toxics on digester malfunction and failure;

  -- Improving polymer hydrolysis; and

  -- Improving methods for feeding digesters at various solids-concentration rates.

### 3. Areas Rated Low for Further RD&D

The final two technology areas, gasification and pyrolysis, received both low relative impact and high relative cost scores. They received these ratings because the Peer Review Group felt that the technical advances needed for each technology to become commercially viable within 5 to 10 years are unlikely and because both R&D and full-scale demonstration facilities would be very costly.

- **Gasification** is the thermal decomposition of a material in an oxygen-free atmosphere to produce gaseous product that can be used directly as fuel gas or as synthesis gas to be upgraded to value-added products such as ammonia, methanol, or other alcohols. The panel of technical experts rated one RD&D area as essential:

  -- Comparing gasification and combustion and documenting the history of gasification efforts.

  The panel felt that without proving the merits of gasification over combustion, it would be difficult to justify requests for further RD&D spending on gasification.

- **Pyrolysis** is the thermal decomposition of a material in an oxygen-free atmosphere to produce liquid and/or solid product. The panel of technical experts identified two RD&D efforts as essential:

- -- Generating data on MSW pyrolysis and its products; and

- -- Studying the history of past attempts to commercialize MSW pyrolysis.

The remainder of this report is organized into 15 chapters, 3 appendices, and a bibliography. The first chapter introduces the project and its methodology. Chapter 2 presents background information on the changing nature of the MSW resource stream. Chapters 3 through 15 characterize the 12 initial technology areas by describing the technology and its status, identifying RD&D needs, and presenting the technical panels' prioritization of those needs. Chapter 15 documents the results of the two-day Peer Review Group meeting to compare MSW management technologies in terms of their potential RD&D costs and impacts. The appendices identify the study participants, list the evaluation criteria specified by the first Peer Review Group meeting, and provide an overview of past RD&D assessments, programs, and plans.

## Methodology

ICF Incorporated, under subcontract to NREL, used a three-step process to identify and prioritize RD&D needs.

### Literature Review

First, ICF performed a literature review of MSW energy production and resource recovery technologies. The literature search used on-line data bases and reviewed readily available documents, focusing on reports published since the last comprehensive review of MSW RD&D priorities, which was completed in 1979.[1] Twelve technology areas were selected for investigation: anaerobic digestion, ash utilization and disposal, composting, gasification, landfill gas, mass-burn combustion, material recovery facilities and preprocessing, modular mass-burn combustion, pyrolysis, refuse-derived fuel (RDF) production and co-fired combustion, RDF production and dedicated combustion, and source separation and collection. Each of these areas was characterized by:

- Describing the basic technology;
- Reviewing the technology's current status and level of commercialization; and
- Listing RD&D needs identified in the literature by explicit statements that RD&D was needed, further work was planned, or a problem remained to be solved.

These characterizations were used as starting points in the RD&D needs assessment.

[1] U.S. Department of Energy, *Resource Recovery: Research Development and Demonstration Plan*, October 1979.

### Technical Expert Panels

Second, a panel of technical experts, drawn primarily from the waste management industry, academia, the research community, and government, was assembled for each of the 12 technology areas, with one exception: a single panel addressed the RD&D needs for both mass-burn and modular combustion. The panels met in one-day workshops from August 5 to 8, 1991. (Appendix A lists the study participants.) They restructured and updated the lists of RD&D needs identified by the literature review. The panels then assigned priorities to these RD&D needs, using a decision analysis methodology. Their priorities were based upon numerical assessments by individual panel members of the relative potential contribution of each RD&D need towards making the technology technically feasible and commercially viable within a 5 to 10 year period. The initial lists of priorities were reviewed and discussed by the panels, and sometimes modified. The workshop results were summarized and distributed to panel members for review and comment. Their comments were incorporated into this report. (The technology-by-technology RD&D assessments are presented in Chapters 3 to 14.)

### Peer Review Group

Third, a "Peer Review Group" was organized to prioritize RD&D needs across the technology areas and to consider non-technical issues and research needs. While the technical panel groups were largely composed of researchers who were acknowledged experts in specific technologies, the Peer Review Group contained a broad cross section of interests and expertise. This group intentionally included strong representation from the current waste management industry because of its role in implementing MSW management technologies. The Peer Review Group also included representatives from federal and state government agencies, research institutions, trade and professional associations, academia, and consulting firms. While several environmental groups were invited to participate, all but one declined.

The Peer Review Group met twice. At the first meeting on July 26, 1991, the participants developed an initial list of criteria to assess the impact (or benefit) and cost of further RD&D in each technology. At the second meeting on October 1-2, 1991, the Peer Review Group refined these evaluation criteria to be as follows:

### Impact Criteria

- Net energy impact
- Human health and the environment
- Social and institutional acceptability
- Unit cost of energy produced or conserved
- Commercialization risk
- Occupational health and safety
- Flexibility

### Cost Criteria

- Research and development program cost
- Demonstration program cost

The Peer Review Group also expanded the list of 12 technology areas to add "systems studies" and "source reduction." The systems studies area was included for two reasons: (1) different technical panels identified similar RD&D projects that applied to many technologies (e.g., characterizing the waste stream and comparing the health risks of various technologies); and (2) both the Peer Review Group and the technical panels considered these studies to be of paramount importance.

Source reduction was not originally included as a technology area because DOE intended that the project focus on post-consumer wastes that are normally disposed in landfills. The Peer Review Group, however, felt strongly that source reduction should be included due to its importance to MSW management and its potential impact on the implementation of other technologies. For example, many communities are rejecting or delaying the installation of new MSW combustion facilities until the role of source reduction is better determined.

Next, the Peer Review Group scored the relative impact (or benefit) and cost of further RD&D in each of the 14 areas with respect to the evaluation criteria. They examined these technology areas without specifying the precise projects that might be conducted in each area. A general understanding of the RD&D needs associated with each technology area was required by the Peer Review Group members to make their evaluations. There was not, however, enough time for Peer Review Group members to explicitly define the specific RD&D needs and priorities they envisioned. The Peer Review Group was also not asked to endorse the results of the technical panels nor to base cross-cutting priorities on the specific RD&D needs or priorities identified by the technical panels.

Finally, the Peer Review Group assigned relative weights to the evaluation criteria. The normalized average scores for each criterion were then weighted and combined to produce aggregate cost and impact scores for the 14 technology areas.

# 1. INTRODUCTION

This chapter presents an overview of this report (Section 1.1), a description of the methodology used to develop it (Section 1.2), a summary of the key results (Section 1.3), and a description of how the rest of the report is organized (Section 1.4).

## 1.1 Overview

This report identifies research, development, and demonstration (RD&D) needs and priorities associated with municipal solid waste (MSW) management technologies that conserve or produce energy or resources. This assessment of RD&D needs and priorities was prepared for the National Renewable Energy Laboratory (NREL) of the United States Department of Energy (DOE) in recognition of the many changes that have occurred in the nature of MSW management over the past decade. For example:

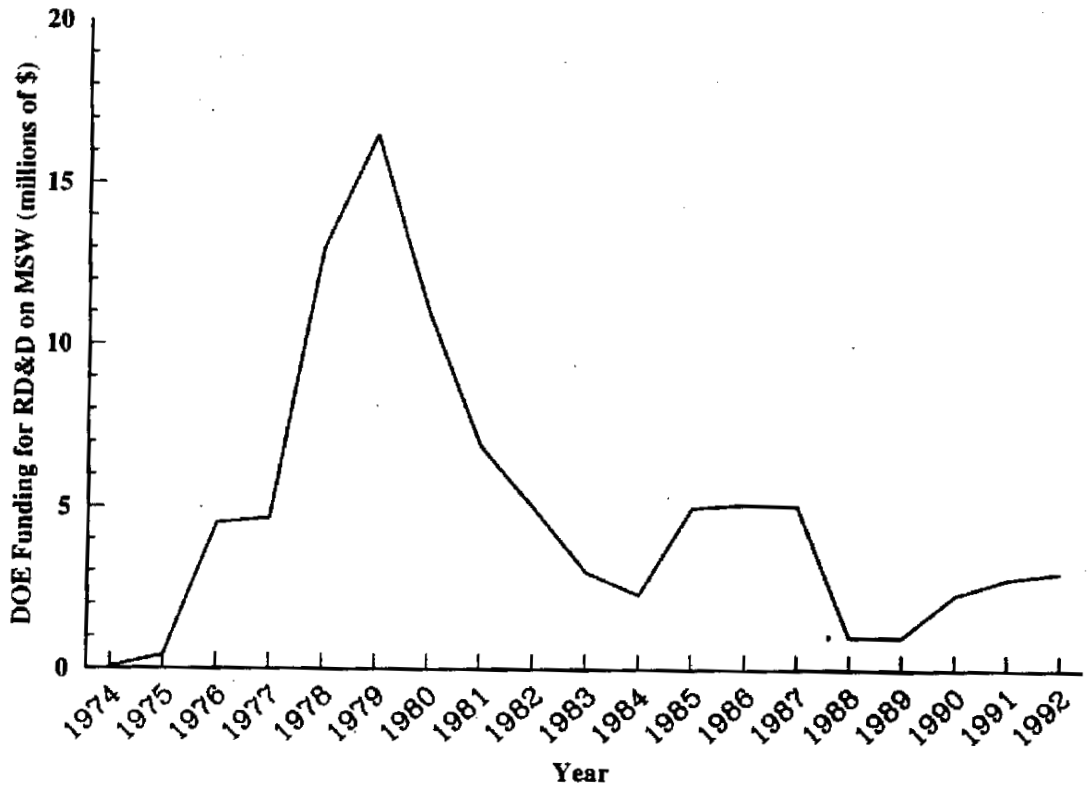
- Recycling programs are being widely established to address certain components of the MSW stream;
- New, more stringent regulations that have been imposed on MSW management technologies to protect human health and the environment will significantly increase the cost of waste management;
- Existing landfill capacity is rapidly declining, while local communities are generally reluctant to support the development of new landfills; and
- The public often does not view waste-to-energy plants as environmentally safe waste management alternatives.

The changing character of MSW waste management and the public's heightened awareness of its real and perceived benefits and costs creates opportunities for RD&D in MSW technologies. Increased recycling, for example, creates new opportunities for energy, chemicals, and materials recovery. New technologies to control and monitor emissions from MSW combustion facilities are available for further improvement or application. Furthermore, emerging waste-to-energy technologies may offer environmental, economic, and other advantages.

The amount of funding available through the Department of Energy for RD&D on municipal solid waste is limited: $3 million dollars were budgeted for Fiscal Year 1992. Exhibit 1-1 displays the annual DOE budgets for RD&D on municipal solid waste since 1974.

Given these developments and the limited DOE funds available for RD&D on municipal solid waste, DOE identified a need to assess RD&D needs and priorities and carefully target RD&D efforts to help solve the nation's waste management problem and further the National Energy Strategy. This report presents such an assessment. It identifies and documents RD&D needs and priorities in the broad area of MSW resource recovery, focusing on efforts to make MSW management technologies commercially viable or to improve their commercial deployment over a 5 to 10 year period. The results of this assessment are intended to

**Exhibit 1-1. DOE Budgets for RD&D on Municipal Solid Waste from 1974-1992**




provide guidance to DOE concerning possible future RD&D projects. Factors in addition to this assessment, however, will also be important to DOE funding decisions.

This report considers the RD&D needs and priorities associated with 12 MSW management technology areas:

1. Anaerobic Digestion;
2. Ash Utilization and Disposal;
3. RDF Production and Co-Fired Combustion;
4. Composting;
5. Gasification;
6. Landfill Gas;
7. Mass-Burn Combustion;
8. Material Recovery Facilities and Preprocessing;

9. Modular Mass-Burn Combustion;

10. Pyrolysis;

11. RDF Production and Dedicated Combustion; and

12. Source Separation and Collection.

In evaluating RD&D needs and priorities, the objective of the project has been to make each technology area commercially viable within 5 to 10 years, or to increase the use of those technologies that are already commercially viable. Chapter 2 considers the current and future (5 to 20 years) size and composition of the municipal solid waste stream. The RD&D needs and priorities for each MSW management technology areas are considered from two perspectives: (1) The RD&D needs specific to each technology area, and the priority of each RD&D need with respect to making the technology area commercially viable or more utilized in 5 to 10 years (Chapters 3 through 14); and (2) the overall cost and impact of further RD&D on each technology area relative to the other 11 technology areas (Chapter 15).

The RD&D needs specific to each technology area were identified and prioritized by eleven panels of technical experts in a series of one day workshops. The results of these workshops were added to and integrated with working papers based on a literature review, and are presented in Chapters 3 through 14. Each of the chapters addressing the RD&D needs and priorities of a specific technology area include:

- A brief description of the technology;
- The current status of the technology, generally with respect to its level of commercialization;
- A description of the RD&D needs identified by the expert panels and the literature review;
- The technical panel's prioritized list of RD&D needs; and
- The technical panel's views on the technology with respect to the preliminary evaluation criteria developed by the Peer Review Group.

The overall costs and impacts of further RD&D on each technology area and cross-cutting priorities were addressed by conducting two workshops with a Peer Review Group composed of experts from the waste management industry, federal government, state government, and research organizations. The efforts and results of the Peer Review Group's workshops are presented and discussed in Chapter 15 which discusses:

- The composition of the Peer Review Group;
- The methodology used by the Peer Review Group;
- The criteria used to evaluate further RD&D;

- Two additional technology areas considered by the Peer Review Group;
- The cost and impact of further RD&D for each technology area;
- The relative importance of the evaluation criteria; and
- The aggregate cost and impact of further RD&D.

## 1.2 Methodology

This section describes the methodology used to produce this document and the series of working papers and draft reports that preceded it: (1) "Characterization of MSW Resource Recovery Technologies" (June 28, 1991) working papers given to the technical experts prior to the technical workshops; (2) "RD&D Priorities for Energy Production and Resource Conservation from Municipal Solid Waste: Interim Report" (September 23, 1991); and (3) "RD&D Priorities for Energy Production and Resource Conservation from Municipal Solid Waste: Draft Final Report" (October 31, 1991).

### 1.2.1 Development of the "Characterization of MSW Resource Recovery Technologies" and "The Changing Municipal Solid Waste Resource Stream" Working Papers

The general approach used to develop the "Characterization of MSW Resource Recovery Technologies" working paper was to identify potentially useful documents through on-line database searches and a review of immediately available documents (e.g., Department of Energy (DOE) program reports, Environmental Protection Agency (EPA) reports, and professional scientific and engineering journals). Potentially relevant documents were then procured through the National Technical Information Service (NTIS), inter-library loans, and other means. Once received, these documents were categorized by technology and graded according to their potential usefulness. The majority of these documents were then reviewed and information pertaining to technology descriptions, technology status, and RD&D needs was extracted. Each of these steps is discussed below.

**Literature Searches and Document Procurement**

In performing the on-line database literature searches, three types of search strategies were utilized. The first focused on identifying documents with information on waste-to-energy and research, demonstration, or development. This search accessed the National Technical Information Service (NTIS), Energy Science and Technology, and Compendex databases for dates ranging from 1970 to 1990. Full citations (with abstract) were retrieved for all of the 408 documents identified by the search, 17 of which were procured.

The second literature search actually consisted of 12 separate searches, each focused on identifying any domestic or international documents associated with a particular technology. This search accessed the NTIS, Energy Science and Technology, Compendex, Enviroline, Energyline, and PASCAL databases for dates ranging from 1988 to 1991. Due to the large number of documents identified in this search (more than 3,800), only the document titles were retrieved. These titles were reviewed and full citations (with abstract) were retrieved for 550 of the documents, approximately 80 of which were procured. Since a number of these

documents were conference proceedings that contained more than one article of interest, approximately 600 citable documents or articles were actually received.

The third literature search was designed to identify relevant DOE program reports. This search accessed the Energy Science and Technology database for the years from 1974 to 1991. Full citations (with abstract) were retrieved for 50 of the 386 documents identified by the search, and about 10 of the documents were procured.

One problem of relying on a literature search to identify RD&D needs is that recent developments (e.g., within the past two years) may be missed, regardless of how extensive the search is, because of the time it takes to publish experimental results and enter the publications into on-line databases. Another problem is that interest in some of the waste-to-energy technologies (e.g., MSW pyrolysis and gasification) peaked during the 1970s and early 1980s, so that relying on post-1987 literature is likely to have missed some relevant documents.

**Document Screening**

As each document was received, it was screened to (1) determine which technology or technologies it applied to, (2) identify the type of information (e.g., technology description, technology status, or RD&D need) in the document, and (3) grade the potential usefulness of the document. The most useful documents were reviewed in more detail and information on technology status and RD&D needs was condensed and extracted. This condensed set of information was used to develop the outline for each technology characterization and to guide the review of remaining documents.

**Development of Technology Characterizations**

Each technology characterization is made up of three parts: (1) a description of the technology, (2) the current status of the technology, and (3) a description of the RD&D needs associated with the technology.

The purpose of the technology descriptions is to provide enough information to put the RD&D needs in context. While each description identifies the primary characteristics of the technology, no attempt was made to describe the many variations that frequently exist. Detailed descriptions of each technology are not necessary since people familiar with the waste-to-energy technologies are the intended audience

The descriptions of technology status are meant to provide a brief overview of the the technology's current level of commercialization in the United States and elsewhere (when the information is readily available), and any major trends in the level of commercialization. Information on the geographic distribution of facilities in the United States is provided when available. In preparing these status sections, only limited efforts were made to fill information gaps left by the literature review, which was focused on RD&D needs. As a result, these sections are not comprehensive.

In order for an item to qualify as a potential RD&D need, there must be an explicit statement in one or more of the information sources that RD&D is needed, further work is planned, or that there is an unsolved problem. No attempt was made to determine if potential

RD&D needs may have been fulfilled by research performed after the RD&D need was identified. This approach was used because the panels of technical experts, who met in August 1991, could easily determine if the RD&D needs still exist.

### 1.2.2 Identification and Prioritization of the RD&D Needs by the Technical Panels

A panel of technical experts, drawn primarily from the waste management industry, academia, the research community, and government, was assembled for each of the 12 technology areas,[1] with one exception: a single panel addressed the RD&D needs for both mass-burn and modular combustion.

The panels met in one-day workshops from August 5 to 8, 1991. Appendix A lists the workshop participants. The RD&D needs described for each technology in the "Characterization of MSW Resource Recovery Technologies" working paper (June 28, 1991) were used as the starting point by each panel. The panels restructured and updated the lists of RD&D needs identified by the literature review. The panels then assigned priorities to these RD&D needs, using a decision analysis methodology. Their priorities were based upon numerical assessments by individual panel members of the relative potential contribution of each RD&D need towards making the technology commercially viable or more utilized within a 5 to 10 year period. The initial lists of priorities were reviewed and discussed by the panels, and sometimes modified.

When time allowed, each panel evaluated the technology area with respect to the initial list of evaluation criteria (see Appendix B) developed by the Peer Review Group. The initial evaluation criteria considered were

- net energy benefit,
- cost of energy produced,
- full cost of the RD&D program,
- human health,
- environment,
- occupational health and safety,
- funding and regulatory appropriateness,
- difficulty of technology development,
- commercial development risk, and
- flexibility.

The evaluation criteria received different levels of attention from each technical panel depending on the amount of time available to each panel once the RD&D needs had been identified and prioritized.

The workshop results were summarized and distributed to panel members for review and comment. Their comments were incorporated into the June 28, 1991 working papers to

[1] One reviewer felt that more technical panel members should have been drawn from the manufacturers and potential users of the technologies being considered. The panels, however, were assembled with the goal of ensuring a diversity of experience and views.

produce the "RD&D Priorities for Energy Production and Resource Conservation from Municipal Solid Waste: Interim Report" (September 23, 1991). Chapters 3 through 14 present the technology-by-technology RD&D assessments.

### 1.2.3 Development of Cross-Cutting RD&D and Implementation Priorities by the Peer Review Group

A "Peer Review Group" was organized to prioritize RD&D needs across the technology areas and to consider non-technical issues and research needs. While the technical panel groups were largely composed of researchers who were acknowledged experts in specific technologies, the Peer Review Group contained a broad cross section of interests and expertise. This group intentionally included strong representation from the current waste management industry because of its role in implementing MSW management technologies. The Peer Review Group also included representatives from federal and state government agencies, research institutions, trade and professional associations, academia, and consulting firms. While several public interest and environmental groups were invited to participate, all but one declined.

The Peer Review Group met twice. At the first meeting on July 26, 1991, the participants developed an initial list of criteria (see Appendix B) to assess the impact (or benefit) and cost of further RD&D in each technology. At the second meeting on October 1-2, 1991, the Peer Review Group refined these evaluation criteria to be as follows:

**Impact Criteria**

- Net energy impact
- Human health and the environment
- Social and institutional acceptability
- Unit cost of energy produced or conserved
- Commercialization risk
- Occupational health and safety
- Flexibility

**Cost Criteria**

- Research and development program cost
- Demonstration program cost

The Peer Review Group also expanded the list of 12 technology areas to add "systems studies" and "source reduction." The systems studies area was included for two reasons: (1) different technical panels identified similar RD&D projects that applied to many technologies (e.g., characterizing the waste stream and comparing the health risks of various technologies); and (2) both the Peer Review Group and the technical panels considered these studies to be of paramount importance.

Source reduction was not originally included as a technology area because DOE intended that the project focus on post-consumer wastes that are normally disposed in landfills. The Peer Review Group, however, felt strongly that source reduction should be included due to its importance to MSW management and its potential impact on the

implementation of other technologies. For example, many communities are rejecting or delaying the installation of new MSW combustion facilities until the role of source reduction is better determined.

Next, the Peer Review Group scored the relative impact (or benefit) and cost of further RD&D in each of the 14 areas with respect to the evaluation criteria. They examined these technology areas without specifying the precise projects that might be conducted in each area. A general understanding of the RD&D needs associated with each technology area was required by the Peer Review Group members to make their evaluations. There was not, however, enough time for Peer Review Group members to explicitly define the specific RD&D needs and priorities they envisioned. The Peer Review Group was also not asked to endorse the results of the technical panels nor to base cross-cutting priorities on the specific RD&D needs or priorities identified by the technical panels.

Finally, the Peer Review Group assigned relative weights to the evaluation criteria. The normalized average scores for each criterion were then weighted and combined to produce aggregate cost and impact scores for the 14 technology areas.

Based on the aggregate impact and cost scores from the Peer Review Group, the technology areas were classified as being rated as high, moderate, or low for further RD&D. The basis for each technology's classification by the Peer Review Group is summarized below along with the RD&D projects given the highest priority by the technical panels.

The Peer Review Group workshop results were summarized and integrated with the September 23, 1991 "RD&D Priorities for Energy Product and Resource Conservation from Municipal Solid Waste: Interim Report" to produce the October 31, 1991 "RD&D Priorities for Energy Production and Resource Conservation from Municipal Solid Waste: Draft Final Report." This latter report was distributed to the Peer Review Group and at least one member from each of the technical panels for review and comment. The comments received were reviewed and integrated with the October 31 report to produce this document.

## 1.3 Results

Based on the aggregate impact and cost scores from the Peer Review Group, the technology areas were classified as being rated high, moderate, or low for further RD&D. The basis for each technology's classification is summarized below along with the RD&D projects given the highest priority by the technical panels.

### 1. Areas Rated High for Further RD&D

Four technology areas received from the Peer Review Group both high relative impact and low relative cost ratings.

- **Mass-burn combustion** is expected to be the least expensive area for further RD&D because the RD&D needs focus on increasing the technology's social and institutional acceptability, rather than developing, building, or operating expensive facilities. The panel of technical experts for this technology identified the following high priority RD&D projects:

- -- Estimating and comparing the health risks of mass-burn combustion with other MSW management technologies;

- -- Investigating methods to reduce the cost of acid gas air control pollution devices (e.g., lime substitutes); and

- -- Developing mass-burn combustion systems that generate steam at a higher temperature and pressure.

- **Systems studies** were identified as an RD&D area by the Peer Review Group and the technical panels; systems studies were not included in the initial list of 12 technology areas. System studies can be conducted to compare the performance and impacts of alternative technologies and to facilitate the design of optimal MSW management systems. The Peer Review Group supported system studies as a relatively low cost area of RD&D that could be a means of:

  - -- Identifying what is known and unknown about various technologies and their impacts;

  - -- Facilitating the development of optimal MSW management systems by examining when, where, and how various technologies can be used in combination; and

  - -- Decreasing reliance by public officials and the general public on information published by proponents and opponents of various technologies by providing objective and comprehensive information that is tailored to the audience's needs and background.

- **Landfill gas** received a high impact score from the Peer Review Group because further RD&D may facilitate gas collection from a large number of existing landfills; reduce the potential impact of landfill gas releases on human health and the environment; and reduce the unit cost of landfill gas. The technical panel of landfill gas experts identified the following as high priority RD&D needs:

  - -- Determining optimal MSW management techniques considering both energy potential and environmental impacts (e.g., landfilling and landfill gas recovery versus recycling or versus incineration);

  - -- Demonstrating leachate recirculation techniques for enhancing landfill gas generation;

- -- Determining how waste stream composition affects gas generation potential; and

- -- Developing field techniques to estimate gas generation and the portion that is recoverable.

- **Ash utilization and disposal** received favorable scores from the Peer Review Group because better management methods could improve the negative public image of ash and MSW combustion technologies that generate residuals. In addition, reducing the cost of ash management could significantly decrease the cost of producing energy through MSW combustion. The technical panel identified three categories of high priority projects:

  - -- Developing tools for public education about ash disposal and utilization;

  - -- Studying the utilization of ash in structural/non-structural fill, landfills, concrete, asphalt, road base, and ceramic applications; and

  - -- Conducting fundamental research on the following: bottom rejects, fly, scrubber, and utilization by-products; the factors that affect combustion ash quality and quantity; the relationship of the binding states of metals within MSW combustion ash to leachability; trends and changes in monofills; environmental fate models; and risk assessment models.

**2. Areas Rated Moderate for Further RD&D**

The Peer Review Group assigned eight technology areas moderate relative cost and moderate relative impact scores.

- **Material recovery facilities** (MRFs) are centralized facilities where recyclable materials are recovered from MSW or some portion of the MSW stream and prepared for marketing. The panel of technical experts assigned the highest ratings to the following RD&D areas:

  - -- Improving the flexibility of technologies to utilize recovered materials;

  - -- Defining separation requirements for new materials processed by MRFs;

  - -- Developing an efficient automated system to sort bags or other containers of pre-separated wastes; and

- -- Improving automated systems to break open bags of waste at facilities that accept mixed waste.

- **RDF production and dedicated combustion**, for purposes of this project, refers to mechanical processing of MSW to produce a more homogeneous fuel that is used as the sole fuel source for a "dedicated" RDF combustor. The panel of technical experts for this technology area identified RD&D priorities that dealt primarily with environmental concerns. Specifically, their high priorities were:

  - -- Developing technologies for proactive control of regulated heavy metals;

  - -- Identifying components of MSW that contribute to combustion and environmental concerns;

  - -- Evaluating methods and technologies to remove toxic constituents from MSW; and

  - -- Designing boilers that allow higher temperature and pressure steam generation for RDF and that utilize corrosion-resistant materials.

- **Source reduction** involves the design, manufacture, acquisition, and reuse of materials so as to minimize the quantity and/or toxicity of waste produced. The Peer Review Group did not identify specific RD&D projects for source reduction. It did, however, note that such efforts may significantly affect the waste stream managed by other MSW management technologies, but will not obviate the need to implement other MSW technologies.

- **Source separation and collection** refers to the process through which members of a community separate recyclable material from MSW and the separated materials are collected for recycling. The panel of technical experts identified several high priority RD&D needs, including:

  - -- Assessing the impact of source separation on the suitability of downstream MSW management technologies;

  - -- Studying the energy consumption impacts of recycling;

  - -- Comparing the efficiency of co-collecting source separated recyclables materials and solid waste in the same truck versus in a dedicated truck for recyclables;

  - -- Evaluating current and potential glass recycling practices;

- -- Studying the energy impacts of alternative collection programs; and

- -- Studying the environmental impacts of recycling.

- **Modular mass-burn combustion** facilities differ from other types of mass-burn technologies in that they use a system of two refractory-lined combustion chambers, rather than a waterwall combustion chamber, and tend to be prefabricated, smaller capacity units. The panel of technical experts on MSW combustion assigned the highest scores to the following RD&D needs for modular combustion:

  - -- Estimating the health risks of modular combustion and comparing them to the risks of other MSW management technologies;

  - -- Evaluating the impact of source separation on the economics of modular units; and

  - -- Determining the relationships among combustion chamber design, operating conditions, and air emissions.

- **Composting** is a microbially-mediated process through which organic material decomposes into a humus-like substance. The panel of technical experts rated four RD&D needs as having a high priority:

  - -- Examining the conflict between DOE's emphasis on energy recovery and EPA's encouragement of composting in its waste management hierarchy;

  - -- Determining whether government policies reflect the comparative economic, public health, and environmental effects of composting and other MSW technologies;

  - -- Shortening the length of time needed to compost MSW while minimizing space and energy requirements by maximizing the rate of microbial activity; and

  - -- Conducting a detailed health and environmental risk assessment of composting.

- **RDF production and co-fired combustion**, for purposes of the RD&D assessment, focuses on the use of densified RDF in existing coal-fired (or oil- or wood-fired) boilers, in combination with the primary fuel. The panel of technical experts identified two RD&D needs as essential:

- -- Investigating slagging and fouling and the impact of RDF on the removal of inert fines; and

- -- Optimizing methods for removing elemental heavy metals and other waste stream constituents.

The panel identified five other areas as high priority RD&D needs:

- -- Developing better real-time indicators and demonstrating real-time continuous monitoring;

- -- Studying the properties of co-fired bottom and fly ash;

- -- Investigating the effects of varying blends of RDF and coal and burn rates on boiler performance, availability, and capacity;

- -- Studying furnace injection velocity and geometry position in pulverized coal, cyclone, and fluidized bed boilers; and

- -- Studying the effects of RDF additives (e.g., lime).

- **Anaerobic digestion** is the process by which solid wastes and sewage sludge are converted through decomposition by anaerobic microorganisms to produce biogas and carbon dioxide. The panel of technical experts recommended a commercial scale demonstration project to overcome public resistance and concern about the failure of this technology. Panel members felt that a demonstration project would also provide valuable information to fulfill many of the following high priority RD&D needs:

  - -- Developing a better understanding of methano-acetogenesis;

  - -- Studying the physiological requirements and status of microbes;

  - -- Evaluating the role of toxics on digester malfunction and failure;

  - -- Improving polymer hydrolysis; and

  - -- Improving methods for feeding digesters at various solids-concentration rates.

### 3. Areas Rated Low for Further RD&D

The final two technology areas, gasification and pyrolysis, received both low relative

impact and high relative cost scores. They received these ratings because the Peer Review Group felt that the technical advances needed for each technology to become commercially viable within 5 to 10 years are unlikely and because both R&D and full-scale demonstration facilities would be very costly.

- **Gasification** is the thermal decomposition of a material in an oxygen-free atmosphere to produce gaseous product that can be used directly as fuel gas or as synthesis gas to be upgraded to value-added products such as ammonia, methanol, or other alcohols. The panel of technical experts rated one RD&D area as essential:

  -- Comparing gasification and combustion and documenting the history of gasification efforts.

  The panel felt that without proving the merits of gasification over combustion, it would be difficult to justify requests for further RD&D spending on gasification.

- **Pyrolysis** is the thermal decomposition of a material in an oxygen-free atmosphere to produce liquid and/or solid product. The panel of technical experts identified two RD&D efforts as essential:

  -- Generating data on MSW pyrolysis and its products; and

  -- Studying the history of past attempts to commercialize MSW pyrolysis.

## 1.4 Organization of the Report

The remainder of this report is organized into 15 chapters, 4 appendices, and a bibliography. The first chapter introduces the project and its methodology. Chapter 2 presents background information on the changing nature of the MSW resource stream. Chapters 3 through 14 characterize the 12 initial technology areas by describing the technology and its status, identifying RD&D needs, and presenting the technical panels' prioritization of those needs. Chapter 15 documents the results of the two-day Peer Review Group meeting to compare MSW management technologies in terms of their potential RD&D costs and impacts. Appendix A identifies the members of each panel of technical experts and the Peer Review Group; Appendix B lists the initial evaluation criteria developed during the first Peer Review Group meeting; Appendix C provides an overview of past RD&D assessments, programs, and plans; and Appendix D is a glossary of selected terms.

# 2. THE CHANGING MUNICIPAL SOLID WASTE STREAM

## 2.1 Introduction

This chapter describes the material composition and size of the current municipal solid waste (MSW) resource stream and offers projections of the future MSW stream over the next 5 to 20 years. In addition to characterizing the MSW stream at the national level, the report explains how the MSW stream varies by community and includes scenarios of future MSW generation and recovery that incorporate this local variation. The chapter also delineates the various factors that affect the size and composition of the MSW stream and describes how these factors might affect the MSW stream in the future.

The purpose of this chapter is to provide background information on the MSW resource stream so that informed decisions can be made concerning research, development, and demonstration needs in the area of MSW energy production and conservation technologies. In municipal waste management systems that rely exclusively on landfills there is little need to characterize the types and quantities of material disposed. As communities add source reduction, recycling, composting, waste-to-energy facilities, and other facilities to the system, the need for precise, reliable data about what's in the waste stream becomes paramount to the waste management program's success. For example, recycling programs require this understanding because they must target particular materials in the MSW stream and they rely on certain materials (e.g., aluminum) to generate revenue. Waste combustion with energy recovery also requires knowledge of current and future MSW composition because it relies on combustible materials (e.g., plastic, paper) to make energy production possible.

This remainder of this section discusses the following:

- Section 2.1.1 defines municipal solid waste;
- Section 2.1.2 describes the source of and method used to derive the national data that were used in preparing this chapter; and
- Section 2.1.3 distinguishes between local and national waste characterization methods.

### 2.1.1 Definition of Municipal Solid Waste

MSW is generally defined as post-consumer nonhazardous solid waste generated by residences, commercial establishments, institutions, and light industry. (Alter, 1991) MSW can be categorized by either materials or products and usually includes at least the following:

Materials: paper and paperboard, glass, ferrous and nonferrous metals, plastics, rubber and leather, textiles, wood, food waste, and yard waste.

Products: **durable goods** (e.g., appliances, furniture, tires); **nondurable goods** (e.g., magazines, tissue paper, clothing, small plastic products, household cleansers, batteries); and **containers and packaging or wrapping** (e.g., cans, bottles,

boxes, and packaging made of paper, paperboard, plastic, glass, ceramic, and wood).

Different individuals, institutions, and studies, however, often include different materials and products in the definition of MSW, sometimes creating confusion and often leading to inconsistencies among sources of MSW data. Construction and demolition debris, for example, may be included in commercial MSW estimates or broken out separately. In some areas, this material, consisting of concrete, asphalt, masonry, lumber, wallboard, and metals, is a significant portion of waste generated and a good source of recyclable materials. In addition, solid waste from industrial, and sometimes commercial, sources is often not included in local MSW figures.

### 2.1.2 National MSW Data

The MSW data in this chapter are presented by material category rather than product category and are drawn from existing studies, especially the Franklin Associates, Ltd., June 1990 report for EPA *Characterization of Municipal Solid Waste in the United States: 1990 Update* (Franklin Report). No new waste stream data were gathered for this chapter. The Franklin Report is the most recent in a 20-year series of reports that characterize MSW and is the most widely accepted source of MSW data at the national level.

The MSW generation data contained in the Franklin Report were calculated using a "material flows" methodology, with the exception of food and yard waste data which are based on sampling data from a range of sources. The "material flows" methodology estimates the generation of MSW based on production data (by weight) for materials in the waste stream, with adjustments for imports, exports, and product lifetimes. The methodology presents the weight of all materials and products in MSW in their "as generated," or dry state, rather than after moisture transfer has taken place. For example, the amount of paper in the waste stream is based on paper production and consumption data (e.g., from the Department of Commerce and trade associations), and adjusted for amounts of paper lost in manufacturing, lifetimes of products, recycling rates, amounts destroyed during use (e.g., cigarette paper), or diverted from the waste stream for long periods of time (e.g., library books).

Franklin Associates estimates of MSW generation do not include several commonly landfilled wastes, such as construction and demolition debris, municipal sludge, ash from industrial boilers and waste-to-energy plants. In addition, the Franklin Report's recycling statistics do not include items such as junked cars or copper cables or other metal scrap from industrial sources. The data also do not distinguish MSW generated from residential, commercial, and institutional sectors. Finally, using national data for local planning is likely to lead to inaccurate estimates of local MSW weight, volume, and composition, and could result in costly mistakes in purchasing equipment and sizing facilities.

### 2.1.3 Local MSW Data

An alternative approach to quantitatively characterizing MSW involves site specific sampling, sorting, and weighing of the components of the waste stream received at landfills or transfer stations; the method commonly used for local MSW studies. Good sampling studies can provide information about the amount of specific products and materials generated by each sector (i.e., residential, commercial, and industrial), the amount of waste recycled,

seasonal variations in the waste stream, and differences between urban, suburban, and rural areas. A range of sampling studies were used to estimate food and yard waste generation for the Franklin Report because these wastes cannot be estimated using the material flows methodology. In addition, this chapter also contains data from sampling studies to show the variation in MSW composition due to regional differences and population density, as well as seasonal changes and differences in sampling techniques.

## 2.2 Current Municipal Solid Waste Stream

This section describes the current (1988) MSW stream, covering the following areas:

- Section 2.2.1 describes the size, material composition, and management (i.e., recycling, energy recovery, landfilling) of the national MSW resource stream in 1988 by weight;
- Section 2.2.2 characterizes the MSW stream on a volume basis; and
- Section 2.2.3 describes the local variation in the MSW stream and presents a range of MSW data from several MSW sampling studies.

The characterization presented is by material (e.g., paper, glass), although many different products are included in each material category. Product differentiation is important, however, for investigations of recovery policies, such as bottle bills, that are applied to particular products or packaging rather than materials.

### 2.2.1 Size and Composition by Weight

Franklin Associates estimates that 179.6 million tons of MSW were generated nationally in 1988 (the most recent year available), 13.1 percent of which was recycled overall (see Exhibits 2-1 and 2-2). The total amount of MSW generated nationwide continues to increase steadily, as does the per capita generation which is now 4.0 pounds of MSW per person per day. Recycling and composting of materials and energy recovery through combustion have also increased while the portion of MSW that is landfilled has decreased. In 1988, 72.7 percent of MSW was landfilled, 13.1 percent was recovered for recycling (including composting), 13.6 percent was combusted with energy recovery, and 0.6 percent was combusted without energy recovery (see Exhibit 2-3). The recycling estimates presented in this chapter are for amounts of material recovered for recycling and composting and do not necessarily indicate that these materials were actually recycled. It is possible, for instance, that recyclables are collected and stockpiled, rather than actually recycled. Estimates for the post-recycling waste stream are for combined combustion and landfilling because no percentage breakdown by material is available for distinguishing between these two waste management methods.

Paper and paperboard products collectively constitute the largest single portion of the MSW stream and were 40.0 percent of generation, or 71.8 million tons, in 1988. This material category includes nondurable goods such as newspapers, books, magazines, and office paper, as well as containers and packaging, such as corrugated boxes, milk cartons, folding cartons, bags, and sacks. At 25.6 percent of generation, recycling of paper and paperboard was greater than for any other major material category. Paper and paperboard were also the

largest portion of MSW combusted or landfilled (34.2 percent) and represent an important part of MSW with respect to energy recovery because of a high energy value of about 7 Btu per pound.

Yard waste, including grass, leaves, and tree and brush trimmings, represents the second largest constituent of MSW and was 17.6 percent of generation, or 31.6 million tons nationally, in 1988. Although estimates of the amount of yard waste that is composted are difficult to make and do not include practices such as backyard composting, Franklin Associates estimates that about 1.6 percent of yard waste was composted in 1988.

**Exhibit 2-1. Generation, Recycling, and Combustion/Landfill of MSW in 1988**
(millions of tons)

| | Generation | | Recycling[a] | | Combustion/Landfill[b] | |
|---|---|---|---|---|---|---|
| | Weight | Percent of Total | Weight | Percent of Generation | Weight | Percent of Total |
| **Paper and Paperboard** | 71.8 | 40.0 | 18.4 | 25.6 | 53.4 | 34.2 |
| **Glass** | 12.5 | 7.0 | 1.5 | 12.0 | 11.0 | 7.1 |
| **Metals** | | | | | | |
| Ferrous | 11.6 | 6.5 | 0.7 | 5.8 | 10.9 | 7.0 |
| Aluminum | 2.5 | 1.4 | 0.8 | 31.7 | 1.7 | 1.1 |
| Other | 1.1 | 0.6 | 0.7 | 65.1 | 0.4 | 0.3 |
| Total | 15.3 | 8.5 | 2.2 | 14.6 | 13.1 | 8.4 |
| **Plastics** | 14.4 | 8.0 | 0.2 | 1.1 | 14.3 | 9.1 |
| **Rubber and Leather** | 4.6 | 2.5 | 0.1 | 2.3 | 4.4 | 2.9 |
| **Textiles** | 3.9 | 2.1 | 0.0 | 0.6 | 3.8 | 2.5 |
| **Wood** | 6.5 | 3.6 | 0.0 | 0.0 | 6.5 | 4.2 |
| **Food Waste** | 13.2 | 7.4 | 0.0 | 0.0 | 13.2 | 8.5 |
| **Yard Waste** | 31.6 | 17.6 | 0.5 | 1.6 | 31.1 | 20.0 |
| **Other** | 5.8 | 3.3 | 0.7 | 12.1 | 5.1 | 3.3 |
| **Total** | 179.6 | 100.0 | 23.5 | 13.1 | 156.0 | 100.0 |

Source: (Franklin Associates, 1990)
[a] Includes composting.
[b] The amount of MSW remaining after recycling and composting, virtually all of which is combusted or landfilled.

**Exhibit 2-2. Generation of MSW in 1988**

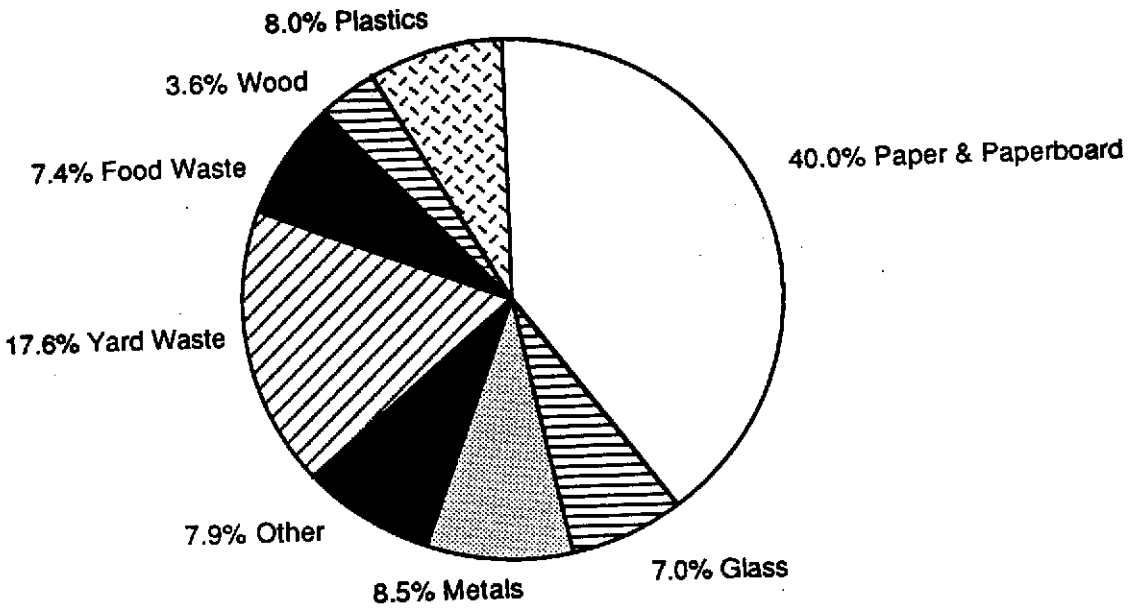
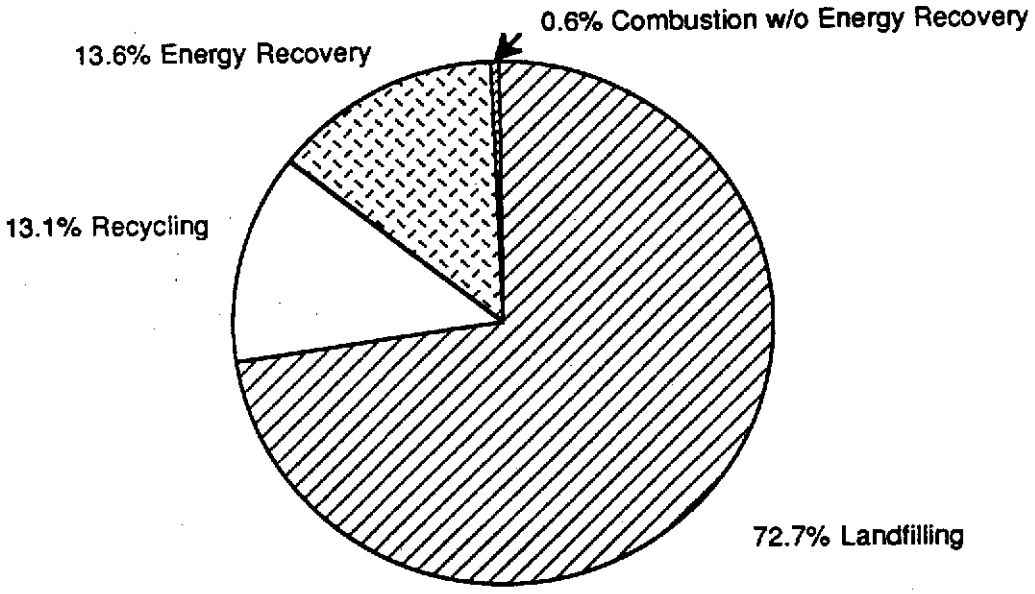



**Exhibit 2-3. MSW Management in 1988**




Source: (Franklin Associates, 1990)

Metals, including ferrous metals, aluminum, and other nonferrous metals, were 8.5 percent of MSW generation in 1988. Ferrous metals constitute the largest portion of metals in MSW and were 6.5 percent of generation (11.6 million tons) in 1988. Recycling of ferrous metals, however, is not as high as for other metals in MSW; about 2 percent of ferrous metal in durable goods and 15 percent of steel cans were recycled in 1988. Aluminum in MSW, primarily containers and other packaging, was 1.4 percent of generation (2.5 million tons). Aluminum has one of the highest recycling rates of any material in MSW; 55 percent of aluminum beer and soft drink cans, 44 percent of all aluminum packaging, and 32 percent of aluminum overall was recycled in 1988. About 1.1 million tons of other metals (0.6 percent of all MSW), including lead from lead-acid batteries (800,000 tons), copper, and zinc, was generated in 1988. The Franklin Report estimates that 65 percent of these metals were recycled in 1988, mostly due to a 90 percent recycling rate for lead-acid batteries.

Plastics, which were 8.0 percent (14.4 million tons) of MSW in 1988, are a fast growing component of MSW generated from containers, packaging, and durable goods. Overall, 1.1 percent of plastics were recycled in 1988, including 21 percent of PET (polyethylene terephthalate) bottles.

Food waste is declining as a percentage of MSW and on a per capita basis and was 7.4 percent of generation (13.2 million tons) in 1988. This decline is at least partially attributable to the increased use of garbage disposals and prepared foods. Although composting of food waste has been practiced in some locations, Franklin Associates found no significant composting of food waste in 1988.

Glass, including containers and some glass in durable goods, was 7.0 percent (12.5 million tons) of MSW in 1988, continuing its decline (in both percent and absolute terms) as it is replaced by plastic and aluminum in containers. An estimated 12 percent of glass (13 percent of containers) was recovered for recycling in 1988.

Wood, rubber and leather, textiles, and other waste were each less than 4 percent of MSW generation in 1988, totalling 11.2 percent (20.8 million tons). Less than 3 percent of these materials were recovered for recycling, with the exception 0.7 tons of battery electrolytes included in "other" wastes, which were probably not recycled.

### 2.2.2 Size and Composition by Volume

This section discusses estimates of the volume of materials in post-recycling MSW (i.e., the amount combusted or landfilled), which the Franklin Report estimated by multiplying the weight of each material (as given in Exhibit 2-1) by its density under landfill conditions (see Exhibit 2-4). Volume is important for decision making regarding issues such as the consumption of landfill capacity, as well as collection costs.

Franklin Associates estimates that 400.0 million cubic yards of MSW were either combusted or landfilled nationally in 1988. Estimates are given for MSW remaining after recovery for recycling because volume data are based on landfilled waste which does not include waste diverted for recycling.

On a volume basis, paper and paperboard are the largest material category of post-recycling MSW; 34.1 percent of generation, or 136.2 million cubic yards, in 1988. Plastics are

**Exhibit 2-4. MSW Combusted or Landfilled in 1988: Volume Versus Weight Comparison**

| | Amount | | Percent of Total | | Ratio |
|---|---|---|---|---|---|
| | Volume ($10^6$ $yd^3$) | Weight ($10^6$ tons) | Volume | Weight | Volume Percent / Weight Percent |
| **Paper and Paperboard** | 136.2 | 53.4 | 34.1 | 34.2 | 1.0 |
| **Glass** | 7.9 | 11.0 | 2.0 | 7.1 | 0.3 |
| **Metals** | | | | | |
| Ferrous | 39.0 | 10.9 | 9.8 | 7.0 | 1.4 |
| Aluminum | 9.3 | 1.7 | 2.3 | 1.1 | 2.1 |
| Other | 0.0 | 0.4 | 0.0 | 0.3 | 0.0 |
| Total Metals | 48.3 | 13.1 | 12.1 | 8.4 | 1.4 |
| **Plastics** | 79.7 | 14.3 | 19.9 | 9.1 | 2.2 |
| **Rubber and Leather** | 25.7 | 4.4 | 6.4 | 2.9 | 2.3 |
| **Textiles** | 21.1 | 3.8 | 5.3 | 2.5 | 2.1 |
| **Wood** | 16.3 | 6.5 | 4.1 | 4.2 | 1.0 |
| **Food Waste** | 13.2 | 13.2 | 3.3 | 8.5 | 0.4 |
| **Yard Waste** | 41.3 | 31.1 | 10.3 | 20.0 | 0.5 |
| **Other** | 10.0 | 5.1 | 2.5 | 3.3 | 0.7 |
| **Total** | 400.0 | 156.0 | 100.0 | 100.0 | 1.0 |

Source: (Franklin Associates, 1990)

second in volume, at 19.9 percent of the total, and metals are third, at 12.1 percent. Glass, yard waste, and food waste are a much smaller percentage of MSW volume than weight because of their relatively high density.

The ratio of volume percent to weight percent is a measure of the relative density of the various material components of MSW; materials that are relatively dense constitute a lesser portion of MSW on a volume basis and have ratios below 1.0. Paper and paperboard have a ratio of 1.0, as does wood. Glass, food waste, and yard waste are relatively dense components with ratios of 0.3, 0.4, and 0.5 respectively. Plastics, rubber and leather, and textiles are relatively voluminous components of MSW with ratios greater than 2.0.

### 2.2.3 Variation in Local MSW Sampling Studies

Most studies of MSW composition performed at the local level employ a form of the waste sampling methodology described in Section 2.1.3. It is useful to compare data from these studies to the national data presented throughout this chapter in order to appreciate the regional variation in MSW composition that exists due to differences in climate, population density, community type (urban, suburban, rural), and type and level of industrial activity. A San Francisco study found, for example, that 33 percent of the residential waste stream was food waste and yard waste accounted for only 7 percent. As a result, the City's backyard

composting program focused on starting worm composting systems. (Worms degrade food waste more efficiently than other methods.) Sampling data will also vary due to seasonal variations in the waste stream or differences in sampling methodology and may not be comparable to one another, or to the national data presented in this chapter, due to inclusion or exclusion of certain wastes (e.g., construction and demolition debris, sewage sludge). Per capita generation of MSW also varies by community; local studies report per capita MSW generation rates from 2 to 9 pounds per day. (U.S. Congress, 1989)

Exhibit 2-5 presents percentage estimates of the material composition of post-recovery MSW found using the waste sampling methods, as well as the "material flows" methodology (see Exhibit 2-1). The exhibit presents both mean (average) values and ranges for two sets of sampling data included in the Office of Technology Assessment (OTA) 1989 report *Facing America's Trash: What Next for Solid Waste?*, including a set of 9 sampling studies conducted by OTA for the report and a set of 40 sampling studies compiled for an article in *Chemical TIMES & TRENDS.* The percentage of each material in MSW for the sampling studies ranges from +21.5 to -18.5 percent of the mean value for the material. The largest variations are for yard waste and food waste, probably because these components are difficult to separate and measure relative to other materials in MSW. In addition, yard waste may vary significantly by region, climate, and by season.

**Exhibit 2-5. MSW Combusted or Landfilled in 1988**
(percent)

| | Waste Flow Method[a] | 9 Sampling Studies[b] | | 40 Sampling Studies[b] | |
|---|---|---|---|---|---|
| | | Mean | Range | Mean | Range |
| **Paper and Paperboard** | 34.2 | 38.8 | 29.9-45.9 | 46.7 | 36.5-54.7 |
| **Glass** | 7.1 | 7.8 | 3.6-12.9 | 8.4 | 6.0-13.7 |
| **Metals** | | | | | |
| Ferrous | 7.0 | N.A. | N.A. | N.A. | N.A. |
| Aluminum | 1.1 | 1.6 | 1.0-2.6 | N.A. | N.A. |
| Other | 0.3 | 1.0 | 0.0-3.4 | N.A. | N.A. |
| Total Metals | 8.4 | 4.9 | 1.5-9.4 | 8.5 | 4.0-14.7 |
| **Plastics** | 9.1 | 8.8 | 5.3-12.6 | 5.3[c] | 2.0-9.0 |
| **Textiles** | 2.5 | 3.4 | 1.1-6.2 | 3.3 | 0.7-5.0 |
| **Wood** | 4.2 | 2.6 | 0.7-8.2 | 2.6 | 0.5-7.0 |
| **Food Waste** | 8.5 | 14.7 | 1.3-28.8 | 7.8 | 0.9-18.2 |
| **Yard Waste** | 20.0 | 18.2 | 0.0-39.7 | 9.5 | 0.4-25.0 |
| **Other** | 6.2 | 9.6 | 3.8-17.6 | 1.5 | 1.0-12.9 |

[a] Source: (Franklin Associates, 1990)
[b] Source: (U.S. Congress, 1989)
[c] Plastic, rubber, and leather were combined.

## 2.3 Factors Affecting the Municipal Solid Waste Stream

To anticipate changes in the size and composition of the MSW stream and to make decisions concerning its management, it is important to understand the impact of several factors on the MSW stream. This section discusses five such factors:

- Demographics,
- Consumer behavior,
- Product composition,
- Source reduction, recycling, and composting initiatives, and
- Waste to energy.

### 2.3.1 Demographics

Changes in MSW generation due to demographics can be broken down into two basic factors: (1) changes in population and (2) changes in per capita generation. Population growth or decline due to changes in the birthrate, deathrate, or migration will significantly affect the generation of residential, commercial, and industrial MSW. At the national level, the population is expected to continue to increase, but regions and localities can expect to see much more dynamic changes due to migration and other factors.

Over time, changes in MSW generation due to demographic factors will depend not only on population changes, but also on the amount and type of waste that each person generates (i.e., per capita generation). Per capita generation depends on at least three major factors:

- Socioeconomic status,
- Degree of urbanization, and
- Household size. (U.S. Congress, 1989)

The effect of socioeconomic status on MSW generation is uncertain. A clear impact is that, as U.S. citizens have, on average, become more affluent, they have purchased more of all goods, which increases waste generation. Differences in the relative proportions of materials in MSW due to socioeconomic status is more unclear, although at least one study has suggested that higher household income is positively related to the generation of newspapers and yard waste. (Rathje and Thompson, 1981)

Although the majority of the U.S. population lives in urban areas, the degree of urbanization has some effect on MSW generation. Rural areas may have lower per capita generation rates for at least some components of the waste stream (e.g., less newspapers because they are printed weekly rather than daily and are often burned as fuel).

Some studies have suggested that smaller households produce more waste per capita, and since household size is decreasing, from 3.3 in 1960 to 2.7 in 1986, this leads to higher per capita generation on average. (U.S. Congress, 1989)

### 2.3.2 Consumer Behavior

Consumer behavior is another very important factor that affects MSW generation and composition, but its overall impact is somewhat ambiguous: the increasing demand for convenience is thought by some people to be increasing the use of prepackaged and single use products, while increasing environmental awareness may be leading many consumers to purchase products with less packaging and to reuse products. Data presented in the Franklin Report indicate the amount of packaging in MSW has actually declined since the early 1970s, so that the perception that packaging has proliferated may not be true. The impact of the demand for convenience on overall per capita generation rates is, therefore, questionable. The demand for light weight plastic bottles and microwaveable dishes is, however, changing the relative proportion of different materials in the MSW stream. This consumer trend toward more plastics may be tempered, however, by changing environmental attitudes toward such packaging.

### 2.3.3 Product Composition

The flip side of product consumption (demand) is always production (supply). Whether product composition is driven by what consumers demand or what producers decide to supply is disputable, but it is clear that the material composition of products is changing and ultimately affects the waste stream. The most evident change has been the replacement of glass and metals by plastics in containers, packaging, nondurable, and durable products. This trend may slow, but is expected to continue in the same direction. There is, however, increasing pressure on manufacturers to increase the content of post-consumer materials in their products and to make products using recyclable materials.

### 2.3.4 Recycling, Composting, and Source Reduction Initiatives

Changes in demographics, consumer purchasing behavior, and product composition generally influence the amount and composition of MSW generation. The same is true for source reduction initiatives, which aim to reduce the overall amount of the waste stream, as well as particular components, through a variety of incentives. Recycling programs, on the other hand, affect the MSW stream after it has been generated and before it is landfilled, combusted, or otherwise recovered. These initiatives alter the MSW stream by reducing the portion of certain materials in the waste stream and, thus, increasing the proportion of components that are not targeted. Recycling and source reduction approaches include:

- Source separation and curbside collection,
- Composting,
- Materials recovery facilities, and
- Economic incentives (deposit/refund, disposal, and predisposal fees).

Much of the recycling activity in the U.S. is being driven by state recycling laws. More than 140 recycling laws were enacted by 38 states in 1990 and at least 33 states now have comprehensive laws that require separation of recyclables, recycling incentives, and/or detailed statewide plans. Most comprehensive recycling laws also establish recovery goals. As of 1990, 29 states and the District of Columbia have set goals for recycling ranging from 15 percent to more than 50 percent of the waste stream between 1991 and 2005. (See Exhibit 2-6.)

## Exhibit 2-6. State Recycling Goals and Achievements

| State | Recycling Goals[a] | Percent Recycled in 1990[b] | Curbside Recycling Programs[b] | | | | No. of MRFs[c] |
|---|---|---|---|---|---|---|---|
| | | | No. | Population Served | Mandatory | Voluntar | |
| Alaska | -- | 6 | 0 | -- | -- | -- | 0 |
| Arizona | -- | 5 | 6 | 50,000 | 0 | 6 | 2 |
| Arkansas | -- | 5 | 3 | 100,000 | 1 | 2 | 0 |
| California | 50% by 2000 | 11 | 254 | 6,475,000 | 24 | 230 | 14 |
| Colorado | -- | 20 | 7 | 285,000 | 0 | 7 | 0 |
| Connecticut | 25% by 1991 | unk | 80 | n/a | 80 | 0 | 4 |
| Delaware | | 20 | 0 | -- | -- | -- | 0 |
| Dist Columbia | 45% by 1994 | 8 | 1 | 630,000 | 1 | 0 | 0 |
| Florida | 30% by 1994 | 15 | 150+ | 5,000,000 | n/a | n/a | 4 |
| Georgia | 25% by 1996 | 5-10 | 20 | n/a | n/a | 18 | 0 |
| Hawaii | -- | 4 | 2 | 25,000 | 0 | 2 | 0 |
| Idaho | -- | 3 | 1 | 100,000 | 0 | 1 | 0 |
| Illinois | 25% by 2000 | 6 | 175 | 2,200,000 | 0 | 175 | 7 |
| Indiana | 50% by 2001 | 5 | 28 | 125,000 | 2 | 26 | 0 |
| Iowa | 50% by 2000 | 7-10 | 17 | n/a | 11 | 16 | 0 |
| Kansas | -- | 5 | 5 | n/a | 0 | 5 | 0 |
| Kentucky | -- | 3-10 | 10 | n/a | 0 | 10 | 0 |
| Louisiana | 25% by 1992 | 3 | 10 | 500,000 | 10 | 10 | 0 |
| Maine | 50% by 1994 | 16 | 7 | 70,000 | 1 | 6 | 0 |
| Maryland | 20% by 1994 | 10 | 37 | n/a | 1 | 36 | 3 |
| Massachusetts | 56% by 2000 | 16 | 23 | 890,000 | 18 | 5 | 2 |
| Michigan | 50% by 2005 | unk | 40 | n/a | 7 | 33 | 1 |
| Minnesota | 25% by 1993 | 22 | 381 | 2,200,000 | 44 | 337 | 7 |
| Mississippi | 25% by 1996 | unk | 12 | n/a | 0 | 12 | 0 |
| Missouri | 40% by 2000 | <10 | 16 | n/a | 2 | 14 | 1 |
| Montana | -- | 6 | 4 | 3,000 | 0 | 4 | 0 |
| Nebraska | 25% | 10-12 | 1 | 300 | 0 | 1 | 0 |
| Nevada | -- | 5 | 1 | 8,500 | 0 | 1 | 0 |
| New Hampshire | 40% by 2000 | 8 | 18 | n/a | 0 | 18 | 1 |
| New Jersey | 25% by 1992 | 39 | 492 | 7,000,000+ | 492 | 0 | 15 |
| New Mexico | 50% by 2000 | 1 | 2 | 20,000 | 0 | 2 | 0 |
| New York | 50% by 1997 | 15 | 162 | n/a | 76 | 86 | 20 |
| North Carolina | 25% by 1993 | 5 | 25 | n/as | 0 | 25 | 1 |
| North Dakota | -- | 3-4 | 2 | 7,500 | 0 | 2 | 0 |
| Ohio | 25% by 1994 | 9 | 56 | 1,000,000 | 3 | 53 | 1 |
| Oklahoma | -- | 2 | 8 | n/a | 0 | 8 | 0 |
| Oregon | -- | 20-25 | 108 | 2,000,000 | 0 | 108 | 0 |
| Pennsylvania | 25% by 1997 | 4-5 | 412 | 5,500,000 | 274 | 138 | 13 |
| Rhode Island | max. possible | 18 | 23 | 640,000 | 22 | 1 | 2 |
| South Carolina | -- | 8 | 4 | 75,000 | 0 | 4 | 0 |
| South Dakota | 20% by 1995 | 1 | 1 | n/a | 0 | 1 | 0 |
| Tennessee | -- | unk | 8 | n/a | 0 | 8 | 1 |
| Texas | -- | 8 | 10 | n/a | 0 | 10 | 0 |
| Utah | -- | 10 | 1 | n/a | 0 | 1 | 0 |
| Vermont | 40% by 2000 | 15-18 | 8 | 10,000 | 0 | 8 | 0 |
| Virginia | 25% by 1995 | 10 | 25 | 1,200,000 | 3 | 22 | 1 |
| Washington | 50% by 1995 | 28 | 34 | n/a | 0 | 33 | 2 |
| West Virginia | 30% by 2000 | 5-10 | 14 | 50,000 | 0 | 14 | 0 |
| Wisconsin | -- | unk | n/a | -- | -- | -- | 2 |
| Wyoming | -- | 3 | 1 | n/a | 0 | 1 | 0 |
| Total | | | 2,711 | 37,054,300 | 1,052 | 1,507 | 104 |

[a] Source: (National Solid Wastes Management Association, 1990)
[b] Source: (Glenn and Riggle, 1991)
[c] Source: (Berenyi and Gould, 1990a)

The likelihood of states achieving these goals is difficult to evaluate given inadequate and noncomparable data on current recycling levels. In a 1991 *Biocycle* Survey, 45 states reported 1990 recycling rates ranging from 1 to 39 percent, but the majority of states were recycling between 1 and 10 percent of their waste. *Recycling Times* found that only 14 states based their recycling rates on quantified data, and just six of those states had compiled data from municipalities on the materials recycled. In cases where states have set unreasonably high rates or short time frames, however, there are reasons to be somewhat skeptical that these goals will be achieved.

Different methodologies for calculating recycling rates can also make comparisons among states difficult. Inclusion of materials not typically classified as municipal waste, such as junked automobiles, construction and demolition debris, and nonhazardous industrial waste can have a dramatic influence on the level of recycling achieved. For example, New Jersey estimated that 24 percent of traditional MSW was recycled in 1989, but when other materials such as construction and demolition debris and junked cars were included, the recycling rate was 42 percent for the entire waste stream.

**Source Separation and Curbside Collection**

As of late 1990, every state except Alaska and Delaware had one or more curbside recycling programs in place and at least 19 states had mandatory curbside recycling in some municipalities (see Exhibit 2-6). There were a total of approximately 2,711 of such programs covering a population of about 37 million Americans. Virtually all programs include source separation of several materials including glass, paper, metal cans, and yard waste.

As curbside programs cover more and more of the country and collect a broader spectrum of materials over the next 10 years, their impact on the waste stream will increase. The impact in terms of total waste reduction will depend on program participation rates, enforcement, and the number of materials collected. The proportional impact on individual materials will depend on the breadth of materials collected by recycling programs and the ease with which these materials are separable; a broader program will have smaller proportional impacts on materials as long as they are recovered at similar rates.

Changes in the post-recycling MSW stream size and composition will affect recovery technologies. For example, such changes will affect the amount of MSW available for energy recovery through combustion, the energy content of this waste, and the prevalence of waste constituents that are thought by some to lead to slagging, fouling, or increased air emissions.

**MSW and Yard Waste Composting**

Excluding backyard composting, by the end of 1990 there were 13 facilities nationwide for composting mixed MSW (i.e., entire waste stream) and 10 under construction, up from 7 operating facilities in 1989. (Glenn and Riggle, 1991) The growth in MSW composting is expected to continue for some time; 10 facilities are in procurement stages beyond those currently under construction and another 72 are under consideration.

Yard waste composting, on the other hand, is much more widespread and continues to grow at about the same rate as curbside collection programs. Driven by state bans on landfill disposal of yard waste, there are currently 1,407 composting facilities (excluding backyard

composting) -- a 43 percent increase over last year. At least 44 states have yard waste composting facilities and 7 states have over 100 each. Yard waste composting has traditionally focussed on leaves, although about 20 percent of facilities also included at least grass by the end of 1990.

**Materials Recovery Facilities**

About 92 materials recovery facilities (MRFs) are currently operating nationwide, 17 are under construction, 20 are in procurement, and at least another 49 are under consideration. (Glenn and Riggle, 1991) These numbers represent a significant increase over last year when only 40 MRFs were operating and 64 were in planning and construction stages (see Exhibit 2-6).

**Economic Incentives and Mandates for Source Reduction and Recycling**

Creating economic incentives (e.g., deposits and refunds, taxes, fees, credits) for waste minimization and recycling is an increasingly popular policy approach for solid waste management and revenue generation. Specific programs include:

- Front-end fees that assess specific products or materials (e.g., taxes or fees on tires, batteries, newsprint);
- Waste-end fees (e.g., landfill tipping fee and MSW collection surcharges, variable trash can rates);
- Recycling incentives (e.g., deposit/refund systems, tax credits, exemptions, loans, and grants for the purchase of recycling equipment); and
- Disposal and recycling mandates (e.g., bans on landfilling yard waste or burning household hazardous waste, recycled content regulations for newspapers, plastic, or glass).

At least 20 states have front-end fees on specific products or materials. About 19 states have legislation to create incentives for businesses to produce goods made with recycled materials. In addition, some states have set mandatory recycled content targets for certain industries, such as California's requirement that glass containers contain an increasing percentage of recycled glass cullet.

As of early 1991, at least 9 states had mandatory deposit laws for beverage containers and 13 states had deposit systems for vehicle batteries. Disposal bans on specific items, currently in place in 29 states, have focussed on tires, batteries, yard waste, white goods, and motor oil. During 1990, Wisconsin legislated the most extensive disposal ban listing to date, including aluminum containers, corrugated paper and other container board, foam polystyrene,glass containers, magazines, newspapers, office paper, plastic containers, steel containers, and bimetal containers.

### 2.3.5 Waste-to-Energy Combustion

Combustion is analogous to recycling in that it, too, reduces the weight and volume of material in the waste stream. The products of combustion are predominantly minerals and metals in an ash, which represents only about 10% of the volume of waste as it is collected at curbside. Combustion, as a component of an integrated waste management system, can treat waste and residues from materials recovery and recycling to reduce landfill capacity requirements for these by up to 90%.

Combustion is analogous to materials recycling in a second way. The product of combustion is usable, saleable energy in the form of steam and/or electricity. Income from the sale of energy from waste-to-energy combustion helps to defray the cost of MSW management and displaces the fossil fuels would have otherwise been used to produce that energy.

About 145 waste-to-energy facilities of several types were operating in 1990. These facilities were located predominantly in the eastern Unites States with the greatest concentration in the northern states.

## 2.4 Projections of the Future MSW Stream

This section is organized in three subsections:

- Section 2.4.1 gives projections of the size and material composition of national MSW generation in 1995, 2000, and 2010;
- Section 2.4.2 offers predictions of the impacts of recycling on the MSW stream for 1995; and
- Section 2.4.3 provides hypothetical scenarios of future MSW generation and recycling by type of community and for different levels of recycling program effectiveness.

### 2.4.1 Future MSW Generation and Management

Figures provided in this section are summarized from Franklin Associates projections of the size and material composition of national MSW generation in 1995, 2000, and 2010. The Franklin Report's projections are based on historical trends, industry projections, and best professional judgement. These projections estimate that MSW generation will increase at an average annual rate of 1.6 percent by weight from 179.6 million tons in 1988 to 216.0 million tons in 2000 (see Exhibit 2-7). Per capita generation of MSW is projected to increase from 4.0 pounds per person per day in 1988 to 4.41 pounds per person per day in 2000.

By 1995, Franklin Associates projects that MSW recovery through recycling, composting, and waste-to-energy combustion will divert about 47 percent of the nation's MSW away from landfills. Specifically, recycling is expected to capture 19 percent, composting 5 percent, and combustion about 23 percent of the MSW stream in 1995, with the remaining 53 percent going to landfills (see Exhibit 2-8).

Paper and paperboard are expected to continue to be the dominant material in MSW and to rise in amount (2.5 percent annually by weight) and as a percent of the total waste stream, as over the past 30 years, from 40.0 percent of generation in 1988 to 44.5 percent (96.1 million tons) in 2000.

As glass containers are replaced by plastics and aluminum, the tonnage of glass in MSW is expected to continue to decline 1.6 percent annually by weight, as it has since the mid-1970s, from 7.0 percent of generation in 1988 to 4.8 percent, or 10.3 million tons, in 2000.

**Exhibit 2-7. MSW Generation in 1988, 1995, 2000, and 2010**

| | Weight in Millions of Tons | | | | Percent of Generation | | | |
|---|---|---|---|---|---|---|---|---|
| | 1988 | 1995 | 2000 | 2010 | 1988 | 1995 | 2000 | 2010 |
| **Paper and Paperboard** | 71.8 | 85.5 | 96.1 | 121.2 | 40.0 | 42.8 | 44.5 | 48.4 |
| **Glass** | 12.5 | 11.1 | 10.3 | 9.5 | 7.0 | 5.6 | 4.8 | 3.8 |
| **Metals** | | | | | | | | |
| Ferrous | 11.6 | 11.7 | 12.0 | 12.0 | 6.5 | 5.9 | 5.5 | 4.8 |
| Aluminum | 2.5 | 3.1 | 3.5 | 3.8 | 1.4 | 1.6 | 1.6 | 1.5 |
| Other | 1.1 | 1.4 | 1.5 | 1.7 | 0.6 | 0.7 | 0.7 | 0.7 |
| Total Metals | 15.3 | 16.2 | 16.9 | 17.5 | 8.5 | 8.1 | 7.8 | 7.0 |
| **Plastics** | 14.4 | 18.6 | 21.1 | 25.7 | 8.0 | 9.3 | 9.8 | 10.3 |
| **Rubber and Leather** | 4.6 | 4.9 | 5.3 | 5.8 | 2.5 | 2.4 | 2.5 | 2.3 |
| **Textiles** | 3.9 | 4.1 | 4.3 | 4.6 | 2.1 | 2.0 | 2.0 | 1.8 |
| **Wood** | 6.5 | 7.4 | 8.4 | 10.2 | 3.6 | 3.7 | 3.9 | 4.1 |
| **Food Waste** | 13.2 | 13.2 | 13.3 | 13.7 | 7.4 | 6.6 | 6.2 | 5.5 |
| **Yard Waste** | 31.6 | 33.0 | 34.4 | 36.0 | 17.6 | 16.5 | 15.9 | 14.4 |
| **Other** | 5.8 | 5.7 | 5.9 | 6.4 | 3.2 | 2.9 | 2.7 | 2.5 |
| **Total** | 179.6 | 199.8 | 216.0 | 250.6 | 100.0 | 100.0 | 100.0 | 100.0 |

Source: (Franklin Associates, 1990)

Metals, as a group, are expected to decline as a percentage of MSW generation from 8.5 percent in 1988 to 7.8 percent, by 2000; the tonnage of metals in MSW, however, is expected to increase slightly (0.8 percent annually by weight). Although steel container use, like glass, continues to decline, a slight increase in the tonnage of ferrous material in MSW is projected because steel as a component of durable goods is an increasing component of MSW. Thus, ferrous material is projected to increase slightly from 11.6 million tons in 1988 to 12.0 million tons in 2000, but will continue to decline as a percentage of total MSW generation. Aluminum, on the other hand, has grown rapidly and is expected to continue to grow from 2.5 million tons of generation in 1988 to 3.5 million tons in 2000. Due to its light weight, however, aluminum will continue to constitute a small percentage of total MSW generation by weight; 1.4 percent in 1988 increasing to 1.6 percent in 2000. Other metals,

including lead, copper, and zinc are projected to increase from 1.1 million tons in 1988 to 1.5 million tons in 2000, but will remain less than 1 percent of total MSW generation.

**Exhibit 2-8. MSW Management in 1988 and 1995**

| | Millions of Tons | | Percent of Generation | |
|---|---|---|---|---|
| | 1988 | 1995 | 1988 | 1995 |
| **Generation** | 179.6 | 199.8 | 100.0 | 100.0 |
| Recovery for Recycling | 23.1 | 38.8 | 12.9 | 19.4 |
| Recovery for Composting | 0.5 | 9.5 | 0.3 | 4.8 |
| **Total Recovery**[a] | 23.5 | 48.3 | 13.1 | 24.2 |
| **Discards after Recovery** | 156.0 | 151.5 | 86.9 | 75.8 |
| Combustion w/ Energy Recovery | 24.5 | 45.0 | 13.6 | 22.5 |
| Combustion w/o Energy Recovery | 1.0 | 0.5 | 1.5 | 0.3 |
| **Total Combustion** | 25.5 | 45.5 | 14.2 | 22.8 |
| **Landfill, Other Disposal** | 130.5 | 106.0 | 72.7 | 53.1 |

Source: (Franklin Associates, 1990)
[a] The Franklin Report used an average of high and low recovery estimates for these figures.

Plastic material in MSW has increased rapidly over the past 30 years and is projected to continue to increase 3.2 percent annually by weight, from 8.0 percent of MSW generation in 1988 to 9.8 percent, or 21.1 million tons, by 2000.

Based on sampling studies conducted over a long period of time, both food and yard wastes are projected to continue to increase slightly in tonnage (0.1 and 0.7 percent annually by weight), but are expected to decrease in percentage of total MSW generation. Thus, food waste is projected to be 6.2 percent of generation (13.3 million tons) in 2000 and yard waste 15.9 percent of generation (34.4 million tons) in the same year.

### 2.4.2 Recycling and Composting

Given the dramatic increase in recycling and composting over the last few years, it is difficult to predict how these initiatives will affect the waste stream in the future. For this reason, and due to data limitations, Franklin Associates chose to limit its recycling/composting projections to 1995 and to present both high and low recycling estimates. The Franklin Report based its recycling/composting projections for 1995 were based on industry goals, current recycling rates, recycling trends and initiatives, and other assumptions. They estimate that between 20.0 and 27.7 percent of MSW, by weight, will be recycled in 1995 (see Exhibit 2-9). Exhibit 2-10 compares 1988 recovery rates for certain materials to high and low recovery estimates for 1995.

Paper and paperboard recycling projections were based on an industry goal of 35 percent overall recovery in 1995. (Franklin, 1990) This projection assumes that, in the high range, 63 percent of corrugated boxes, 55 percent of newspapers, 25 percent of books and magazines, 30 percent of office papers, and 25 percent of commercial printing paper will be recycled in 1995. The low range assumes recycling rates about 10 percent lower for each of these paper products.

Assuming that glass beverage container collection rates double through continuation of current beverage container deposit laws and expansion of other recycling programs, glass recovery rates will range from 35 to 45 percent in 1995. Additional recovery of other glass containers is projected to create an overall glass recycling rate of between 19 an 28 percent in 1995.

**Exhibit 2-9. MSW Recycling and Combustion/Landfilling in 1995**

| | Weight in Millions of Tons | | | | | Percent | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Generation | Recycling[a] | | Combustion and Landfill[b] | | Generation | Recycling[a] | | Combustion and Landfill[b] | |
| | | Low | High | Low | High | | Low | High | Low | High |
| **Paper and Paperboard** | 85.5 | 26.3 | 32.6 | 52.9 | 59.2 | 42.8 | 30.8 | 38.1 | 36.6 | 37.0 |
| **Glass** | 11.1 | 2.1 | 3.1 | 8.0 | 9.0 | 5.6 | 18.9 | 27.9 | 5.5 | 5.6 |
| **Metals** | | | | | | | | | | |
| Ferrous | 11.7 | 1.5 | 2.4 | 9.3 | 10.2 | 5.9 | 12.8 | 20.4 | 6.4 | 6.4 |
| Aluminum | 3.1 | 1.1 | 1.4 | 1.7 | 2.0 | 1.6 | 35.4 | 45.1 | 1.2 | 1.3 |
| Other | 1.4 | 0.8 | 0.9 | 0.5 | 0.6 | 0.7 | 58.4 | 65.7 | 0.3 | 0.4 |
| Total Metals | 16.2 | 3.4 | 4.7 | 11.5 | 12.8 | 8.1 | 21.0 | 29.0 | 8.0 | 8.0 |
| **Plastics** | 18.6 | 0.5 | 1.3 | 17.3 | 18.1 | 9.3 | 2.7 | 6.7 | 12.0 | 11.3 |
| **Rubber** | 4.9 | 0.1 | 0.3 | 4.6 | 4.8 | 2.4 | 2.0 | 5.4 | 3.2 | 3.0 |
| **Food Waste** | 13.2 | 0.0 | 1.0 | 12.2 | 13.2 | 6.6 | 0.0 | 7.6 | 8.4 | 8.3 |
| **Yard Waste** | 33.0 | 6.6 | 11.0 | 22.0 | 26.4 | 16.5 | 20.0 | 33.3 | 15.2 | 16.5 |
| **Other** | 17.2 | 1.1 | 1.3 | 15.9 | 16.1 | 8.6 | 6.4 | 7.3 | 11.0 | 10.1 |
| **Total** | 199.8 | 40.1 | 55.3 | 144.5 | 159.8 | 100.0 | 20.0 | 27.7 | 100.0 | 100.0 |

Source: (Franklin Associates, 1990)
[a] Includes composting. Percentages represent the portion of generation that is recycled.
[b] The amount of MSW remaining after recycling and composting, virtually all of which is combusted or landfilled.

Franklin Associates projects that metals will be recovered from MSW at an overall rate of between 21 and 29 percent in 1995. This rate assumes that:

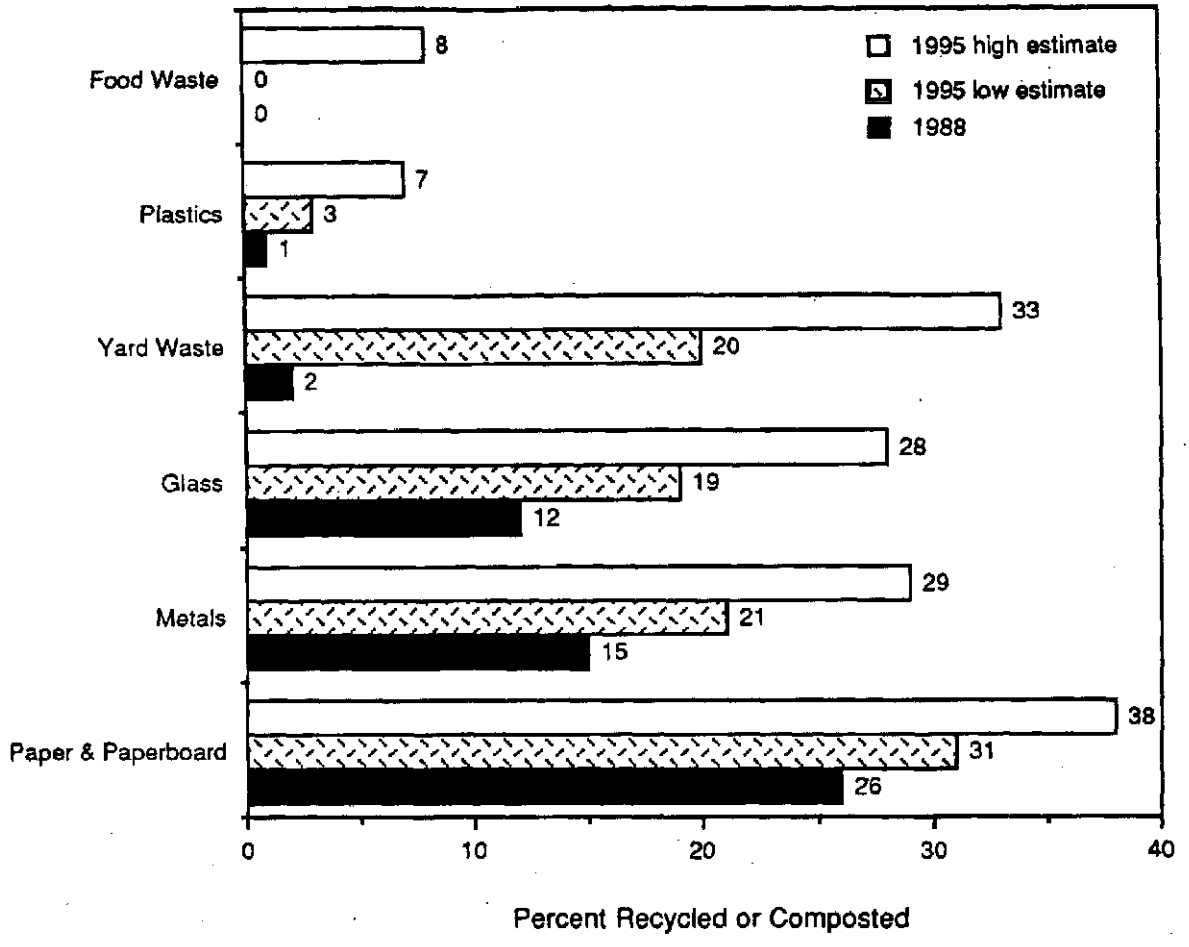
- Between 45 and 55 percent of steel cans and up to 17 percent of ferrous metals in appliances will be recovered for an overall ferrous metal recovery rate of 13 to 20 percent;

- Recycling of between 60 and 75 percent of aluminum cans and some additional aluminum packaging will lead to an overall aluminum recycling rate of 35 to 45 percent; and

- Recovery of other nonferrous metals will remain fairly constant.

Franklin Report projections of plastics recycling range from approximately 3 to 7 percent of total plastics generation. They assume that between 25 and 40 percent of plastic bottles, 10 to 25 percent of plastic milk and water bottles, and up to 12 percent of other plastic packaging will be recycled in 1995 through continuation and expansion of current collection efforts.

**Exhibit 2-10. MSW Recycling and Composting in 1988 and 1995**




Source: (Franklin Associates)

### 2.4.3 Scenarios of MSW Generation and Management in 2000

Recent emphasis on composting is projected to remove from 20 to 33 percent of yard waste and up to 8 percent of food waste from the MSW stream by 1995. Small amounts of rubber, wood, and textile recovery are also projected for 1995.

This section provides hypothetical scenarios of future MSW generation and recycling by type of community and for different levels of recycling program effectiveness. Exhibits 2-11 and 12 present scenarios of MSW generation and management in the year 2000 for two different community types: (1) Urblanda, a 300,000 person urban community and (2) Hamlet, a 10,000 person exurban/rural community. The influence of community type on the MSW stream is reflected in the amount of MSW generation for each community and the proportion of each material in the waste stream. The total amount of MSW generation was developed in the same way for both communities: by multiplying the population by a per capita MSW generation rate of 4.0 pounds per person per day. The percent of paper and paperboard in the waste stream, however, is higher for Urblanda than Hamlet, reflecting more commercial development. The portion of yard waste in MSW, on the other hand, is higher for Hamlet than Urblanda, indicating more residential or agricultural development.

The exhibit for each community also includes a low and a high scenario for recycling and composting of the various components of MSW. The low and high recycling scenarios represent different levels of recycling program effectiveness and are the same, on a percentage basis, for each community. The low scenario applies recycling rates similar to those estimated by Franklin Associates for the nation in 1988, as shown in Exhibit 2-1. The low scenario assumes that Urblanda and Hamlet would, over the next 10 years, reach the current recycling and composting levels of the nation as a whole. The high scenario applies optimistic recycling rates that states, local communities, and associations are setting as goals for recycling over the next 10 years.

#### Implications of Scenario for Urblanda

Urblanda's large size and high density will affect the options available for MSW management, including recycling, composting, landfilling, landfill gas recovery, and combustion. Curbside collection of recyclable materials, for example, is more feasible for Urblanda than Hamlet due to Urblanda's higher density of development. Urblanda may, however, need to develop special programs for recycling in office buildings, particularly for paper and multifamily dwellings. The high amount of recyclables that could be recovered from Urblanda's waste stream also make a MRF feasible for processing waste gathered through curbside collection and office recycling. In addition, if yard waste was banned from landfills, Urblanda would potentially need to create a local composting facility because backyard composting could be limited by the dense urban setting.

Urblanda's high MSW generation rate and possible proximity to scrap markets make it possible for it to support landfill gas recovery operations. In addition, given the large amount of MSW, and potential for a high concentration of organic waste (paper, food waste, and yard waste), landfill gas recovery is a viable option for Urblanda. Methane produced through waste decomposition could be captured and used to generate energy.

## Exhibit 2-11. Urblanda MSW Management Scenario for 2000

| | Weight in Thousands of Tons | | | | | Percent | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Generation | Recycling | | Combustion and Landfill | | Generation | Recycling | | Combustion and Landfill | |
| | | Low | High | Low | High | | Low | High | Low | High |
| **Paper and Paperboard** | 98.6 | 24.7 | 51.3 | 47.3 | 73.9 | 45.0 | 25.0 | 52.0 | 44.4 | 39.6 |
| **Glass** | 17.5 | 2.6 | 13.1 | 4.4 | 14.9 | 8.0 | 15.0 | 75.0 | 4.1 | 8.0 |
| **Metals** | | | | | | | | | | |
| Ferrous | 15.3 | 1.5 | 13.8 | 1.5 | 13.8 | 7.0 | 10.0 | 90.0 | 1.4 | 7.4 |
| Aluminum | 2.2 | 0.7 | 1.5 | 0.7 | 1.5 | 1.0 | 30.0 | 67.0 | 0.7 | 0.8 |
| Other | 2.2 | 1.3 | 2.1 | 0.1 | 0.9 | 1.0 | 60.0 | 95.0 | 0.1 | 0.5 |
| Total Metals | 19.7 | 3.5 | 17.4 | 2.3 | 16.2 | 9.0 | 18.0 | 88.0 | 2.1 | 8.7 |
| **Plastics** | 17.5 | 1.8 | 4.2 | 13.3 | 15.7 | 8.0 | 1.0 | 24.0 | 12.5 | 8.4 |
| **Rubber** | 2.2 | 0.0 | 0.7 | 1.5 | 2.2 | 1.0 | 0.0 | 30.0 | 1.4 | 1.2 |
| **Food Waste** | 17.5 | 0.0 | 1.8 | 15.7 | 17.5 | 8.0 | 0.0 | 10.0 | 14.7 | 9.4 |
| **Yard Waste** | 24.1 | 0.0 | 21.7 | 2.4 | 24.1 | 11.0 | 0.0 | 90.0 | 2.3 | 13.0 |
| **Other** | 21.9 | 0.0 | 2.2 | 19.7 | 21.9 | 10.0 | 0.0 | 10.0 | 18.5 | 11.7 |
| **Total** | 219.0 | 30.9 | 112.1 | 106.9 | 188.1 | 100.0 | 14.1 | 51.2 | 100.0 | 100.0 |

Source: ICF analysis.

At recycling levels ranging from zero percent to the high recycling scenario (about 50 percent diversion) Urblanda's post-recycling waste stream is over 290 tons per day. This is large enough to support a mass-burn combustor. Communities that generate less than approximately 100 tons per day of MSW, however, need to consider the impact of recycling efforts on the feasibility of a mass-burn facility and the choice of a mass-burn technology. Diversion of 50 percent of this waste stream will mean that about 50 tons per day of MSW is available for combustion. This size waste stream is probably not sufficient to support a mass-burn facility, other than a modular unit, which generally has a capacity of less than 50 tons per day. This example demonstrates the need for local MSW managers to fully consider the mutual impact of different components of the MSW management system and to integrate goals and plans. In some cases, even large urban communities can benefit from regional planning and cooperation when larger regional waste management facilities are more technically and economically feasible than smaller local facilities.

### Implications of Scenario for Hamlet

The low density, residential nature of communities like Hamlet also has implications for MSW management. The predominance of single family dwellings, as opposed to apartment buildings, may increase the feasibility of recovering a greater portion of potentially recyclable

wastes. Yet, it could be costly for Hamlet to reach the high recycling levels because:

- Residences are spread out, leading to higher curbside collection costs; and

- Markets for recyclable materials may be inadequate or distant, reducing the value of recovered materials.

If residents bring their recyclables to a central recycling drop-off center, however, this could reduce public costs and increase the feasibility of a local MRF. In addition, although Hamlet generates a greater proportion of yard waste in MSW than does Urblanda, Hamlet may have less need for a local composting facility because residents have a greater ability to conduct backyard composting. Thus, Hamlet could ban landfilling of yard waste without needing to create a local composting facility. Landfill gas recovery would be a viable option for Hamlet, given the large proportion of yard waste generated.

The relatively small amount of MSW that Hamlet generates (about 20 tons per day) makes combustion at modular units the only potentially sensible option for energy recovery through combustion. Hamlet may lack a MSW generation rate sufficient for other mass-burn combustion technologies and it may even be too low to make modular combustion cost effective. Smaller communities like Hamlet can benefit significantly from regional planning and cooperation in cases where larger regional waste management facilities are more technically and economically feasible than smaller local facilities.

# 3. ANAEROBIC DIGESTION

## 3.1 Technology Description

Anaerobic digestion is a conversion process that utilizes solid wastes and sewage sludges. The organic fraction of these wastes undergoes decomposition by anaerobic microorganisms, producing biogas gas and carbon dioxide. A residue of undigested materials is also produced that may be landfilled, composted, incinerated, or used as landfill cover. The major elements of the anaerobic digestion process are pretreatment, digestion, product recovery, and residue management. While anaerobic digestion and landfill gas production both use the process of anaerobic microbial degradation to produce biogas, anaerobic digestion occurs in controlled digesters that allow digestion conditions to be regulated more precisely.

MSW may be preprocessed in order to separate organic matter from inorganic matter and materials that do not biodegrade and may disrupt the mechanical operation of the digester. Separation processes provide a feedstock with a high concentration of digestible matter that is relatively free of metals, plastic stringers, glass, and grit. This separation may be accomplished by either wet or dry methods. During this preparation process, the MSW may also be reduced in size to increase the efficiency of the separation. Other preprocessing steps might involve a composting or chemical pretreatment. An example of chemical pretreatment is alkali cooking of MSW to increase the solubility of cellulosic materials (Tsai and Tsao, 1988). Finally, before the waste enters the digester, nutrients may be added in the form of raw sewage sludge and other chemicals may be added for control purposes, as shown in Exhibit 3-1. Either raw water or recycled filtrate from the digester tank may be added to facilitate mixing and pumping the slurry. Recycling filtrate conserves heat, water, nutrients, alkalinity, and inoculum. (Chynoweth and Legrand, 1988)

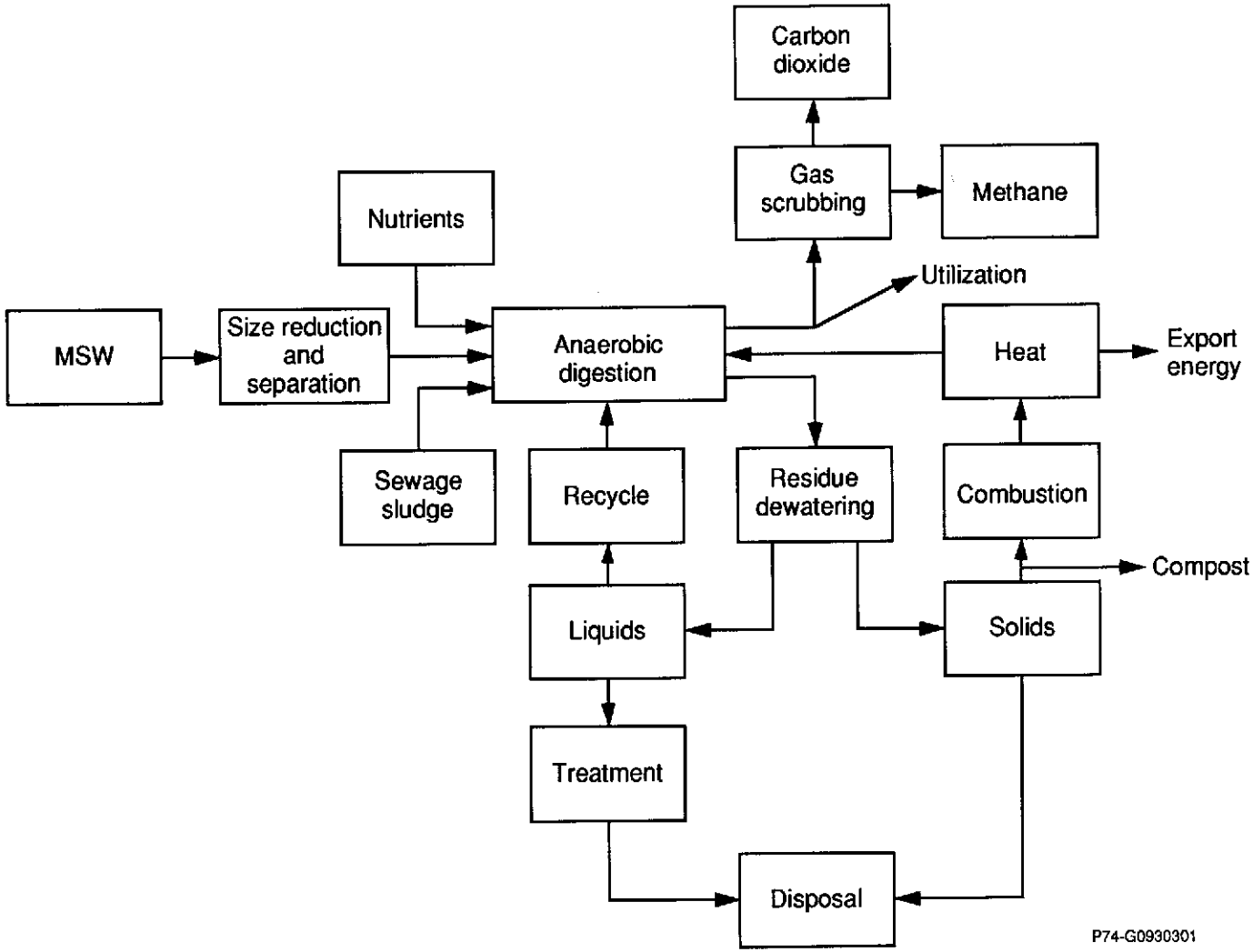
Anaerobic digestion results in the decomposition of organic matter and the production of gas. In the conventional anaerobic digestion process, materials in the digester tank are stirred continuously by one or more mixing devices. The conversion occurs in two steps: (1) solids are solubilized or digested by enzymatic action; and (2) the soluble products are fermented in a series of reactions producing biogas and carbon dioxide. (Scaramelli, 1979)

The conventional anaerobic digestion process described above can be modified in several ways, including the following:

- **High solids digestion** involves limiting the amount of water added to the waste resulting in a higher concentration of organic material in the digester tank than in the conventional system. With higher solids concentrations, smaller digesters can be used and costs can be reduced.

- **Two-stage digestion** incorporates a combination of high-rate digestion and conventional unmixed digestion. The first stage is a percolating bed (Rivard et al., 1988), or continuously fed, completely mixed biological unit from which gases are collected. The second stage is a quiescent unit for solids separation and concentration.

**Exhibit 3-1. Anaerobic Digestion Process Flow Diagram**



- **Two-phase digestion** involves two biologically active digester tanks in series. The first tank is managed to favor microorganisms that produce volatile fatty acids. The second tank is managed to favor microorganisms that convert fatty acids to methane and carbon dioxide.

- **Plug flow digestion** systems consist of horizontal reactors through which digester substrate continuously moves. Feedstock is continuously loaded at one end and effluent discharged from the other.

The anaerobic digestion products are released in two streams. The product gas from the digester has methane and carbon dioxide and trace quantities of other gases. The gas produced may be burned to produce heat or purified by removing carbon dioxide to obtain pipeline-quality methane gas (Chynoweth and Legrand, 1988).

The second product stream is an aqueous suspension of undigested organic matter. Water and undigested matter must be removed from the digester at a rate equal to the rate of feed. This slurry is typically managed by separating the solids from the liquid. The liquid is either recycled or treated for final disposal. Solid sludges or cakes may be incinerated, composted, or sent to a landfill.

## 3.2 Technology Status

A comprehensive inventory in 1985 showed that, in addition to 209 municipal wastewater treatment facilities that produce biogas as a fuel, approximately 100 farm-scale and industrial anaerobic digestion reactors had been constructed between 1972 and 1985 in 30 states and Puerto Rico. Sixty of the anaerobic digestion systems were operational, seven were temporarily shut down, and the remainder were in various stages of development. As shown in Exhibit 3-2, 44 of the operational or shut down systems (1.55 million cubic feet of volume) were used for digesting animal manures, with 35 for dairy or beef cattle manure and the remainder for swine or poultry manure. Most farm-scale digesters used plug flow and stirred tank configurations and unheated lagoons. Fourteen of the facilities (3.81 million cubic feet of volume) provided wastewater clean-up services to agricultural product processing plants, breweries, and related food production facilities. Only a few additional commercial digestion systems have been installed since this inventory was completed. The table below estimates the potential methane gas recovery from all commercial anaerobic digestion systems, including farm-scale under conventional operating conditions. (Klass, 1990)

In 1984, a survey on the use of anaerobic digestion for biogas production found that the majority of individual digesters had volumes ranging from 8,800 to 26,500 cubic feet, with some as large as 460,000 cubic feet for municipal sewage treatment, some of which do not use the gas. These facilities were scattered across 30 states. (Klass, 1990) A large-scale test facility located at Pompano Beach, Florida was in operation during the early 1980s, but

**Exhibit 3-2. Potential Methane Production from Commercial Anaerobic Digestion Systems**

| NO. EXISTING PLANTS | FEEDSTOCK | ESTIMATED DIGESTER VOLUME $10^6$ feet$^3$ | ESTIMATED METHANE PRODUCTION POTENTIAL[c] | |
|---|---|---|---|---|
| | | | $10^6$ feet$^3$/day | Quad/Year |
| 209[a] | Municipal waste water | 7.54[b] | 7.35 | 0.0027 |
| 44 | Animal manures | 1.55 | 1.51 | 0.0006 |
| 14 | Industrial wastes | 3.81 | 3.71 | 0.0014 |
| | | TOTALS | 12.57 | 0.0047 |

Source: Klass, 1990

[a] "1984 Needs Survey Report to Congress: Planned and Existing Projects in the U.S.," U.S. EPA and Roy F. Weston, Inc., revised January 1985, DOE/CE/30784/1, August 1985. These are treatment plant unit processes (not individual digesters) that produce and use digester gas; the flow capacity is 3.76 million gallons per day.

[b] Assumes 15-day high residence times.

[c] Assumes 65 volume percent of methane in product gas and 1.5 volume gas/culture volume per day.

has since shut down after meeting technical objectives. A number of other pilot-scale and commercial MSW anaerobic digestion systems in the United States have also been reported.[1]

New York and California have taken a special interest in funding and developing anaerobic digestion systems (Klass, 1990). The California Energy Commission has funded methane fermentation projects at dairy and swine farm operations through the California Biomass Demonstration Program. Many of these projects have used the recovered biogas for on-site electricity generation and have subsequently sold excess electricity to the Southern California Edison Company. As of 1989, the New York State Energy Authority was sponsoring projects using anaerobic digestion techniques to accelerate the rate of gas production and recovery at existing and future landfill sites. Municipalities in New York were working with methane-gas-producing anaerobic digesters and "in-ground" anaerobic reactor/recirculation trenches to maximize energy benefits while reducing biodegradable fractions in landfill leachate (Mathusa, 1989).

## 3.3 Description of RD&D Needs

Many of the RD&D needs associated with anaerobic digestion tend to focus on either overcoming apprehension to the anaerobic digestion technology on the part of many potential

[1] One reviewer stated that VOLARGA currently has two commercial plants and another under construction, DRANCO and BTA have plants under construction, and pilot plants have been successfully operated by the Solar Energy Research Institute (now called the National Renewable Energy Laboratory), the University of Florida, and Cornell.

users or improving the mechanical processes of preparing the MSW feedstock and adding, mixing, and removing substrate materials. Establishment of the technical feasibility and reliability of the anaerobic digestion process, as well as some commercial development of the technology, will be necessary to overcome the public apprehension to anaerobic digestion. This will require the demonstration of a fully operational plant before the technology will develop on a large scale.

Psychological barriers to the development and use of anaerobic digestion systems result from reports of unstable digesters and digester failures. Infrequent failures have a much more profound influence on the development of anaerobic digestion than many documented successes. If a digester goes unstable it may take an extended period of time to restore stability to the unit and substantial costs would be incurred by the facility due to disposal and down-time. It is important to develop a better understanding of the causes of process instability and develop means to overcome instability and prevent digester failures.

Due to the lack of full-scale anaerobic digestion facilities, very little is reported in the relevant technical literature about specific RD&D needs on such things as the preparation of optimal anaerobic digestion feedstock, the transportation of the material into the digester, handling (mixing) the digesting slurry, the removal of digested material from the digester, or handling of the residues. Specific RD&D needs in these areas are likely to appear during increased development of full-scale MSW fueled facilities. The panel of technical experts also indicated the importance of examining information gained in previous studies such as RefCoM, DRANCO, VALORGA, and SEBAC, as well as information developed in other countries.

For anaerobic digestion products to be competitive in the marketplace, costs will need to be reduced through faster and more efficient bioconversion (Himmel et al., 1989). To accomplish this goal, research will be needed to better understand the microbiological processes involved in anaerobic digestion, to develop better methods of controlling the digesters, and to design new digesters that are more efficient.

Sections 3.3.1 through 3.3.9 describe the RD&D needs for anaerobic digestion that were identified by ICF's literature review and the panel of technical experts (see Appendix A). Each of the RD&D needs is assigned a reference number (i.e., 1, 2, 3, ... 35) that is used in later sections when the RD&D needs are prioritized and discussed. Section 3.3.10 describes RD&D topics that were identified in the literature review (see Section 1.2 on methodology), but were not subsequently accepted by the panel of technical experts. The RD&D areas in Section 3.3.10 are not prioritized or discussed further.

### 3.3.1 Understanding Microbial Ecology

To understand the microbial ecology of the anaerobic digestion system, it will be necessary to isolate, identify, and characterize higher yielding bacteria. To better understand bacterial interactions research is needed on organisms that hydrolyze polymers, methano-acetogenesis, and conditions promoting process stability.

Research is currently being conducted to quantify microbial populations by identifying and characterizing the organisms present within anaerobic digesters that either produce or affect the production of methane gas (Goodman, 1988). Further research is necessary to

isolate, identify, characterize, and compare strains of faster acting methane-producing bacteria for increased digester efficiency (Weaver and Maness, 1988; U.S. Dept. of Energy, 1986). Research is also needed to identify additional strains of bacteria, not normally found in digesters, that may enhance methane production (de Macario et al., 1988). For example, certain photosynthetic bacteria have been shown to enhance the conversion of organic acids to methane by utilizing solar energy to "drive" this chemical reaction (Weaver and Maness, 1988; Weaver and Maness, 1989).

Bioconversion of MSW to methane in anaerobic digestion reactors is accomplished by a combination of many types of microorganisms. Additional research is needed to identify and characterize the activities, functions, interactions, and criteria for growth of each of these types of organisms (Antonopolos and Wene, 1986; U.S. Dept. of Energy, 1986). More knowledge is needed of acetogenesis and methanogenesis as they relate to gas production, transportation, and storage systems (Frank and Hayes, 1990). Enhanced bioconversion research should focus on increasing the yields of methane production through gaining a better understanding of the biochemistry and physiology of the organisms within a reactor (Goodman, 1988). The following are summary descriptions of the previously discussed RD&D needs:

1. Study the interactions between microorganisms found in anaerobic digestion reactors;

2. Develop a better understanding of methano-acetogenesis as it relates to methane gas production;

3. Identify and quantify microbial populations found in anaerobic digestion reactors;

4. Study the physiological requirements and status of microbes found in anaerobic digestion reactors;

5. Identify and quantify enzyme activity (other than polymer) within digesters that promotes the generation of methane gas; and

6. Evaluate photo enhancement of anaerobic processing.

### 3.3.2 Stress Impacts on Organisms

Digester malfunction has been a problem in many anaerobic digestion systems (Goodman, 1988). The causes of these malfunctions are not well understood. Further studies of digester malfunctions are needed to better understand digester processes and to achieve stable operating conditions in digesters using MSW (Antonopoulos and Wene, 1988).

Mixing of the digester contents, while necessary in many systems, may induce stress within the digester by causing detachment of microbes from feedstock surfaces and a disruption in the biodegradation of the MSW. Additional studies are needed to better understand the mechanisms behind microbial attachment to digester material surfaces and the effects of disturbance on the microbial populations within mixed digesters (McKinney, 1988).

Digester malfunctions may be caused by the presence of materials in the digester that are toxic to microbes. These materials may be generated in the digester or added as a constituent of the feedstock. Studies are needed to identify toxic materials and evaluate their effect on digester performance. This will require information on the metabolic pathways of the bacteria, how they are regulated, and rate limiting factors (Weaver and Maness, 1988). Microbiological studies of stressed anaerobic digestion systems are needed to help determine which bacteria are the most sensitive and the most easily affected by unstable conditions (McKinney, 1988). Understanding the causes of digester malfunctions, such as reduced biodegradation rates caused by chronically high volatile acids contents (Speece, 1988) or recalcitrant materials like polyaromatic hydrocarbons (Frank and Hayes, 1990), could improve biomass to methane production.

Improved polymer hydrolysis of the MSW feedstock will enable higher bioconversion rates in digesters by increasing the proportion of the MSW that is biodegraded. If the feedstock can be treated before, within, or between stages to improve hydrolysis, then gas generation rates should improve. The following are summary descriptions of the previously discussed RD&D needs:

7. Study the effects of disturbing forces (e.g., mixing) on microbes and communities within the digester;

8. Evaluate the role of toxics on digester malfunction and failure;

9. Examine toxicity of feedstock components (e.g., sulfates such as gypsum) and the effects on digester performance due to the changing nature of feedstock;

10. Improve polymer hydrolysis including improved fermentability;

11. Examine microbial attachment to particles;

12. Evaluate microbial pre/post treatment; and

13. Study interfacial effects on enzyme activity.

### 3.3.3 Bioconversion Properties of Organic Wastes

In order to control the nutritional balance of the digester, determinations as to nutritional value, bioconversion properties, and subsequent effects on the digester for each major type of organic wastes are necessary (McKinney, 1988). Types of MSW feedstock, as well as individual components of MSW feedstock, should be characterized according to their ability to produce methane gas in anaerobic digestion systems. Much of this information is already available but is difficult to identify and retrieve because it is not well organized. If the information were in a readily accessible database, it is more likely that it would be used in the development of anaerobic digestion systems. The following is a summary description of the previously discussed need:

14. Establish a database on bioconversion properties of organic wastes.

### 3.3.4 Materials Handling and Feeding

The engineering problems of getting feedstock and residual materials (wet or dry) into and out of the digester need to be resolved. Research is needed to determine the best methods for maximizing enzyme loadings and retaining high microbial populations within the digester during process operations (U.S. Dept. of Energy, 1986; Himmel et al., 1989). Front-end processing methods need to be developed to decrease the process sensitivity to the variations in feed consistency by removing feed impurities, normally found in MSW, and decrease the occurrence of resulting malfunctions (Vilppunen, 1990). The following are summary descriptions of the previously discussed RD&D needs:

15. Develop improved methods for feeding wet and dry feed digesters at various solids-concentration rates; and

16. Examine clean feed options including front-end processing and the impact on these options of variable feedstock consistency (e.g., seasonal change in MSW).

### 3.3.5 Digester Design

New digester designs may improve system performance and efficiency. Improved reactor design may increase the methane content of the digester gas to greater than 90 to 95 percent (Walter, 1990). This would simplify gas purification requirements and reduce the overall cost of producing pipeline quality gas. New anaerobic digestion technologies, such as the use of high solids and photosynthetic bacteria, will also require innovative changes in digester design to take full advantage of these advances (Weaver and Maness, 1988; Goodman, 1988). Another design uses microaerophilic conditions within the digester to enhance degradation of MSW as part of an effort to optimize two-stage anaerobic digestion (U.S. Dept. of Energy, 1986). Other systems are designed to increase conversion efficiency through increased digester solids content and decreased solids residency time (Walter, 1989; Goodman, 1988). Additional data are needed to determine optimum system designs based on retention time, solids content, and the amount of material recycled into the next batch. This information will be necessary to minimize reactor volumes and maximize conversion efficiency in high solid content reactor designs (Frank and Hayes, 1990; Clausen and Gaddy, 1988; U.S. Dept. of Energy, 1986). The completely stirred tank reactor (CSTR) design has been the most demonstrated and may be considered as a conventional design. Other designs have not been well demonstrated and do not yet have adequate operational histories to justify their use. These alternative designs, however, need to be evaluated based on their performance relative to the more conventional CSTR design.

The energy required for mixing digester contents, in systems that require intermittent, minimal, or continuous mixing, is the biggest energy drain in the entire process. The amount and type of mixing, with respect to solids concentration, needs further study. Additional studies are needed to better understand the impact of organic loading and mixing on the dispersion of bacteria within digesters (McKinney, 1988).

Heat is added to anaerobic digestion systems to enhance the bioconversion process. Microbes can generate differential amounts of metabolic heat which may potentially supplement or heat an anaerobic digestion system. The heat generation potential of microbes

needs to be evaluated as a possible means of decreasing the energy requirement of digester systems.

Methane enrichment digestion (MED) is a technique to improve gas quality that is important if the produced gas is to be used for pipeline gas or vehicles. New and existing MED techniques need to be developed and evaluated. The following are summary descriptions of the previously discussed RD&D needs:

17. Evaluate mixing techniques as they relate to energy requirements and digester performance;

18. Examine the effect of mixing on the microbial distribution within digesters;

19. Study the metabolic heat generation potential of microbes;

20. Evaluate commercial anaerobic digester designs as alternatives to the CSTR design; and

21. Evaluate methane enrichment digestion techniques.

### 3.3.6 Demonstrate Digestion Process Control

The performance of any anaerobic digester can be optimized through control of the process. Efficient control of the anaerobic process requires timely information on the conditions inside the reactor. Assays that serve as indicators of digester conditions need to be developed for hydrolytic enzymes in the supernatant of anaerobic digesters being fed MSW and for the hydrolytic enzymes bound to solids in the digesters (Himmel, et al., 1988; U.S. Dept. of Energy, 1986; Himmel et al., 1989). The development of control mechanisms that are based on feedback from the digester will also improve reactor control and stability (Walter, 1989; Goodman, 1988).

The development of best management practices for anaerobic digestion systems will require an improved understanding of the bioconversion process and the interactions of factors affecting the process. These factors include MSW pretreatment, retention time, solids content, amount of recycled fluid used as inoculum, frequency of mixing, external power inputs (e.g., heating and mixing), distribution of microorganisms and nutrients, pH, temperature, and nutrient supplementation (Clausen and Gaddy, 1988; Mathusa, 1989; U.S. Dept. of Energy, 1986). An improved understanding of process factors, the establishment of process indicators, and the development of process feedback and control mechanisms will enable the development and evaluation of best management practices that optimize the effectiveness of microbial populations and improve bioconversion efficiencies (Antonopolos and Wene, 1986).

The start up of a new digester or the reestablishment of a failed digester can take many months to accomplish. This period may generate substantial costs before the biogas producing microbe populations are established. Techniques need to be developed to reduce the duration of this unproductive period. This may include examining different inoculation practices or sources of inoculum. The following are summary descriptions of the previously discussed RD&D needs:

22. Evaluate best management practices for reactor and process control;

23. Develop on-line monitoring and control techniques, devices, and indicators, that will provide an early warning for instability and aid in process control; and

24. Examine methods of reducing start up time including optimal inoculation practices and inoculum sources.

### 3.3.7 Systems Analysis

An integral part of optimizing digester performance is providing the best possible bacterial growth conditions for bioconversion of MSW to methane. Pilot scale tests are needed to confirm bench-scale research on the effects of additives and supplemental nutrients and to determine the optimum requirements of MSW for nitrogen and supplemental nutrients (U.S. Dept. of Energy, 1986). Investigation is also needed to elucidate the role of trace metals in enhancing digester performance and possibly averting digester malfunctions (Speece, 1988).

Pretreatment techniques are needed that will enable shorter retention times and higher bioconversion rates of MSW feedstock. Pretreatment techniques such as using lime and heat to increase MSW solubility before high solids anaerobic digestion should be developed and evaluated (U.S. Dept. of Energy, 1986).

Production of methane gas has been the major objective of anaerobic digestion systems. This gas can be used directly, such as producing heat for the production of electric power, or converted into other products such as pipeline quality natural gas or methanol. The suitability of biogas for different use options should be evaluated based on expected gas quality and the possibility of containing contaminants such as vinyl chloride.

More investigation is needed to develop and evaluate beneficial uses of other materials produced by the process. Organic acids are produced in anaerobic digesters as an intermediate step in the conversion of MSW to methane. Organic acid production could be enhanced by suppressing their conversion to methane. This will require additional research to determine the effects of pH, hydrogen pressure within digesters, and other solvent/extraction combinations on acid production and methane suppression (Antonopolos and Wene, 1986; Wene and Antonopoulos, 1989). Once these acids are extracted from the digester, they can be converted into liquid fuels such as diesel fuel or gasoline (Antonopoulos and Wene, 1988; Rivard et al., 1988). Further research is needed to develop systems that would enhance organic acid production or terminate the anaerobic digestion process once these organic acids were produced (Tinning, 1985).

A major part of demonstration and development of the technology will include systems analysis. A systematic cost analysis is needed to evaluate this technology in comparison to other MSW technologies. A similar evaluation should be performed comparing the environmental costs/benefits of anaerobic digestion to other MSW technologies. These analyses should include tradeoffs within this technology such as the cost of controls and their associated expected environmental benefits. The following is a summary description of the previously discussed RD&D needs:

25. Examine the chemical and energy requirements of digesters including nutrients and additives;

26. Develop and evaluate pre/post treatment methods;

27. Evaluate options for the use of generated gases including the impact of trace gases, such as vinyl chloride, on restricting gas use options;

28. Examine potential beneficial uses of by-products including organic acids;

29. Perform cost analyses of anaerobic digestion alternatives as compared to other MSW technologies; and

30. Evaluate environmental benefits of anaerobic digestion as compared to other MSW technologies including tradeoffs within this technology such as the cost of controls with their associated expected environmental benefits.

### 3.3.8 Residue Processing

The anaerobic digestion process produces a residue of undigested materials. This material requires management practices which may include landfilling as well as beneficial uses such as thermal gasification, composting, landfill cover, soil mulching, and solid fuel. The presence of toxic substances in MSW, however, may create problems for certain residue uses. The following are summary descriptions of the previously discussed RD&D needs:

31. Examine potential uses of anaerobic digestion residues including thermal gasification, composting, landfilling, landfill cover, soil mulching, and solid fuel.

### 3.3.9 Physical Behavior of Solids and Liquids

A major development need for the anaerobic digestion technology is overcoming the mechanical problems of preparing, adding, mixing, and removing MSW feedstock and the resultant materials. A precise understanding of the physical characteristics of materials within the system is necessary to adequately overcome these problems through management practices and the design of system components.

The Sequential Batch Anaerobic Composting (SEBAC) process was developed as an attempt to solve materials handling problems by making the reactor very accessible. In this process leachate is percolated through stationary feedstock (Chynoweth et al., 1988). The hydraulic conductivity of the substrate material (MSW) is the principal potentially limiting factor for this process. Hydraulic conductivities need to be determined for various MSW feedstocks at full-scale depths to be able to optimize bioconversion rates in the SEBAC process.

Under all anaerobic digestion processes the collection of biogas can take place only after the gas has been liberated from the solution. The release of gas bubbles from the substrate is affected by complex interfacial gas/liquid phenomena. A better understanding of this phenomena may lead to increased bioconversion rates by exploiting more of the

generated gas. The following are summary descriptions of the previously discussed RD&D needs:

32. Evaluate the flotation potential of MSW feedstocks;

33. Evaluate the foaming potential of MSW feedstocks;

34. Determine hydraulic conductivities of MSW feedstocks; and

35. Investigate interfacial gas/liquid phenomena as they relate to gas bubble liberation.

### 3.3.10 Other Potential RD&D Topics

The following RD&D topic was identified in the literature review, but was not subsequently accepted by the panel of technical experts.

Development of new bacterial strains through genetic engineering. Recent advances in genetic engineering may provide a means of enhancing digester performance through the use of genetically altered methanogenic bacteria (Goodman, 1988; U.S. Dept. of Energy, 1986). Construction of new methanogenic strains with genetic engineering will require innovative techniques to isolate methanogenic genes (Ho, 1988). Further research is needed to select and genetically breed organisms to optimize reactor performance (Walter, 1989; Goodman, 1988). The use of improved strains could increase digestion rates, reduce reaction times, and improve process efficiency (de Macario et al., 1988).

## 3.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on anaerobic digestion (identified in Appendix A) are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making anaerobic digestion technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. (See the introduction chapters for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 3-3, from highest to lowest priority. The normalized scores for each RD&D need are in the left hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 3.3 is in the right hand column. The rationale discussed by the panel of technical experts is presented below. The rationale tends to focus on RD&D needs where panel members had very different opinions on the priority of the RD&D need, and to ignore RD&D needs on which there was a group consensus. Also, the discussion of rationale was constrained by the limited amount of time available to the panel.

The failure of digesters is not a common event, but may have a large impact on how potential users of the technology perceive its viability. The most important research needs, therefore, relate to the prevention of failures and the demonstration of a continued successful experience base for the process. Panel members believe that a sufficient amount of successful experience is already available and that sufficient knowledge is now available to

successfully build a demonstration unit. Due to past problems at certain facilities, however, it was decided that a successful demonstration of the process at a commercial scale is needed to overcome public resistance to the technology. This commercial demonstration plant should have sufficient redundancy built into the system to prevent digester failure.

The demonstration plant could provide valuable information to fulfill many of the research needs outlined in this report. The most important gaps in knowledge relate to material handling problems and microbial ecology. Material handling is most important to large-scale facilities utilizing the wet process (No. 15) whereas it is not a problem for leached bed systems. Material handling problems that need further research are generally engineering problems relating to feeding (wet or dry) materials into digesters, mixing the materials within the digesters, and getting the material out at the end of the process (No. 15). Digester stability is the most critical aspect of the process and is the least understood. Monitoring the physiological status of digesters and a better understanding of methano-acetogenesis are crucial to understanding the causes of digester instability and failure (Nos. 2 and 4)**. The role of toxics and trace metal additives on digester stress and failure also need additional study (No. 8). Polymer hydrolysis is an important rate-limiting factor affecting the amount of organic material that is readily biodegradable. Improving polymer hydrolysis -- before, within, or between stages -- may improve yield (No. 10). One panel member, however, doubted that much progress could be made in this area.

An important part of demonstrating the commercial acceptability of the anaerobic digestion technology will be the establishment of a demonstration facility. A demonstration facility is needed to provide commercial-scale testing of an integrated system. The design that will be best suited for this integrated system has not been determined. There are currently three viable major system designs that have somewhat different research needs. The CSTR design is considered to be the conventional design but other designs should also be evaluated and considered for the demonstration system (No. 20). It should not be presupposed that one design is clearly better than another. Future digester designs may follow from the materials handling and stability studies.

The priorities of research needs relating to mixing, leachability, and stability are unique for each design. Mixing is the biggest energy drain in the entire process for anaerobic digestion systems that require mixing. For these systems, the amount and types of materials to mix relative to given specific solids concentrations must be better understood (No. 17). The effect of shear on digester performance is an important factor to wet process systems that mix digester materials (No. 7). Mechanical disturbance of digester contents due to mixing is believed to have considerable effect on the distribution of microbes within the digester (No. 18), the attachment of microbes to biodegrading surfaces (No. 11), and the activity of enzymes (No. 13).

Research needs relating to mixing of digester contents are less important for systems such as leached bed systems (SEBAC) in which the biodegradable substrate is not mixed. Of more concern for nonmixed systems is the permeability or hydraulic conductivity of the feedstock materials. Feedstock characteristics or measures that enhance permeability of

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**One reviewer noted the potential desirability for research on the modification of organisms.

## Exhibit 3-3. Prioritized RD&D Needs for Anaerobic Digestion

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| 100 | Develop better understanding of methano-acetogenesis | 2 |
| 100 | Study the physiological requirements and status of microbes | 4 |
| 100 | Evaluate role of toxics on digester malfunction and failure | 8 |
| 100 | Improve polymer hydrolysis | 10 |
| 100 | Improve methods for feeding digesters at various solids-concentration rates | 15 |
| 75 | Study interactions between microorganisms | 1 |
| 75 | Evaluate alternatives designs to CSTR | 20 |
| 60 | Identify and quantify microbial populations | 3 |
| 60 | Evaluate microbial pre/post treatment | 12 |
| 60 | Examine clean feed options and impact of variable feedstock | 16 |
| 56 | Evaluate mixing techniques related to energy use and digester performance | 17 |
| 50 | Identify and quantify enzyme activity | 5 |
| 45 | Develop and test early warning monitoring and control devices and techniques | 23 |
| 40 | Examine toxicity of feedstock components and effects of changing feedstock | 9 |
| 40 | Examine potential uses of anaerobic digestion residues | 31 |
| 38 | Examine effect of mixing on microbial distributions | 18 |
| 38 | Determine hydraulic conductivities of MSW feedstocks | 34 |
| 30 | Examine microbial attachment to particles | 11 |
| 30 | Study interfacial effects on enzyme activity | 13 |
| 30 | Examine methods of reducing start-up time | 24 |
| 25 | Study effects of disturbing forces on microbes | 7 |
| 20 | Establish a database on bioconversion properties of organic wastes | 14 |
| 18 | Evaluate best management practices for reactor and process control | 22 |
| 10 | Evaluate photo-enhancement of anaerobic processing | 6 |
| 10 | Evaluate methane enrichment digestion techniques | 21 |
| 8 | Study metabolic heat generation potential of microbes | 19 |
| 5 | Investigate interfacial gas/liquid gas bubble liberation | 35 |
| 3 | Evaluate flotation potential of MSW feedstocks | 32 |
| 3 | Evaluate foaming potential of MSW feedstocks | 33 |
| -- | Examine chemical and energy requirements of digesters | 25 |
| -- | Develop and evaluate pre/post treatment methods | 26 |
| -- | Evaluate options for use of generated gases | 27 |
| -- | Examine potential beneficial uses of by-products | 28 |
| -- | Perform cost analyses of anaerobic digestion | 29 |
| -- | Evaluate environmental benefits of anaerobic digestion | 30 |

feedstock substrates need to be determined for a variety of feedstock substrates at full scale depths (No. 34). Residue management is mainly an important issue for public relations concerns but is not considered to be a research need that limits development of the technology (No. 31).

Data on the bioconversion properties of organic wastes are available and should be compiled into a large database (No. 14). The potential for enhancement of biodegradation rates by photosynthetic bacteria was considered to be low to negligible by most of the panel members (No. 6). Information on the physical behavior of solids and liquids within digesters was considered to be important, but not crucial, for the development of the technology (Nos. 32 and 33). Foaming was reported to be a problem in some systems, but is generally only associated with the use of organic feedstocks such as sewage sludge (No. 33).

In large digesters handling high solids feedstocks, a significant amount of metabolic heat may be produced. As heat is commonly added to anaerobic digestion systems to enhance biodegradation (approximately five percent of derived methane is used for heating digesters), exploiting metabolic heat may provide a substantial net energy benefit and should be researched under a controlled calorimetric study (No. 19).

Systems analysis needs (Nos. 27-32) have not been given scores because the panel decided that these needs represent necessary work that is not considered to be research. (Other expert panels, however, broadened the definition of RD&D to include this type of need.) The major need is for an economic and environmental evaluation of anaerobic digestion systems compared to other MSW technologies (Nos. 29 and 30). There may be issues of liability concerning possible hazardous properties of residuals that have not been studied (No. 30). Nutrient limitations are important but sufficiently understood to operate a successful system and should, therefore, require less research (No. 25).

## 3.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate anaerobic digestion with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The cost of energy produced by anaerobic digestion systems was estimated by the panel members to be less than that produced from pyrolysis or gasification. The total system cost is comparable to in-vessel composting but more expensive than windrow composting. Anaerobic digestion systems can handle approximately 70 percent of the municipal waste stream at rates of 0.25 to 0.50 pounds of MSW per cubic foot per day. A panelist stated that this technology is believed to be more economical for small scale (less then 400 tons per day) waste streams than other technologies and thus may be more appropriate for certain locations. With waste streams of more than 600 tons per day, other MSW technologies may be more viable.

Demonstration costs for a 50 tons per day facility would include approximately $10 million for the construction of a digester plus other related costs. These other costs would include $5 million for phased modifications and $1.5-2.0 million for miscellaneous costs. This facility would be expected to produce 0.25-0.50 cubic foot of methane gas per pound of MSW at a 0.2-0.4 pounds per cubic foot per day loading rate. The sale of gas without upgrading will return approximately $35-$40 per ton of MSW.

**Human Health and the Environment**

If digester temperatures are maintained, anaerobic digestion systems will kill any pathogens that may be introduced with the MSW. Anaerobic digestion systems are totally enclosed and release fewer aerosols than other technologies. Therefore, the overall risk to human health and the environment is low.***

**Net Energy Benefit**

Approximately 30 percent of the MSW feedstock mass may be recovered as methane. Residues generated by the process may then be further converted into energy by combustion. The overall net energy benefit of anaerobic digestion systems is rated as acceptable to good. The MSW to electricity energy conversion rates for anaerobic digestion systems and MSW combustion were estimated by the panel to be approximately the same:****

| | |
|---|---|
| MSW to Steam Efficiency | 45-50 |
| Steam to Electricity Efficiency | 50 |
| Total Combustion System Efficiency | 25 percent |
| MSW to Methane Efficiency | 30 |
| Methane to Electricity Efficiency | 80 |
| Total Anaerobic Digestion System Efficiency | 25 percent |

**Occupational Health and Safety**

The overall occupational health and safety of anaerobic digestion systems was rated by the panel as excellent. Composting is considered to be less risky overall, though one panel member expressed concern about the possibility of vinyl chloride gas in compost emissions.

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*** One reviewer commented that this overlooks emissions from the composting process and the metals that are left in the compost.

**** Two reviewers estimate that the Methane to Electricity Efficiency value of 80 percent is too high. It is approximately 33 percent at 5 megawatts. It approaches 50 percent in the larger turbine sizes. The total system efficiency is expected to be less than 15 percent.

Another reviewer believes that 50 percent is too high for the Steam to Electricity Efficiency value and noted that the best available gas turbines are only 50 percent efficient. The same reviewer also believes that the Methane to Electricity Efficiency value is closer to 50 percent.

### Appropriateness for Government Funding

The overall appropriateness for government funding of anaerobic digestion systems was rated by the panel as excellent.

# 4. ASH UTILIZATION AND DISPOSAL

## 4.1 Technology Description

This section addresses methods of managing ash residue from MSW combustion. The first part of this section describes in general terms the characteristics of ash. The second part discusses technologies used in the disposal of ash. The final part describes methods of utilizing combustion ash.

### 4.1.1 Ash Characteristics

MSW combustion invariably generates ash. This ash represents about 10 percent by volume and 25 percent by mass of the MSW burned (Kosson et al., 1991; Goodwin, 1990). Ash can be divided into two categories: bottom ash and fly ash or air pollution control residue. Bottom ash is completely or partially burned material that passes through or is discharged from the combustion grate. The term "fly ash" is used to describe particulates captured from flue gas by the air pollution control system; it may include scrubber residue and baghouse dust. Fly ash typically contains higher concentrations of volatile heavy metals (e.g., barium, cadmium, lead, mercury, and zinc) than bottom ash. In one test, extract obtained from untreated bottom ash using the Toxicity Characteristic Leaching Procedure (TCLP)(see 40 CFR §261 Appendix I) did not exhibit the characteristic of toxicity (see 40 CFR §261.24), whereas TCLP extract obtained from untreated fly ash did exhibit the toxicity characteristic for barium, lead, and mercury (Kosson et al., 1991). The total ash generated by mass-burn combustion systems is 75-85 percent (by weight) bottom ash and 15-25 percent (by weight) fly ash (Goodwin, 1990; Kosson et al., 1991). Ash generated by RDF combustion systems contains a greater proportion of fly ash, about 40 percent by weight, because much of the RDF burns in suspension thereby increasing entrained particles (Goodwin, 1990). In the United States, bottom ash and fly ash are usually mixed together and referred to as "combined ash".

Although the characteristics of ash depend on the operating conditions of the combustor and the design of the combustion chamber and air pollution control system, ash often contains constituents that, if present in high enough concentrations, could pose a threat to human health or the environment (Finkelstein, 1991; Kosson et al., 1991; Holmes et al., 1991). In particular, much public concern has focused on dioxins, furans, cadmium, and lead (Roffman, 1990; Holmes et al., 1991; Finkelstein, 1991). Because of these characteristics, the investigation of methods to utilize or dispose of ash that limit the release of contaminants has become important.

### 4.1.2 Ash Disposal

One method of managing ash from MSW combustion is by disposal in a monofill, a landfill that is often specially lined -- by regulation -- and is dedicated to ash disposal. Ash may also be stabilized or solidified prior to disposal. Methods of stabilization and solidification include the use of the following (Wiles et al., 1990; Holmes et al., 1991; Kosson et al., 1991):

- Portland cement to form a solid monolithic mass;
- Portland cement and polymeric additives to form a stable, soil-like mixture;

- Portland cement and soluble silicates to immobilize heavy metals in silica compounds;
- Waste pozzolans and water to form a soil-like mixture that hardens to a solid mass; and
- Water soluble phosphate to convert lead and cadmium to insoluble forms without altering the physical state of the ash.

Ash may also be handled through vitrification processes that melt ash to form a glass-like material. Vitrification differs from the traditional method of stabilization using portland cement in that the ash is not encapsulated, but instead has its physical form altered. (Richards and Bennett, 1990)

### 4.1.3 Ash Utilization

Ash from MSW combustion has been tested or suggested for a number of uses. One application that has received considerable attention is use in asphalt road construction. Ash has been used as a substitute or extender for natural rock aggregate material in the construction of subbase, bituminous base course, and wearing course pavement. Ash has also been used as aggregate in the manufacture of ceramic or masonry bricks, cinder blocks, and similar construction materials. Many of these potential uses require preprocessing of the ash to make a suitable aggregate material. Preprocessing operations include screening the ash, mixing ash with hot asphalt to form briquettes, pelletizing the ash, and fusing ash in submerged electric arc furnaces, to name a few. MSW combustion ash has also been suggested for use as a substitute for cement clinker or coal combustion ash in the manufacture of portland cement. Ash may also be used as a structural fill in land reclamation or embankments, and as a landfill cover to replace or be combined with natural soil. Similarly, sources have suggested the use of ash as a landfill liner, alone or with the addition of portland cement (Vence, 1984; Goodwin, 1990; Eighmy and Gress, 1991).

Technologies exist to recover valuable materials from ash including the glass-rich fraction, which might be used in the manufacture of mineral wool. Other by-products that might be extracted include ferrous metals and aluminum. However, these materials may require extensive processing in order to be clean enough to compete with recycled metals from other sources (Vence, 1984).

## 4.2 Technology Status

With the recent upswing of resource recovery activity in the United States and the declining landfill capacity, the recycling, reuse, and disposal of ash residue have become subjects of greater interest than ever before (Vence, 1984). Ash utilization varies greatly across the nation and around the world. In the Netherlands 60 percent of bottom ash is reused in road base, embankments, and as aggregate in concrete and asphalt. In western Germany 50 percent of bottom ash is used in road base, sound barriers, concrete, and asphalt. In Denmark 31 percent of bottom ash is used in road base and 34 percent is used in land reclamation. (Eighmy and Gress, 1991)

According to EPA, approximately 36 percent of all MSW ash residue is disposed of in ash monofills. Seventeen percent is co-disposed with MSW. The fate of the remainder is

unknown as it was not surveyed by EPA. The amount sent to monofills is probably an underestimate: One company estimates that it generates over 50 percent of all ash in the United States, and that all of this ash is either disposed of in a monofill or used as final cover over closed MSW landfills (U.S. EPA, 1987).

At least one U.S. company is currently contracting to manage ash residue from MSW waste-to-energy facilities and produce an environmentally tested artificial aggregate for road construction. A demonstration project using this aggregate is ongoing in Hennepin County, Minnesota (Gustin and Shannonhouse, 1990). Bottom ash is currently used as road aggregate in several European countries, usually under some guidelines or regulations. For example, Denmark's rules governing the reuse of ash residue require that the ash contain less than 25 percent fly ash and that reuse occur at least 20 meters (60 feet) from drinking water wells. Over two dozen U.S. companies have expressed interest in using solidified ash in roadbeds or concrete construction (U.S. Congress, 1989). Little research has been conducted, however, into the long-term fate of metals in road aggregate and on leachate concentrations.

In Japan, fly and bottom ash are most often combined and landfilled by themselves or with the noncombustible materials that were separated out prior to incineration. About 10 percent of the ash generated in Japan is mixed with cement. In addition, one facility reuses its ash in road pavement, and a handful of facilities use vitrification (or melting) to treat the combined ash and produce a hard, glassy slag which is landfilled (U.S. Congress, 1989). Several companies in the United States are also actively pursuing vitrification as a method of ash residue management (Richards and Bennett, 1990; ASME/U.S. BOM, undated).

Research into the use of blocks of solidified ash as building blocks for artificial reef construction is ongoing and is focusing on the retention of metals in the blocks after long periods of submersion in seawater (U.S. Congress, 1989; Shieh and Wei, 1990). These efforts have shown that the majority of metals prone to transport in water have been retained in the blocks. This research has expanded to on-land construction uses as well. Research is also continuing into the chemical treatment of ash. One company has been compacting combined ash and scrubber residues and adding lime in efforts to decrease permeability and reduce the possibility of leaching. Laboratory and field studies have also been conducted on combining ash residue with sewage sludge to reduce solubility. (U.S. Congress, 1989)

## 4.3 Description of RD&D Needs

Many people perceive ash disposal as an issue that limits the public acceptance of new MSW combustion facilities. Significant questions in municipal waste combustion ash management include whether bottom and fly ash should be managed separately; whether residues should be treated before disposal; and whether residues can be beneficially utilized (Kosson et al., 1991). RD&D needs for ash disposal and utilization are described in this section. Each RD&D need has been assigned a reference number (i.e., 1, 2, 3, ... 26) that is used in later sections of this chapter when the RD&D need is being discussed. The RD&D needs that were identified in ICF's literature review, but were not accepted by the expert panel on ash disposal and utilization are described at the end of this section. The order of needs described in this section does not reflect their priority. The prioritized RD&D needs are discussed in the next section.

### 4.3.1 General RD&D Needs

Significant experience in ash management has been gained in Japan and Scandinavian countries where published documents concerning residue management exist, but need translation before full advantage can be obtained from research that may have already taken place (Vence, 1984). Therefore, there is a need to:

1. Translate literature from Japan.

While much of the literature is two to three years old, translation is needed to fill in the gaps. The expert panel indicated that translating the European literature would not be as useful.

### 4.3.2 Analytical Methods

Uniform protocols for sampling and characterizing ash need to be established, including validation and quality assurance/quality control (QA/QC) procedures (Chandler et al., 1991). Research is needed to determine the applicability of specific tests (or sets of tests) to accurately characterize leaching behavior and toxicity of MSW combustion ash under various disposal or utilization scenarios. Research needs associated with analytical methods include:

2. Validate uniform protocols and establish QA/QC procedures; and

3. Define the applicability of specific tests.

### 4.3.3 Ash Characteristics

Research is needed to determine what characteristics should be measured to determine the suitability of ash for the available disposal options and/or uses. Adequate characterization of ash will necessarily include analyzing the relationship of changes in ash characteristics, such as particle size and chemical composition, to variations in feedstocks, furnace and boiler configurations, pretreatment, flue gas treatment, combustion techniques, and incinerator operating conditions (Kosson et al., 1991; Hasselriis, 1989). This effort may be aided somewhat by review of existing data and operating records (Dent and Krol, 1990). Determination of the fractions of municipal waste streams that contain the trace metals that most adversely affect combustion ash quality would allow increased control over residue characteristics through front-end processing (Wiles, 1991). Changes in the waste stream due to seasonal or policy changes (e.g., increased recycling and preprocessing) that affect ash chemical properties also need to be investigated (Kosson et al., 1991). Characterization of ash will provide needed information to guide management decisions and indicate if further processing of the residue is desirable (Kosson et al., 1991). Specific research needs are:

4. Determine which ash characteristics are relevant to measure for specific ash applications;

5. Research variability within and between samples and facilities;

6. Research bottom rejects, fly, scrubber, and utilization by-products; and

7. Identify factors that affect combustion ash quality and quantity.

### 4.3.4 Contaminant Release Potential

Leaching has been identified as the most important contaminant release mechanism from ash to the environment (Kosson et al., 1991). The primary environmental concern focuses on high levels of heavy metals that may occur in ash. The nature of lead, cadmium, and other elements in incineration residues and their stabilized products needs to be studied to:

8. Relate the chemical nature and binding states of metals within ash to leachability (Wiles, 1991).

The effects of ash leachate from ash monofills on clay liners, flexible membrane liners, and geosynthetic liners should be studied to determine whether landfill lining components will maintain their integrity when exposed to ash leachate (Wiles, 1991). Ash leachate also needs further study focusing on the differences between the different segments of the ash stream (i.e., bottom ash, fly ash, combined ash). Data from field measurements at ash landfill sites are needed to determine long-term trends and changes in the composition of ash, soils, and leachates in ash monofills for a realistic evaluation of health risks from ash monofills (Kellermeyer and Ziemer, 1989; Roffman, 1990). These long-term evaluations will require the development of methods and procedures that can accurately measure and predict environmental behavior of ash over extended periods (Wiles, 1991).

Differences in ash leachate characteristics between analytical results from lab leaching studies and those predicted by geochemical models may be explained through investigations that differentiate the chemical species dissolved in ash leachate (Van Der Sloot et al., 1989). Understanding the leachability of MSW incinerator ash exposed to varying environmental conditions will provide valuable insight for sound management decisions and allow improved model predictions (DiPietro et al., 1989). Improved models must be developed to predict the environmental fate of constituents in MSW combustion ash under various management scenarios. In particular it is important to understand the rate of release and the affect of these rates on the environment. Improved models must also be developed to predict the risks to human health and the environment from both utilization and disposal of ash. Therefore, additional research is needed to:

9. Determine the effects of ash leachate on liner materials;

10. Identify trends and changes in monofills;

11. Develop environmental fate models;

12. Develop ash risk assessment models; and

13. Characterize contaminant releases from different segments of the ash stream.

### 4.3.5 Ash Processing for Disposal

Further research is needed on methods of reducing the risk of leachate from ash disposed of in monofills and MSW landfills (Walter, 1990; Tinning, 1985). A variety of methods of processing or treating ash prior to disposal should be investigated, including:

14. Stabilization as a method of processing ash for disposal;

15. Chemical reaction approaches to processing ash for disposal;

16. Separation approaches to processing ash for disposal; and

17. Asphalt as a method of processing ash for disposal.

Attention should be given to assessing the environmental impact and fate, economics, mode of operation and effectiveness, and scale of each of these methods. Both physical and chemical separation approaches should be studied, including the use of ash washing and biological leaching to remove heavy metals. Particular attention should be given to the detoxification potential of separation and asphalt.

#### 4.3.6 Utilization

Technically sound criteria for utilizing ash need to be developed to prevent adverse environmental impacts and enhance physical properties needed to meet utilization requirements (Wiles, 1991). Specific topics within the area of ash utilization that need further research include:

18. Ash utilization in structural/non-structural fill;

19. Ash utilization in concrete;

20. Ash utilization in asphalt;

21. Ash utilization in road base;

22. Ash utilization in brick;

23. Ash utilization in ceramics;

24. Landfill uses for ash; and

25. Utilization by-products.

The utilization of ash as substitute aggregate in concrete includes use as flowable fill or in construction blocks. Preliminary studies indicate that stabilized MSW ash blocks are safe for marine applications. Further investigation, however, is needed to assess the mobility of dioxins and furans from stabilized incineration residue when solidified and utilized to build artificial reefs and embankments (Wiles, 1991; Shieh and Wei, 1990). More data are needed to evaluate the physical, chemical, and biological properties of ecosystems surrounding artificial reefs made from residue streams and portland cement (Andrews, 1991). This research should be expanded to evaluate the use of ash block in on-land construction as well.

Asphalt applications for ash, which include substitute aggregate for road construction, should be studied. More research is needed on the performance of residue aggregate in wearing surface pavements (Andrews, 1991; Vence, 1984). More research is also needed on the performance of residue aggregate as a substitute for crushed limestone or soil-cement in

road base construction (Andrews, 1991; Vence, 1984). The utilization of ash in the manufacture of bricks should be studied. In particular, the feasibility of making bricks of marketable quality from solidified ash needs to be further investigated (Strauss, 1989). Technologies that use ash in ceramics have the highest potential for use of fly ash and air pollution control residues. Landfill uses for ash include daily or final cover or road construction material.

For each utilization method, attention should be given to the following issues: the long-term performance of the product; the fate of the product after use; which ash fractions (i.e., bottom ash and fly ash) are suitable for use; the environmental impacts of utilization; social, political, and economic criteria including liability and markets; development of policy supporting utilization; development of standards for product certification; and demonstration of the technology.

### 4.3.7 Public Education

Public concerns about combustion ash disposal and utilization have created barriers to the acceptance of MSW combustion. Therefore, there is a need to:

26. Develop tools for educating the public about ash disposal and utilization.

### 4.3.8 Other Potential RD&D Topics

A number of RD&D needs were identified in the literature review, but not accepted by the expert panel. Toxic characteristics of solid wastes are commonly estimated using the extraction procedure (EP) toxicity test and the more recent toxicity characteristic leaching procedure (TCLP) tests. The validity of these tests has been questioned indicating that the relationship of test results to the actual characteristics of ash from disposal facilities needs to be better established (Roffman, 1990; "Tests Used on Incinerator Ash ...", 1990). Research could be performed to endorse an existing test or establish a new standard test that will accurately characterize the leaching behavior and toxicity of combustion residues (Dent and Krol, 1990).

Research could generate the data required to better understand ash characteristics and support development of technical criteria for safe utilization of residues (Wiles, 1991; Sussman, 1989). Widespread utilization will require the establishment of production standards and material classification for residues (Vence, 1984). Research characterizing the properties of ash would aid in identifying potential uses such as landfill cover and aggregate for asphalt (Mathusa, 1989).

Techniques developed to utilize coal ash could be evaluated for their applicability to fly ash, bottom ash, flue gas desulfurization sludge, and combined MSW ash are as follows:

- **Vitrification.** Better control techniques in vitrification could be developed to produce products with increased utilization potential (Richards and Bennett, 1990).

- **Cement.** MSW ash has properties that are very similar to materials used in the manufacture of portland cement. Utilization of MSW ash in the manufacture of portland cement could be further investigated because preliminary research indicates that residues could be substituted for other materials at rates of up to 71 percent (Kosson et al., 1991; Vence, 1984).

### 4.3.9 RD&D Topics Identified by Reviewers

One reviewer stated that in addition to RD&D items 14 through 17, RD&D is also needed on the use of ash washing to remove soluble heavy metals prior to disposal. The reviewer believes that washing the ash to remove heavy metals would enhance utilization of the ash.

## 4.4 Prioritized RD&D Needs

This section discusses the priorities assigned to the RD&D needs by the panel of technical experts on MSW ash management (listed in Appendix A). The ash management panel did not follow exactly the same process used by other panels to prioritize RD&D needs. (See the introduction chapter for a discussion of the prioritization process.) The panel did not assign numerical rankings to the RD&D needs. Instead, the panel members categorized the needs as being high priority, medium priority, or low priority based on consensus opinion. Because of this procedure, the ash management workshop's list of priorities is structured differently than the others.

The participants identified a research program that consists of three areas of equal priority: public education, technology applications, and fundamental research. The participants believed that an appropriate research program for ash management would have a portfolio of projects in each of these three areas. The highest priority research needs are categorized into blocks representing these three subject areas and are identified in the high priority section of Exhibit 4-1. The identified needs within each block are listed in approximate priority order. Again, each of the blocks is of equal importance. The RD&D needs that did not fall within one of the high priority blocks are also listed in approximate order of priority within the medium and low priority sections of Exhibit 4-1. A brief description of each RD&D need is in the center column of the exhibit and a reference number for locating a more detailed discussion of the need in Section 4.3 is in the right-hand column.

The panel emphasized a few general points in identifying and prioritizing RD&D needs. First, they stated that a good deal of data have been generated from industry research and monitoring activities. However, the panel agreed that these data may not be useful for addressing RD&D needs, since they may be related to fulfilling regulatory requirements and may thus be limited in scope. Second, the panel stated that in order for RD&D to move forward the ash management sector must address the pertinent socioeconomic, political, and regulatory factors that tend to inhibit such activities. Third, the participants noted that some current research efforts parallel each other and that an integrated RD&D program might reduce such redundancies.

The rationale used by the panel of technical experts is discussed below. The rationale reflects the brief deliberations of the panel; for example, it tends to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus.

## Exhibit 4-1. Prioritized RD&D Needs for Ash Management

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **High Priority** | |
| Panel did not assign scores | **Block A: Public Education** | |
| | Develop tools for educating the public about ash disposal and utilization | 26 |
| | **Block B: Application** | |
| | Study ash utilization in structural/non-structural fill | 18 |
| | Study landfill uses for ash | 24 |
| | Study ash utilization in concrete | 19 |
| | Study ash utilization in asphalt | 20 |
| | Study ash utilization in road base | 21 |
| | Study ash utilization in ceramics | 23 |
| | **Block C: Fundamental Research** | |
| | Research bottom rejects, fly, scrubber, and utilization by-products | 6 |
| | Identify factors that affect combustion ash quality and quantity | 7 |
| | Relate the binding states of metals within MSW ash to leachability | 8 |
| | Identify trends and changes in monofills | 10 |
| | Develop environmental fate models | 11 |
| | Develop ash risk assessment models | 12 |
| | **Medium Priority** | |
| Panel did not assign scores | Specify which ash characteristics are relevant to measure for specific applications | 4 |
| | Research variability within and between samples and facilities | 5 |
| | Study stabilization as a method of processing ash for disposal | 14 |
| | Study chemical reaction approaches to processing ash for disposal | 15 |
| | Study separation approaches to processing ash for disposal | 16 |
| | **Low Priority** | |
| Panel did not assign scores | Validate uniform protocols and establish QA/QC procedures | 2 |
| | Define applicability of specific tests | 3 |
| | Study ash utilization in bricks | 22 |
| | Study utilization by-products | 25 |
| | Study asphalt as a method of processing ash for disposal | 17 |
| | Determine the effects of ash leachate on liner materials | 9 |
| | Translate literature from Japan | 1 |

### High Priority

Research in ash management must consist of research in three areas: public education, applications, and fundamental research. The RD&D program must combine all three areas; each area is equally important. The panel estimated that up to 85 to 95 percent of the total benefits of a research program could be achieved in these high-priority blocks.

Some panelists stated that test data showed that heavy metals do not leach out from the ash at high concentrations, and do not appear to be the main problem with ash leachate. It was pointed out that the actual leachates contained high concentrations of salts and that these salts were the main problem involved in leachate treatment and disposal. These salts are mainly the result of acid gas controls. Nevertheless, the panelists agreed that further study of ash leachate was warranted. Some panelists felt that ash characteristics should be thoroughly identified, because the character of the MSW will be changing as more materials are recycled. The panelists also believed that RD&D on contaminant release potential is necessary for communicating with the public and for better understanding of this complex issue. For these reasons, fundamental research (Block C) and public education (Block A) are high priority needs. Current research focuses less on ash utilization than on processing for disposal, making application (Block B) a high priority area.

### Medium Priority

According to the panel, up to 99 percent of the benefits would be achieved if the medium priority RD&D needs were also funded. These medium priority needs are of lesser importance than the high priority needs, in many cases because research is currently being done in these areas. For example, several entities are currently investigating what ash characteristics are relevant to measure for specific applications (No. 4): the Canadian National Incinerator Testing and Evaluation Program (NITEP), the International Energy Agency (IEA) Ash Working Group, the New York State Energy Research and Development Authority/Long Island Regional Planning Board (NYSERDA/LIRPB) Program, the Coalition on Resource Recovery and the Environment (CORRE), EPA, Denmark, the Netherlands, Sweden, Germany, and Japan. Variability within and between samples and facilities (No. 5) is being researched by the NYSERDA/LIRPB Program, CORRE, EPA, California, Minnesota, Florida, New Jersey, and New Hampshire. Similarly, each of the ash processing technologies (Nos. 14, 15, and 16) is being studied under several research programs. The panel agreed that cement stabilization (No.14), although not as effective as some stabilization methods, is a well-established technology whose application to MSW ash should be further researched.

### Low Priority

The low priority RD&D needs have little additional value and may not be worth funding. Validating analytical methods (No. 2), for example, was not viewed as a high priority because a significant amount of research is already being conducted on this issue by CORRE, the IEA Ash Working Group, the New York State Combustion Institute, EPA, Denmark, the Netherlands, Sweden, Germany, and Japan. Similarly, EPA is already studying the effects of ash leachate on liner materials (No. 9).

## 4.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate MSW ash management research with respect to some of the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

**Cost of the RD&D Program**

In general, the panel noted that an RD&D program in ash management would have a high rate of return in terms of the amount of data produced for the number of dollars invested. The panel members also provided specific information about the costs of both short-term (three years) and long-term (ten years) RD&D programs in ash management. For each program, the panel members specified the minimum funding that would be required to achieve noticeable results and also indicated the most desirable level of funding. Minimum funding levels for a three-year RD&D program in ash management would be as follows:

- $100,000 for public education (Block A), 1-2 projects per year;
- $1 million in fundamental research (Block C), 4-8 projects per year; and
- $1 million in applications (Block B), 4-8 projects per year.

Thus, $2 to $3 million a year total would be required for the program to produce any impact. More desirable funding levels for a three-year program would be:

- $200,000 for public education (Block A), 2-4 projects per year;
- $2 million in fundamental research (Block C), 8-16 projects per year; and
- $2 million in applications (Block B), 8-16 projects per year.

For a longer term (ten-year) ash management RD&D program, the following minimum funding levels would be required:

- $100,000 for public education (Block A), 1-2 projects per year;
- $500,000 in fundamental research (Block C), 3-6 projects per year; and
- $500,000 in applications (Block B), 4-8 projects per year.

More desirable funding levels for a ten-year program would be:

- $200,000 for public education (Block A), 2-4 projects per year;
- $1.5 million in fundamental research (Block C), 6-12 projects per year; and

- $2 million in applications (Block B), 8-16 projects per year.

**Difficulty of Technology Development**

Development of ash management technology is not expected to be difficult or risky.

**Commercial Development Risk**

Additional research in ash management will improve political and public understanding, not only of ash disposal, but also of waste-to-energy conversion in general. Ash is a by-product of many combustion technologies, so research in ash management will benefit the commercial development of these technologies, which require effective ash management systems. The panel stated that research into combustion technologies will not advance significantly unless the issue of ash disposal is addressed. Furthermore, the commercial development of ash management technologies will allow energy projects to proceed that would otherwise be held up by ash disposal problems.

**Cost of the Energy Produced**

More effective ash management will reduce the costs of operating MSW combustion systems and therefore will reduce the cost of energy production.[*****]

**Net Energy Benefit**

Ash utilization results in increased material recovery and the reduced use of natural resources such as limestone, sand, and aggregates. This reduction conserves the energy associated with extracting, processing, and transporting these resources.

**Human Health and the Environment**

Ash utilization is low-to-medium risk with regard to long-term environmental impacts and reduces demand for landfill capacity. As noted above, utilization results in reduced use of natural resources. Because much of the research focuses on minimization of contaminant releases, RD&D in ash management will provide an environmental benefit.

**Appropriateness for Government Funding**

RD&D in ash management is appropriate for DOE funding and compatible with evolving regulations. Research will help to address much of the current regulatory confusion. Furthermore, increased ash utilization will help some states to meet their recycling goals.

[*****] One reviewer believes that ash utilization will increase the cost of energy produced.

# 5. RDF PRODUCTION AND CO-FIRED COMBUSTION

This chapter addresses the RD&D issues associated with RDF production and co-fired combustion. Although there are unique circumstances particular to RDF production and co-fired combustion as compared to dedicated RDF combustion, there are similarities. In an effort to make the discussion of each technology an independent unit, there is some duplication of material in each chapter.

## 5.1 Technology Description

In a broad sense, refuse derived fuel refers to MSW in any form that may be used as fuel. For purposes of this discussion, however, RDF refers to MSW that has undergone mechanical processing to produce a more homogeneous fuel for combustion. Similarly, for this discussion, an RDF combustor is one that burns preprocessed MSW, as opposed to MSW in its as-discarded form. Limited preprocessing of MSW is required for all waste-to-energy systems other than mass-burn or modular incineration because of the need for homogeneous fuel.

The specific characteristics of RDF are determined by the processing system used to produce it. In general, RDF can be classified as coarse, fine, powdered, or densified. The American Society for Testing and Materials (ASTM) has established an RDF classification system as described in the dedicated RDF chapter.

For example, densified RDF (dRDF) is produced by compacting shredded RDF into pellets, cubes, or briquettes. One method is to extrude fine RDF through a pellet mill similar to mills used in the animal feed industry, which typically produces dRDF pellets of 0.5 inch by 1.25 inches. This process requires 20 to 30 percent moisture in the refuse. Densified RDF is easier to store and handle than other types of RDF. (Scaramelli, 1979; U.S. Congress, 1989; Donnelly, 1991)

As an alternative to combustion in a specially designed "dedicated" MSW boiler, RDF may be burned in existing coal-, or wood-fired boilers in combination with the primary fuel. This procedure is known as co-firing. The primary advantage of co-firing is avoiding the cost of a new dedicated MSW combustor. Disadvantages exist in that RDF can cause deterioration in the conveying device, boiler wall and tube slagging, and increased air emissions in units not specifically designed to accommodate this type of feed. (Scaramelli, 1979; U.S. Congress, 1989)

In general, existing solid-fuel boilers are readily adaptable to co-firing through the addition of RDF feed systems. Densified RDF has received considerable attention for use in co-firing in boilers designed to burn lump coal. The use of dRDF with physical and combustion properties similar to coal may minimize the need to modify feed and combustion systems. In any case, co-firing is possible in several different combustor configurations, including suspension fired units, spreader-stoker or semi-suspension fired units, grate or stoker fired units, cyclone furnaces, fluidized bed combustors, and cement kilns. Each of these configurations is discussed below.

In <u>suspension fired</u> units, the RDF and pulverized coal are injected separately to the combustion chamber. Suspension firing does, however, result in a high incidence of particle entrainment in the flue gas. Fine RDF is the best type of RDF for co-firing in suspension fired

units because its small particle size allows for quick, complete combustion in suspension. Fine RDF may also be co-fired in this type of unit. However, because fine RDF has a larger size distribution and higher moisture content than pulverized coal, some of the fuel will not be completely burned in suspension. Thus, dump grates must be added at the bottom of the furnace to ensure complete combustion of fine RDF.

In spreader-stoker fired units, the lighter portion of the fuel burns in suspension, while the heavier portion burns on a grate. The grate is usually a traveling grate that moves from the back of the unit to the front. Other types of grates include stationary, intermittent-dumping, reciprocating, and vibrating grates. Spreader-stoker fired units are equipped with a distributor that uniformly distributes fuel, either mechanically or pneumatically, into the furnace and on the grate. Coarse, fine, or densified RDF may be co-fired with coal or biomass in a spreader-stoker fired unit.

In fluidized bed combustion, fuel is injected into a heated sand bed fluidized by an air stream. Heat is transferred from the sand to boiler tube surfaces, to heat the walls above the bed, and to conventional heat exchange surfaces. Fluidized bed units have been shown to burn low grades and wide varieties of fuel, while successfully controlling sulfur dioxide and nitrogen oxide emissions. These units may therefore be especially suitable for co-firing. (Robinson, 1986)

Cyclone furnaces may be used to burn coal, oil, coal gas and by-products, petroleum, and wood. In these furnaces, the fuel and primary combustion air are injected tangentially into the burner end of the combustor and high velocity secondary air is introduced tangentially to the main section of the cyclone combustor. This system imparts a cyclonic motion to the combustion process, resulting in rapid combustion. The resultant products of the combustor exit the combustor and flow into the main furnace. In addition the ash slags and is removed in a molten state. Cyclone units typically do not require finely pulverized fuel, operate with only 10 to 15 percent excess air, and are well suited to multiple fuel firing. However, combustion temperatures are very high and may result in increased $NO_x$ emissions. Cyclone furnaces have been used to co-fire powdered RDF with oil and fine RDF with coal. (Robinson, 1986)

Rotary kilns are used in a number of industries, including cement production. In this process, raw material is successively dried, calcined, and clinkered or burned as it moves through the kiln. The heat for this process can be supplied by suspension firing pulverized coal through burners at the front of the kiln. Gas, oil, or petroleum coke may also be used as fuel. The majority of ash generated in the burning process falls to the bed of the kiln and is combined with the product. RDF may be co-fired in this process, with the advantage that ash is entrained in the product, reducing ash disposal requirements. (Robinson, 1986)

## 5.2 Technology Status

A recent information source reported that in the United States there are 33 operational RDF production and/or combustion facilities and an additional 11 such facilities that are in a state of advanced planning, construction, or shakedown. Of these 44 facilities, 7 co-fire RDF, 14 only produce RDF for off-site use, and 22 are dedicated RDF combustion facilities. (Ohlsson et al., 1991) The data from all the sources show that co-firing, a process still under investigation in the United States, has not been applied on a wide scale.

Of the facilities that co-fire RDF, 86 percent produce electricity as their primary energy form. Facilities constructed since 1985 have increasingly been equipped with the most sophisticated air pollution control equipment. According to the 1991 data, 73 percent of the facilities burning RDF use a baghouse, electrostatic precipitator (ESP), or a scrubber system, while the remaining 27 percent use a ESP/baghouse or ESP/scrubber combination (Ohlsson et al., 1991). Kiser (1990) reports that facilities co-firing RDF most often use a baghouse/ESP combination for air pollution control.

Outside the U.S., RDF technology has been applied commercially to some extent in at least three countries: Canada (two RDF production facilities and one facility utilizing a grate combustor to burn coarse RDF); United Kingdom (solid fuel boilers burning pelletized RDF at several existing facilities and one facility burning coarse RDF); and Sweden (three circulating fluidized bed combustors, five bubbling fluidized bed combustors, and four grate combustors) (Krol and Dent, 1989). It is not clear whether these are facilities co-fire RDF or are for dedicated RDF combustion.

Further information on RDF production facilities is discussed in the chapter on RDF production and dedicated combustion.

## 5.3 Description of RD&D Needs

RD&D needs associated with co-fired RDF units include combustion efficiency, emissions, slagging, and corrosion. Other RD&D needs are associated with ash, which are addressed in the chapter on ash disposal and utilization.

Sections 5.3.1 through 5.3.9 describe the RD&D needs for RDF production and co-fired combustion that were identified by the panel of technical experts (listed in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 25) that is used in later sections when the RD&D needs are prioritized and discussed. Section 5.3.10 describes RD&D topics that were identified in the literature review, but were not subsequently accepted by the panel of technical experts. (See the introduction chapter for a more detailed description of the prioritization process). The RD&D needs in Section 5.3.10 are not prioritized or discussed further.

### 5.3.1 MSW Characterization

Many variable RDF characteristics can influence the quality of the feedstock and ultimate energy recovery. For example, high ash and moisture content in the RDF frequently reduces boiler efficiency (McGowin and Kohan, 1983). Other MSW characteristics can also impair combustor performance. The presence of noncombustible materials can cause slagging and fouling, large objects can damage equipment, and chlorides can cause corrosion. Further, the potential for explosions, harmful fumes, and other biohazards is a very real concern at RDF production and combustion facilities. Improving RDF feedstock quality requires developing methods to better characterize the content of the refuse and to more selectively remove the hazardous and polluting components of refuse (Buekens, 1989). The consistency of the MSW received for processing also needs further attention (McGowin, 1989). In particular, research is needed to:

1. Develop methods and technologies to identify items that damage equipment (dense objects, volatile substances, and metals (greater than 50 pounds)); and

2. Develop methods and technologies for identifying substances in MSW that can be hazardous to occupational health and safety.

Increasing community recycling programs and improvements in presorting technologies ensure that the MSW stream will steadily change in the near future. Further research is needed to:

3. Study how the economic and environmental impacts of RDF combustion could be altered by major changes in the MSW stream.

### 5.3.2 MSW Processing

The primary RD&D goals for RDF processing are to produce from MSW a homogeneous fuel with maximum Btu value through better shredding, presorting, and fuel feeding (Dent and Krol, 1990). Difficulties associated with RDF handling have been listed as a specific co-firing operational problem (Smith, 1988). Argonne National Laboratory, among other institutions, has researched improvements in RDF feedstock preparation (Ohlsson, 1989). Investigations were being conducted in the early 1980s to develop a simpler, more energy efficient process for separating MSW (Kenny and Sommer, 1984). Consistency of the MSW received for processing also needs further attention (McGowin, 1989).

The most common problem encountered in primary shredding occurs when wires and stringy cloth objects wrap around and inhibit free movement of the shredder shaft. This problem is also frequently encountered during secondary shredding. Additionally, massive objects, such as packs of paper, can jam the shredder or break shredder components. This is a greater problem during secondary shredding, when RDF is more finely shredded than in primary shredding. A number of stages and processes have specific issues related to their operation:

- Air classification may be made more efficient in sorting out noncombustible materials by developing an air classifier that operates on particle density rather than aerodynamics (Walter, 1988). The benefits of air classification in contrast to the energy expended in this process are unclear. An improved methodology is needed to determine whether or not to include air classification in RDF-processing systems. (Scaramelli, 1979)

- Magnetic separation effectively removes most ferrous materials, although low-density items within a pile may not be extracted (Scaramelli, 1979).

- Aluminum should be removed because it can melt and foul grates. Although recycling would best solve this problem, development of low-cost and/or high-throughput ways to remove aluminum are recommended (Scaramelli, 1979; Shortsleeve and Roche, 1991). Generally aluminum recovery is of limited success because waste streams of insufficient volume are treatable with the present technology, and because aluminum

recovery units require excessive maintenance (Scaramelli, 1979; Kenny and Sommer, 1984).******

Research is needed to:

4. Optimize methods and technologies for removal of unwanted materials such as inert fines, chlorides, and elemental heavy metals (Scaramelli, 1979);*******

5. Develop real time techniques for determining moisture content of shredded MSW; and

6. Develop methods for removing fine wire and other stringy materials and rags.

### 5.3.3 RDF Storage and Retrieval

RDF storage entails a number of problems that warrant attention. Researchers have noted that processing MSW into RDF that can be stored and blended would reduce waste volume and increase energy recovery (Onischak et al., 1988; McGowin, 1989; Scaramelli, 1979). Specifically, research is needed to:

7. Study bin flow properties of pellets.

### 5.3.4 RDF Quality

RDF technologies can entail a higher capital cost than other MSW combustion technologies because of the preprocessing equipment that must accompany combustion equipment. Better fuel quality is seen as a significant factor in improving the performance of and reducing emissions from the combustion of RDF. (Hayes, 1990)

Slagging and fouling is a common problem among RDF combustion units as well as with other combustion facilities (Massoudi, 1984; Scaramelli, 1979; Seeker et al., 1989; Tinning, 1985; Tweedale, 1988). Clinker formation from ash on the grate reaching temperatures sufficient to cause bonding is also a continuing problem. Noncombustible materials (e.g., ferrous, aluminum, and glass) increase clinker, slag, and deposit formation on furnace heat transfer surfaces (McGowin, 1989; Kenny and Sommer, 1984). Adjustments of air flow to reduce grate temperatures and grate-dumping frequencies to reduce clinker buildup are being tested (Scaramelli, 1979). Some solutions have been developed for deposits on boiler sidewalls and convective tube surfaces, but more research is needed (McGowin and Kohan, 1983). Some on-line cleaning options that have been investigated to control fouling are steam soot blowing, compressed air blowing, mechanical rappers, acoustic blowing, and chemical additives. (Tweedale, 1988) Corrosion from acid gases can also be a major

****** One reviewer commented that existing aluminum eddy current magnets are quite effective as are aluminum detectors and air ejectors.

******* One reviewer believes that this research has already been performed. The reviewer did not indicate when or where the research was performed.

concern. A high chlorine content in the MSW can increase corrosion by hydrogen chloride (HCl) and chlorine on high temperature heat transfer surfaces (McGowin, 1989).

Pelletized RDF works well for spreader-stoker boilers, which are common systems for co-firing. (Ohlsson, 1989) Conventional fluidized-bed shell boilers have been found to be unsuitable for pelletized RDF burning due to excessive boiler fouling and bed contamination (Dent and Krol, 1990). A key problem associated with pelletizing RDF for co-firing involves the additives or binding agents used to modify the RDF characteristics. Unsuccessfully densified RDF will lose its integrity during handling. Efforts have been ongoing to develop better, low-cost binding agents for pelletizing, briquetting, and extruding RDF (Daugherty et al., 1988; Tinning, 1985; Walter, 1989). Better binding agents would also improve the storability and transportability of densified RDF (Ohlsson, 1989).

Some research has compared the use of several RDF binders at elevated temperatures with the results from tests done at room temperature (Tinning, 1985). Other researchers have been developing a binder that will stabilize and strengthen pelletized MSW while binding sulfur and chlorine (Walter, 1988). A technology referred to as the "Neutralysis Process" is being developed to pelletize RDF with clay for a homogeneous fuel pellet with improved combustion efficiency and controllable emissions. The spent clay fuel pellets become lightweight aggregate material. (Merdes, 1991) Internationally, the United Kingdom has focussed its efforts on pelletized RDF production (Dent and Krol, 1990).

Binding agents and other additives may affect boiler tubes and cause die abrasion. Additionally, pulverized-coal fired units that experience slagging problems when firing coal probably should not be converted to co-firing RDF, because the slagging problems will probably be worse for co-firing than for firing only coal (Scaramelli, 1979). Incorporation of coal fines into RDF pellets is a treatment that may prove viable. Further research is needed to:

8. Study the effects of additives (e.g., lime) to RDF (Tinning, 1985);

9. Investigate methods to reduce drying costs prior to pelletization;

10. Investigate the impact of inert fines removal (e.g., glass and stones) on slagging and fouling in co-fired RDF units;

11. Study the implications of pulverizing pellets with coal; and

12. Study the value of pellets made by combining RDF with coal (with or without additives).

### 5.3.5 RDF Feed (Furnace Injection)

Many issues relating to RDF feed RD&D needs have been identified above. Better uniformity of RDF feedstock and distribution in the combustion unit could significantly improve combustor operations (McGowin, 1989; Seeker et al., 1989). A computer model of RDF systems is being developed to allow specifications of size and purity of components for a user-selected system configuration (Ohlsson, 1989). Further research is needed to:

13. Conduct a parametric study of furnace injection velocity and geometry position in pulverized coal, cyclone, and fluidized bed boilers.

### 5.3.6 Boiler Performance and Availability

The efficient combustion and energy recovery of RDF is a high priority because a significant amount of energy, as well as cost and effort, is invested in its preparation. Further testing and research on combustion of MSW and RDF are needed in order to develop means of establishing, maintaining, and optimizing combustion conditions (Hasselriis, 1984). For example, research is being conducted on the relation between trace metals in fly ash and combustion efficiency for RDF (Hartman, 1991).

Better measures of combustion performance are needed because existing methods for measuring the performance of heat recovery incinerators are subject to error (Fernandes, 1984). Development of instrumentation that can be used to optimize boiler performance by monitoring feedstock characteristics such as moisture content is recommended (Tinning, 1985).

The efficiency of thermal conversion is generally limited by the low steam temperatures and pressures necessary to minimize tube corrosion (Scaramelli, 1979). More research is needed to better understand the effects of RDF and RDF/coal mixtures on the thermal conversion process (Tinning, 1985). Broad-reaching research touching all thermochemical conversion pathways needs to be conducted to understand the characteristics and decomposition of RDF and its individual components during combustion, gasification, and liquefaction (Walter, 1989).

Research is being conducted to assess the feasibility of retrofitting units that formerly burned only fossil fuels to accommodate co-firing with RDF. A preliminary investigation, for example, has been conducted for retrofitting a gas firing unit to gas co-firing (Seeker et al., 1989). An advantage of retrofitting these units to co-firing versus dedicated RDF is that the fluctuations associated with feeding and burning the heterogeneous RDF are reduced. Researchers have noted that retrofitting units may negatively affect air pollution control equipment. Although conversion from coal firing to co-firing would not be likely to appreciably affect the performance of baghouses, electrostatic precipitator performance can deteriorate in converted units. (Scaramelli, 1979)

Other research is addressing less conventional methods of co-firing RDF. One study has investigated the feasibility of installing a system to co-incinerate MSW and industrial coke dust (Hayes, 1990). To smooth out the variations inherent in RDF feed, some researchers suggest that incorporating a separate gas-fired superheater in MSW combustion plants should be studied in greater detail (Marks et al., 1989). Gas co-firing may also aid an RDF unit in more efficient cold starting (Seeker et al., 1989). Further research is needed to:

14. Investigate the effects of varying blends and burn rates on boiler performance, availability, and capacity (particularly coal-fired stokers); and

15. Investigate co-fired boiler response to discontinuous feed (grate dump).

Further research is needed to reduce the effects of corrosion which, as with mass-burn units, can affect all of the RDF combustion unit heating surfaces (Seeker et al., 1989; Tinning, 1985; Scaramelli, 1979). Especially vulnerable are the boiler waterwall and superheater tubes (Scaramelli, 1979). Surface coatings and treatments (e.g., silicon carbide coating of superheater tubes) to reduce vulnerability to corrosion are being investigated (Boyhan, 1984). The quality of the RDF also influences corrosion. For example, a high chlorine content increases corrosion by hydrogen chloride (HCl) and chlorine on high temperature heat transfer surfaces. (McGowin, 1989) Researchers suggest that reducing chloride deterioration of surfaces, using techniques such as sulfur addition, should receive further study (Scaramelli, 1979; Zylkowski and Schmidt, 1990). To reduce any of these effects, proper furnace sizing, arrangement of heating surfaces, and correct use of soot blowers is necessary (Massoudi, 1984).

The mechanisms behind the various types of corrosion are not well understood. For example, high-temperature, liquid-phase corrosion is caused by molten alkali-metal sulfates, but the exact mechanism has not been verified. The mechanism behind corrosion by HCl is also unclear. (Massoudi, 1984) Thus, research is needed to:

16. Investigate the effects of acid gas formation on metals performance (more critical in reducing environments such as fluidized beds and dump grate areas).

### 5.3.7 Ash Management

The issues relating to ash management are addressed in full in the chapter on ash disposal and utilization. The panel, however, did feel that the following issues of ash in relation to RDF production and co-fired combustion were worthy of research attention:

17. Confirm that dioxins are suitably destroyed in combustion; and

18. Develop data on heavy metal content of ash and toxicity characteristic leaching procedures (as a function of in-feed characteristics) and study the properties of co-fired bottom and fly ash as compared to ash from other non-waste fuel boilers (including looking at high sulfur coal).

### 5.3.8 Emissions

With concern growing about emissions from the combustion of all fuels, improved emission controls for RDF combustion are needed, including continuous emission monitors (Scaramelli, 1979). Although viewed primarily as a public perception problem, a primary emissions issue is technology to control toxic organic chemicals, particularly polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzo-furans (PCDFs). Argonne National Laboratory has conducted emission studies (i.e., inorganic acid gases, trace metals, organics) of full-scale co-firing of pelletized RDF/coal mixtures (Daugherty et al., 1989). Sweden and Canada have assigned high priority to RD&D for emissions (Dent and Krol, 1990). Likewise, the European Community has been researching the composition of densified RDF feedstock and emissions from their combustion (Van Santen, 1988).

Further RD&D is needed to develop air pollution control equipment.[*******] For example, more widespread industry adoption of spray-dryer absorber/baghouse equipment has been recommended (Ohlsson, 1989) and spray-dryer and dry lime absorber/baghouse equipment is often applied. In addition, improvements are needed in electrostatic precipitator performance (McGowin and Kohan, 1983).[********] Complicating the air pollution control issue is the need to reduce RDF heterogeneity. Moment-to-moment variations (i.e., pulsing) in combustion conditions associated with firing heterogeneous RDF can degrade emission control device performance by momentary overloads (Scaramelli, 1979).

Research is needed to reduce the uncertainty of emissions quality projections involved in designing waste combustion processes. For example, if information about the quality of refuse being burned or the capacity demand on the furnace is lacking, estimates of emission factors are less certain. Continuing efforts at accurate projections should lessen this problem. (Hasselriis, 1984)

Research is also being conducted to more accurately assess the effects of the major variables of coal/RDF combustion, including boiler load, percent RDF fired, and coal composition, on emissions (Norton and Levine, 1990; Tinning, 1985).

The panel indicated that the major issue regarding the control of toxic emissions -- especially PCDDs and PCDFs -- is one of public perception. Although the destruction rate of organic constituents appears to be high, much remains to be understood about such factors as combustion kinetics, degradation parameters, and compound precursors (Dent and Krol, 1990; Clarke and Virag, 1989; McGowin, 1989; Niessen, 1984; Graham et al., 1984; Ohlsson, 1989). State governments are sponsoring research aimed at controlling trace emissions of chlorinated organic compounds (Seeker et al., 1989; Ohlsson, 1989). Additional research is needed to determine whether the more uniform combustion conditions characteristic of fluidized-bed combustion permits a better control of organic emissions.

Better control of acid gas emissions will involve developing a better understanding of acid gases and improving current control technologies (McGowin, 1989; Donnelly, 1991; Zylkowski, 1990). Past research has shown that baghouse (fabric filter) screening will improve acid gas control after lime neutralization in dry scrubbers, while other research has emphasized improvements in electrostatic precipitators (Flynn et al., 1984). Recent efforts towards developing in-furnace lime-neutralization injection, which would streamline emission control processes, suggests an interest in more cost-effective approaches to the current technology of spraying dry scrubbers followed by baghouses (Scaramelli, 1979). Research is also addressing inorganic acid gas emissions from co-firing RDF with coal (Daugherty et al., 1989).

The emission of heavy metals in combustion gases from RDF firing is not well understood (McGowin, 1989; Daugherty et al., 1989; Dent and Krol, 1990; Scaramelli, 1979). In addition, operating at higher temperatures can increase volatilization in the furnace and,

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[*******] One reviewer believes that the development of equipment to control volatile heavy metal emissions is the primary area requiring further RD&D.

[********] One reviewer stated that electrostatic precipitators are no longer used because they are not cost-effective for the removal of metals and dioxins can be formed in them.

thus, increase metals emissions as fine particulates which should be captured in a baghouse (Scaramelli, 1979).

Several researchers have identified the need for a better understanding of nitrogen oxides ($NO_x$) formation and control (Donnelly, 1991; Russell and Roberts, 1984; Ohlsson, 1989). Some reductions in the formation of $NO_x$ are possible through existing technologies, but elimination of $NO_x$ from the flue gas stream is not well understood (Russell and Roberts, 1984). A major recommended step is to adopt continuous $NO_x$ monitoring (Russell and Roberts, 1984).

Carbon monoxide (CO), a product of incomplete fuel combustion, is used by plant operators as an indicator for adjusting combustion unit air systems. Work is needed to better understand CO in RDF combustion (Donnelly, 1991; Zilkowski, 1990; Bacchi and Allen, 1991).

Specific research topics on emissions worthy of further investigation are:

19. Evaluate dioxin and furan formation, decay, and partitioning (into fly ash, bottom ash, vapor phase);*********

20. Investigate ash resistivity and the effect on electrostatic precipitators;**********

21. Study the efficacy of carbon injection on mercury/dioxin control;

22. Develop better and more reliable real time indicators (both direct and surrogates) of specific emissions (e.g., air toxics and inorganics) and develop and demonstrate real-time continuous monitoring systems for organics and metals;

23. Compare emissions from co-fired plants with emission from non-waste fuel boilers (e.g., examine high sulfur coal and use existing databases); and

24. Evaluate the use of additives (e.g., limestone) in fluidized beds for acid gas neutralization.

### 5.3.9 Tire Derived Fuels

Co-firing of RDF is not necessarily accomplished only with coal. Other fuels may be used as well. It is highly beneficial to find technologies to burn materials, such as used tires, that would otherwise be discarded. Thus, research is needed is to:

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********* One reviewer commented that this research has already been done. The reviewer did not indicate, however, where this research was done.

********** One reviewer commented that there is no longer a need for this research. No reasons were given.

25. Determine optimum fuel properties (size, beading, wire content, etc.) and impact of specific boiler applications on co-firing RDF with tire derived fuels.

### 5.3.10 Other Potential RD&D Topics

The following RD&D topics were identified in the literature review, but were not subsequently accepted by the panel of technical experts (listed in Appendix A).

Research could continue to determine optimum grate speeds and bed depths for chain grate combustion systems (Tweedale, 1988). In addition, combustion conditions should be improved to comply with state and Federal emission standards for carbon monoxide (Bacchi and Allen, 1991).

The control of heavy metals in combustion gases from RDF firing requires more research (McGowin, 1989; Daugherty et al., 1989; Dent and Krol, 1990). Researchers note that emissions of fine particulates may permit excessive emissions of metals, demonstrating the need for better control of particulate emissions (Scaramelli, 1979). Development of lower temperature dioxin-destructive combustion technologies would reduce this problem. In general, researchers state that a better understanding of the formation and reaction kinetics of heavy metal compounds, such as the oxides and chlorides of arsenic, cadmium, lead, and mercury, is needed (Donnelly, 1991).

## 5.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on RDF production and co-fired combustion are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making co-fired RDF combustion technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. After a final priority had been assigned to each RD&D need, the panel members categorized the needs as being essential, high priority, medium-high priority, medium priority, low-medium priority, or low priority. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 5-1, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 5.3 is in the right-hand column. The rationale discussed by the panel of technical experts is summarized below. The rationale tend to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

In general, the panel felt that the technology would not advance significantly until three primary issues are resolved: control of slagging and fouling; control of elemental heavy metals; and improvement of real time emissions indicators and monitoring.

## Exhibit 5-1. Prioritized RD&D Needs for RDF Production and Co-fired Combustion

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **Essential** | |
| --- | Investigate the impact of inert fines removal on slagging & fouling in co-fired RDF units | 10 |
| --- | Optimize methods to remove elemental heavy metals and other constituents | 4 |
| | **High Priority** | |
| 100 | Develop better real time indicators and demonstrate real-time continuous monitoring | 22 |
| 100 | Study the properties of co-fired bottom and fly ash | 18 |
| 90 | Investigate effects of varying blends and burn rates on performance/availability/capacity | 14 |
| 90 | Study furnace injection velocity and geometry position in certain boilers | 13 |
| 90 | Study the effects of additives to RDF | 8 |
| | **Medium-to-High Priority** | |
| 80 | Study the value of pellets made by combining RDF with coal | 12 |
| 75 | Study economic and environmental effects of changes in MSW stream | 3 |
| 70 | Determine optimum fuel properties and impact of specific boiler applications | 25 |
| 70 | Study implications of pulverizing pellets with coal | 11 |
| | **Medium Priority** | |
| 60 | Investigate the effects of acid gas formation on metals performance | 16 |
| 55 | Investigate ash resistivity and the effect on electrostatic precipitators | 20 |
| 50 | Evaluate dioxin and furan formation, decay, and partitioning | 19 |
| 45 | Confirm that dioxins are suitably destroyed in combustion | 17 |
| 45 | Compare emissions from co-fired plants with emission from non-waste fuel boilers | 23 |
| | **Low-Medium Priority** | |
| 40 | Evaluate the use of additives in fluidized beds for acid gas neutralization | 24 |
| 40 | Investigate co-fired boiler response to discontinuous feed (grate dump) | 15 |
| 35 | Develop real time techniques for determining moisture content of shredded MSW | 5 |
| 35 | Develop methods to identify occupationally hazardous substances in MSW | 2 |
| 35 | Study the efficacy of carbon injection on mercury/dioxin control | 21 |
| | **Low Priority** | |
| 30 | Develop methods for fine wire removal | 6 |
| 25 | Study bin flow properties of pellets | 7 |
| 20 | Investigate methods to reduce drying costs prior to pelletization | 9 |
| 20 | Develop methods and technologies to identify items that damage equipment | 1 |

### Essential RD&D Needs

The panelists felt that slagging and fouling (No. 10) are by far the most important problems affecting the viability of co-firing. Research in this area should have high priority since it has the largest impact on the product and process. If slagging and fouling problems cannot be solved, the panel stressed that there is little value in spending RD&D dollars on other co-firing issues. The removal of heavy metals and other constituents (No. 4) is part of the slagging and fouling issue, and therefore RD&D in this area was also considered essential.

### High Priority RD&D Needs

The panel believed that real time indicators and monitoring (No. 22) are important due to public perception problems associated with emissions. The ranking reflects concern about the impact of new regulations on emissions. In California, there is a new trend that, instead of blanket destruction requirements, permitted levels are combined with risk assessments at facilities based upon local factors. Blend ratios and burn rates (No. 14) can affect slagging and fouling, so they are ranked high. Blend ratios are particularly critical for coal-fired stoker units as indicated by past studies. Ash management issues (No. 18) must be addressed to avoid long-term disposal consequences. Finally, the panel felt that consistently efficient boiler performance is needed to make the technology viable. For this reason, optimal boiler configurations (No. 13) were assigned a high priority, along with studies of the effects on boiler conditions of RDF additives (No. 8).

### Medium-to-High Priority RD&D Needs

The panelists stated that the market for RDF shows that the majority of coal is used by power companies. In terms of boilers used by utilities, 85 percent are pulverized coal boilers, not grate or stoker units. Adding coal increases the strength of RDF pellets, improves handling ability, raises Btu content, and solves part of the solid waste and coal fines waste problem (Nos. 12 and 11). The panel felt that as the MSW stream changes (No. 3), the severity of this change on the economics of RDF combustion and environmental compliance should be studied. New legislation on tires makes it important to study their fuel properties and impact on air pollution control devices (No. 25).

### Medium Priority RD&D Needs

The group felt that better MSW screening would reduce damage to equipment, which can arise from various combustion products. Acid gases (No. 16) produced in RDF combustion can severely impact boiler components. Ash resistivity negatively affects electrostatic precipitators, especially in retrofit units (No. 20). For example, a degradation in electrostatic precipitator performance in co-fired units has been noted at some facilities. While pollution from co-firing is low, there is a need to address the public perception, particularly with regard to dioxins (No. 17). The body of knowledge on how dioxins form and degrade (No. 19) is limited. The panelists felt that improvements in emissions should be documented in order to promote the technology (No. 23).

### Low-to-Medium Priority RD&D Needs

The panel felt that the environmental impacts of emissions from co-firing are not of major significance, and in general the panel assigned a low priority to investigating impacts(Nos. 24 and 21). In making this ranking, the panel reasoned that other studies have already been done on injection, and dioxins represent a problem primarily in terms of public perception. Boiler response to transient conditions (No. 15) was also deemed of moderate significance. Adequate means to identify hazardous materials in MSW (No. 2) already exist, and not much should be spent on marginal improvements in methods for doing this. The impact of improving moisture content (No. 5) was judged to be minor, since this may marginally improve the efficiency of combustion.

### Low Priority RD&D Needs

According to the panel, a lot of information is already available about what is in the waste stream and how to remove items that may damage equipment (No. 1). Fine wire removal (No. 6) is a minor annoyance, and solving the problem will have a small impact. Most ferrous items are already removed by magnets, and there isn't much copper wire in the MSW stream. Bin flow (No. 7), primarily dependent on the size and shape of the pellets, was not seen as a problem requiring much research attention. Even if better drying methods (No. 9) are found, it is not likely to affect the decision whether or not to use RDF since other issues are much more significant.

## 5.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate co-firing RDF with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The panel projected that to get most of the benefit of the full set of RD&D needs would require a $20 million effort.

### Difficulty of Technology Development

According to the panel, the development of technology for co-firing would have very low difficulty (comparable to dedicated RDF combustion) since the technology is mature and already viable in the near term. On a scale where 100 represents the least difficult technology to develop (e.g., landfill) and 0 represents the most difficult technology (e.g., pyrolysis), co-firing would be a 75.

### Commercial Development Risk

The panel found promise in the expectation that most co-firing operations would be by utilities rather than private industry. However, the size of the market is uncertain. Utilities are

historically slow to adopt new technologies. Co-firing would be attractive to industry if it could break-even. However, the panel felt that a large capital investment -- beyond RD&D -- would be required. The construction of a medium-scale facility (600 megawatts, 300-350 tpd) with retrofit equipment was estimated to cost $15 million.

### Flexibility

This technology is very flexible (comparable to mass-burn, less flexible than landfilling). Sixty to 70 percent of the MSW stream can become RDF. The technology is appropriate on a medium to large scale (500-2,000 tons of raw waste per day). Co-firing is compatible with both existing and future technologies, particularly RDF, tire pyrolysis, and recycling programs. An industrial park waste management concept could be very competitive.

### Cost Impacts

The panel members felt that even if this technology did not reduce the cost per unit of energy, an operation that broke even would nonetheless be worthwhile. The panel reasoned that if tipping fees are high enough, the savings will balance the cost of producing the fuel.

### Net Energy Benefit

As a benchmark, a 1,000 tpd MSW mass-burn facility has a 50 megawatt capability. The group felt that co-firing could achieve 550 kilowatt with a fuel containing 6,000 Btu per pound.

### Human Health and the Environment

In the vicinity of the RDF plant, there should be no impact; burning RDF should be no worse than burning coal. Co-firing is more environmentally benign than most technologies, but there is a problem with public perception. There are still some unresolved issues regarding ash and emissions. Overall, the panel felt that co-firing RDF would result in a net environmental benefit.

### Occupational Health and Safety

The technology is somewhat more dangerous than composting or landfilling due to possibility of explosions and disease. It is, however, safer than hand picking at a materials recovery facility.

### Appropriateness for Government Funding

Co-firing is very compatible with existing regulations and very appropriate for DOE funding.

# 6. COMPOSTING

## 6.1 Technology Description

Composting is a microbially mediated process through which organic material decomposes into a humus-like substance. This end product is referred to as compost while the organic portion of the substrate material and the microbes within this substrate are referred to as biomass. The effectiveness of the composting process and the characteristics of the compost depend on the material being composted and the level of technology applied. Compost may be produced from different organic feedstocks including the organic fraction of MSW, sewage sludge, agricultural by-products, or a combination thereof.

### 6.1.1 Basic Process

In composting, microorganisms break down available organic materials into more stable compounds such as those comprising humus, and in the process generate carbon dioxide and heat. The microorganisms involved may be either aerobic or anaerobic; however, anaerobic bacteria tend to generate offensive odors and composting operations try to manage the process to encourage the dominance of aerobic microbes (Robinson, 1986). The composting process is mainly controlled by four parameters:

- **Available Oxygen:** Available oxygen determines whether aerobic or anaerobic bacteria dominate in the biomass.

- **Temperature**: Low temperatures will slow down the process, while high temperatures (approaching 60 degrees C) will inhibit or kill the composting microorganisms.

- **Moisture**: Moisture is needed for microbial growth, but too much moisture will lower temperatures and create anaerobic conditions leading to odor problems.

- **Carbon to Nitrogen Ratio**: The carbon/nitrogen ratio is an indicator of nitrogen availability to microbes. Optimal nitrogen concentrations enhance rapid microbial growth and tend to speed up the composting process. (Taylor and Kashmanian, 1989)

Composting may be accomplished in open piles, open windrows, enclosed reactors, or a combination of these. The composting process may be allowed to proceed unattended within windrows or piles, but the composting process will slow down unless steps are taken to control the process by periodic turning of the material, forced aeration, or moisture addition. In an enclosed composting system, organic material is placed in closed containers where stirring and forced aeration take place. The two processes may also be combined: material may be processed in a mechanical reactor for a period of time and then partially composted material may be removed and allowed to continue composting in an open system. (Robinson, 1986)

### 6.1.2 Feedstock Characteristics

Because MSW is seldom nutritionally adequate (e.g., nitrogen and carbon) for composting (Diaz and Golueke, 1990), nutrients or sewage sludge are commonly added before composting to improve composting effectiveness. Sewage sludge is typically high in nutrients but cannot be composted without the addition of a bulking agent to provide sufficient structure for internal aeration of the biomass (Robinson, 1986). The practice of combined composting of MSW and sewage sludge, known as co-composting, has been shown to be mutually beneficial: sewage sludge provides the nutrients and MSW provides the bulking agent (Diaz and Golueke, 1988). Alternatively, the organic portion of MSW, which includes yard waste, food processing wastes, and agricultural by-products, may be collected separately for composting. The MSW waste stream must also be preprocessed to remove inorganic materials, such as metal, plastics, and rubber (Robinson, 1986) which will not compost and cause poor compost quality.

### 6.1.3 Product Characteristics

The composting process reduces the volume of organic material and produces a product similar to humus, which may provide low levels of nutrients for plant uptake (Taylor and Kashmanian, 1989) and enhance soil physical properties when added to the soil. Because of these characteristics, compost may be used as a soil conditioner, as a mulch to reduce soil moisture losses and control weeds, or as a soil cover to reduce soil erosion. Prior to sale, use, or storage, the compost may be further processed through screening, grinding, granulation, or blending with various additives to produce a product to meet particular market needs or for specific applications (Robinson, 1986).

## 6.2 Technology Status

Composting activities in the U.S. can be divided into two major categories: sewage sludge composting and municipal solid waste (MSW) composting. The latter category has one sub-group that is called co-composting, in which sewage sludge is added to MSW to facilitate and enhance the composting process. As of 1988, 115 sewage sludge composting facilities were operating in the U.S. The processes utilized at these facilities were aerated static piles (61), windrows (29), in-vessel composting (19), aerated windrows (5), and vermicomposting (1). In addition, 14 pilot facilities were conducting sewage sludge composting activities and 90 such projects were in various stages of development from consideration (36) to planning (40) to construction (14). Over 50 percent of the projects in the developmental stage were designed to utilize in-vessel composting techniques (Diaz and Golueke, 1990).

As of 1989, eight commercial MSW composting facilities were operating in the U.S., including a research facility employing a digester which has been operating for many years. Six of the facilities had been in operation from one to eight years, while one had been in operation for only one month. Their design capacities ranged from 5 to 100 tons per day, with the largest facility rated at 1,000 tons per day. All of the commercial facilities conduct some front-end processing or recycling, which recovers from 10 to 20 percent of the solid waste stream at the source of the composting facility itself. Three of the facilities initiate composting in rotating vessels before final composting utilizing windrows, while four use particle shredders or hammermills before finishing with windrows. At least three of the eight active facilities add

sewage sludge to MSW to conduct co-composting. One facility also produces refuse derived fuel (RDF) as part of its operations. (Goldstein, 1989; Goldstein and Spencer, 1990)

In 1989, two MSW composting facilities were under construction in the U.S., 4 were in the advanced planning stage, and 51 other projects were in various stages from early consideration to permitting. From 1988 to 1989, the number of operational and proposed projects increased almost 80 percent from 42 to 75 (Goldstein, 1989; Goldstein and Spencer, 1990).

## 6.3 Description of RD&D Needs

Composting MSW can help municipalities achieve their recycling goals and reduce the demand for increasingly scarce landfill space. For MSW composting to be widely accepted, however, it must be economically and environmentally competitive. This will require technologies that have low energy consumption, a high quality end-product, a net beneficial effect on the environment, and a solution to offensive attributes such as flies and odors which would contribute to public opposition (Diaz and Golueke, 1990; de Bertoldi et al., 1988). In the past, MSW composting has been limited by problems in maintaining consistent compost quality. Research is needed to better understand the microbiology of composting, develop better preprocessing of the materials to be composted, improve composting procedures, design new composting systems, improve compost quality, and reduce objectionable emissions. These research needs, which are discussed below, generally apply to MSW, sludge, and co-composting practices.

Sections 6.3.1 through 6.3.8 describe each area of RD&D needs for composting that were identified by the panel of technical experts (identified in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 21) that is used in later sections when the RD&D needs are prioritized and discussed. Section 6.3.9 describes RD&D needs that were identified in the literature review (see the introduction chapter), but were not subsequently accepted by the panel of technical experts. Section 6.3.10 presents RD&D needs that were identified by people reviewing this document. The RD&D needs in Sections 6.3.9 and 6.3.10 are not prioritized or discussed further.

### 6.3.1 Technology Transfer

Panel members agreed that the most important need for the development of the MSW composting technology is a state-of-the-art demonstration facility. Composting systems can be implemented now and have been implemented successfully in various forms at many locations. The composting process can be controlled, through monitoring of the biomass, to provide reliable results. The panel concluded that while much remains to be learned about microbial processes in composting, enough knowledge is available to build a successful demonstration plant.

Current knowledge is not adequately reflected in existing systems. Subsequently, many systems that do not work as well as they could may harm public perception of MSW composting. Education of industry and the public concerning composting is also necessary. There is a conflict between a policy of maximum energy production benefit and EPA's waste management hierarchy, which places composting above incineration. While composting and incineration may compete for the same raw resources, incineration clearly has the higher net

energy benefit when other relevant tradeoffs are ignored. Approximately 40 to 60 percent of the MSW stream can be composted.

A significant amount of composting research has been conducted in Europe and other foreign countries. Data from these studies need to be gathered, organized, and characterized to avoid excessive duplication of research efforts. Similarly, sludge composting experience, as it relates to MSW composting, should also be examined. A clearinghouse of information should be established as a central resource with up-to-date information on all aspects of MSW composting. The following are summary descriptions of the previously discussed RD&D needs:

1. Establish a state-of-the-art demonstration facility;

2. Transfer MSW composting information and technology to industry and the public;

3. Compare economic, public health, and environmental effects of composting and other MSW technologies to governmental priorities;

4. Characterize related composting work from Europe;

5. Relate knowledge gained from sludge composting experience to MSW composting;

6. Establish a clearinghouse of MSW composting information; and

7. Examine the conflict between the DOE energy policy and the EPA hierarchy.

### 6.3.2 Waste Characterization and Preprocessing

Public acceptance of the MSW composting technology depends upon the public acceptance of the compost which, in turn, depends upon the quality of the compost. The biggest factor affecting the quality of the compost is the type and composition of the MSW substrate used in the process. Thus preprocessing of the MSW is crucial to the development of the technology (Golueke and Diaz, 1989). Components in MSW that cannot be composted are more easily separated from the substrate before composting than after the process is complete. Better means of preprocessing the solid waste substrate are needed in order to maintain quality and marketability of the compost (Diaz and Golueke, 1988). Additional research is also needed to develop methods of pretreatment that will adequately reduce inputs of heavy metals and toxic chemical compounds (Diaz and Golueke, 1990).

A major constraint to optimization of the composting process is the variability in physical properties found within the solid waste stream. Preprocessing methods need to be developed that will provide a more homogeneous biomass with respect to moisture, chemical content, and physical size (Diaz and Golueke, 1990). Although homogeneity is a desired characteristic, excessive mechanical mixing will reduce substrate particle size and limit internal aeration of the compost. Mechanical means of obtaining a homogeneous substrate mixture,

while minimizing the reduction of particle size and maintain biomass porosity, need to be developed. (Diaz and Golueke, 1988)

Preprocessing necessary for composting is similar to that required for other MSW technologies. The exact role of MSW preprocessing relative to its effect on composting needs to be researched. Each technology addresses preprocessing as it relates to the demands of the individual process. Preprocessing must be efficient and cost-effective. The cost-benefit relations of processing at the source versus at the facility should be examined. It is difficult to generalize about the cost-benefit relationship because the decision will be very site-dependent. While there is clearly a need to develop methods for separate non-compostables and heavy metals from MSW, standardized methods for characterizing (composition, properties, chemistry, and toxicity) the MSW are also needed.

Optimization of the MSW composting process will require knowledge of feedstock properties, understanding of the changes that occur during composting, and thorough identification and characterization of the biomass. Although standardized methodologies for general characterization of MSW exist, information on specific MSW characteristics such as composition, chemistry, toxicity, etc. is needed. MSW can contain chemicals (e.g., inorganic printing inks) that cannot be eliminated by preprocessing and affect the compostability of the substrate and possibly render the compost useless. The following are summary descriptions of the previously discussed RD&D needs:

8. Develop efficient, cost-effective preprocessing methods and study options of separation at the source or at the composting facility; and

9. Develop standardized methods of characterizing the waste stream for composition, properties, chemistry, and toxicity.

### 6.3.3 Process Engineering and Control

Although demonstration of a MSW composting system using current technology is considered to be an important need, microbial research may also be required to solve some problems of the technology (e.g., odor). Future progress in refining composting procedures will also depend on an increased understanding of the biological processes. Further research is needed to isolate, identify, and characterize microbes that generate odors and those that control the composting process. Studies that have attempted to identify and quantify populations of bacteria during composting have been difficult to evaluate due to great temporal and spacial variabilities within a composting operation. This information may be more reliably obtained under controlled composting conditions. (Macauley et al., 1990)

Lack of a thorough understanding of all microbial processes does not preclude significant advancements that can be made by examining how the microbial populations respond to different treatments. These studies would be based on input-output relationships where parameters that are known to affect composting rates are varied to find the conditions that optimize microbial growth.

Water is a critical factor for growth of aerobic microbes within the compost, not only for hydration, but also for the effect of water content on aeration. The physics of water in composting ecosystems needs further study. Further nutritional studies are needed to define

optimal nutritional status at discreet composting stages. Data show that initially high nutrient levels do not correspond to an increase in final nutrition. This indicates that the addition of nutrients at certain times during the composting period may provide better nutrient utilization efficiency. (Macauley et al., 1990)

A better understanding of biological composting requirements will require corresponding improvements in system design and control to reduce waste water production, to shorten processing periods, and to provide more consistent processing (Macauley et al., 1990). Systems need to be developed to optimize the composting processes while minimizing space and energy requirements (Diaz and Golueke, 1990).

Odor control is one of the most difficult and vexatious problems facing full-scale composting operations (Diaz and Golueke, 1990). Further research is needed in mitigating odor problems (Macauley et al., 1990). Past research has focused on odor control after odors have been generated, rather than on the prevention of odor through process control (Diaz and Golueke, 1990). Studies to establish the relationship of odor generation to the timing and amount of nutrient addition may provide valuable information that would help reduce odor problems (Macauley et al., 1990). Similarly, basic research is needed on the microbiological processes responsible for odor and emissions. Research is also needed to investigate other gaseous emissions from solid waste composting and evaluate the possible need for biological scrubbers.

Leachate is another potential problem for composting systems. A properly controlled composting system will minimize leachate, however, even well-controlled open composting systems will produce leachate when subject to excessive precipitation. Studies are needed to characterize and assess the benefit-harm of biomass leachate and develop new methods to treat, handle, and minimize leachate. This is especially important for MSW composting systems that operate without enclosures or barriers to prevent the release of leachate into the environment. The following are summary descriptions of the previously discussed RD&D needs:

10. Investigate microbial conditions that cause offensive odors and other gaseous emissions;

11. Optimize control factors through input-output relationships;

12. Investigate the treatment or utilization of leachate; and

13. Shorten composting periods while minimizing space and energy requirements by maximizing the rate of microbial activity.

### 6.3.4 System Design

A plant designed to operate profitably for 20 years should be able to accept differing waste streams by more thoroughly preprocessing the waste stream. A system designed to handle any waste stream will be more versatile and robust than a more specific design.

The system design should adequately address the prevention or containment of odor as it is the major problem confronting implementation of MSW composting systems. As with

emission problems of other MSW technologies, tradeoffs need to be evaluated between prevention and containment (e.g., are scrubbers more economical than the necessary design changes to prevent the odors). System designs need to be developed that will have preprocessing capabilities specific to MSW composting needs, accept a wide variety of wastes, and control odor and emission problems. The following is a summary description of the previously discussed RD&D need:

14. Design efficient MSW composting systems that have preprocessing capabilities specific to MSW composting needs, accept a wide variety of wastes, and control odor and emission problems.

### 6.3.5 Product Quality

One of the major problems facing solid waste composting is the acceptability and marketability of the compost. Standards are needed to judge compost acceptability. Compost produced from different materials or under different conditions exhibit different properties and levels of acceptance. The composting process reduces the biomass into simpler forms with the ultimate release of carbon dioxide and water. Inorganic components of the substrate are not released and will concentrate as the biomass is reduced. This raises a concern that increasing inorganic (metal) concentrations may raise human or plant toxicity levels. Compost may also be subject to potentially toxic substances from the MSW stream that are not removed during preprocessing.

Compost standards should also be a function of the particular end use that may range from partial daily landfill cover to full landfill cover to vegetable mulching. MSW compost cannot be considered as a fertilizer due to its relatively low nutritional content. The organic material in compost will further decompose in the soil which may immobilize some existing plant nutrients in the soil and cause a temporary decrease in soil fertility. The main benefit of compost to the soil is as a soil conditioner. Much research has been done on the effects of adding organic matter to the soil, but further study is needed to establish the applicability of the results of this research to soil-applied compost generated from MSW. Research is needed on the specific nutrient availability and the possible effects of toxics in MSW compost on plant growth. The presence and level of toxics and metals in MSW compost that may be released to the environment is also a crucial problem relating to the acceptability of the product.

Studies are needed to define and establish standards of compost quality (Macauley et al., 1990) based on end-user requirements, public and occupational health, and potential environmental impact. These standards should include setting safe, acceptable levels of organic contaminants and inorganic accumulations in the finished product. The following are summary descriptions of the previously discussed RD&D needs:

15. Define and establish standards of compost quality as function of end-user requirements, public health, and the environment;

16. Characterize the nutrient availability and possible toxic content of MSW compost; and

17. Investigate the use of MSW compost as a soil conditioner.

### 6.3.6 Environmental Impacts

MSW composting is presently experiencing good public acceptance due to current recycling efforts and the poor public acceptance of MSW incineration. For composting to continue to have good public acceptance, it must be demonstrated that composting can be successfully implemented without having negative public impacts such as offensive odors or damaging effects on human health or the environment.

There are some concerns about health problems associated with composting. Health and environmental risk assessments should be conducted at composting facilities to evaluate the exposure potential of composting workers to toxic vapors. Such studies should consider the feasibility and economics of prevention and control measures to support policy-making decisions. A clear, coherent evaluation of composting health risks based on specific management practices needs to be developed to reduce public concerns.

Potential environmental impacts of MSW compost production, such as the migration of leachate into the soil and groundwater, also need to be carefully evaluated under different management practices and compost systems. All potential environmental impacts of compost production should be accurately identified and quantified for all potential migration pathways including ground water, surface water, air, bio-uptake, and soil.

Enclosed buildings may reduce potential effects of compost-related hazards on the environment but increase the hazards of emissions on workers. Enclosure of biomass in tunnels may eliminate or significantly reduce all hazards (Section 6.3.8). The following is a summary description of the previously discussed RD&D need:

18. Assess health and environmental risks, including emissions and identification and quantification of potential environmental impacts on ground water, surface water, air, and soil.

### 6.3.7 Benefits

Composting cannot compete with other energy producing technologies if energy production is the primary criterion. Composting may provide a net energy conservation, however, and net energy benefit may thus be a better comparative criterion. This net energy benefit has not been documented and needs to be explicitly established before valid energy-based comparisons can be made to other MSW technologies. This study will require examination of what currently used products can be completely or partially replaced through beneficial uses of compost. Once this is done, the net energy saving will be a comparison of the energy required to produce the compost and the energy required to produce the displaced commodity.

When longer-term goals of environmental preservation are considered, in addition to the energy considerations, composting should have a potentially stronger position. This position must be demonstrated through a careful analysis based on a combination of energy, conservation, economic, and environmental factors. These required studies will be controversial and some panel members doubt that they can be done to an acceptable degree of credibility. This doubt is partly due to the lack of consensus on a method of handling some of the complex issues involved in trading off societal goals and assessing the impacts of

technologies with respect to such goals. Analytic tools are available to conduct a systematic and comprehensive consideration of problems at a broad level covering all MSW technologies. The following are summary descriptions of the previously discussed RD&D needs:

19. Evaluate the net energy benefits of composting; and

20. Perform a comprehensive study comparing energy, conservation, economic, and environmental factors of composting and other MSW technologies.

### 6.3.8 Markets Identification and Establishment

To assist with the benefits studies and enhance the utilization of composting, new markets need to be identified and developed. Industry is not interested just in a net energy benefit, but rather in short- and long-term profits. Therefore, market studies are needed that identify the short- and long-term markets for composting. Specific market studies would include identifying barriers that might restrict the use of MSW compost. The marketing of compost in a specific location may also be regulated or restricted by state authorities. A study is needed to compile state regulations that affect the production or use of MSW compost along with the justifications for those regulations.

The general feeling of the panel was that the government should take the lead in identifying and mitigating disincentives as well as creating incentives for composting MSW. This would include such actions as evaluating and modifying, if necessary, government procurement policies that would utilize MSW compost when possible. The following is a summary description of the previously discussed RD&D need:

21. Identify compost markets and develop these markets through mitigation of disincentives and implementation of incentives for using compost.

### 6.3.9 Other Potential RD&D Topics

The following RD&D needs were identified in the literature review, but were not subsequently accepted by the panel of technical experts (listed in Appendix A).

Development of the environmentally controlled composting (ECC) system for use in MSW composting may eliminate many of the health and environmental concerns associated with this technology (de Bertoldi et al., 1988). The ECC system can address these issues in two ways. First, precise management of the biological process will minimize odors and reduce harmful emissions. The ECC system is completely enclosed, allowing careful control of all inputs to the system. This provides a uniform composting environment that minimizes spacial variation of the composting process throughout the substrate. Second, because the system is completely enclosed, all emissions and leachate can be contained within the system and treated, if necessary, before being released.

ECC designs developed for the laboratory may also be more useful for evaluating detailed biological studies (Macauley et al., 1990). Although this type of design is currently being used in the mushroom industry, research is needed to evaluate ECC system applicability to solid waste composting.

### 6.3.10 RD&D Topics Identified by Reviewers

One reviewer stated that RD&D is needed to compare aerobic and anaerobic composting with respect to conversion versus time. Lab and field trials are needed to test the resulting composts. Another reviewer believes that there is a need for RD&D on the leachability of metals from MSW compost.

## 6.4 Prioritized RD&D Needs

In this section, the priorities assigned to the RD&D needs by the panel of technical experts on composting are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making composting technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 6-1, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 6.3 is in the right-hand column. The rationale discussed by the panel of technical experts is summarized below. The rationale tends to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

The most important research needs are related to technology transfer and demonstrating to regulatory agencies and the public that MSW composting is a viable and valuable technology. Some panel members expressed the opinion that MSW composting technology is encouraged by EPA and discouraged by DOE. This inherent conflict is caused by DOE's emphasis on energy recovery and EPA's encouragement of recycling. This conflict should be resolved by examining how their respective policies agree with the economic, health, and environmental impacts of MSW technologies (No. 7). This will require the health and environmental risk assessments which are also necessary to alleviate public concerns about the technology (No. 18).

The most important goal to make the technology more commercially viable is to shorten the processing period (No. 13). To accomplish this goal, an understanding of the microbial ecosystem is needed to optimize the processing rate. Management factors can, and should, be optimized before a thorough understanding of the microbial processes are understood. This can be accomplished through analyses of variable management factors and their effect on the process (No. 11).

The demonstration facility is next in importance because adequate knowledge to implement the technology is already available (No. 1). The capability to safely and effectively implement MSW composting needs to be demonstrated to industries, the public, and government. Panel members expressed the concern that good information about MSW composting is not readily available to potential users of the technology. Much of the information currently available is confusing or erroneous. The industry needs to make high-quality technology-related information available to the public and industry (No. 2). More experience has been gained concerning sludge composting than MSW composting. The

**Exhibit 6-1. Prioritized RD&D Needs for MSW Composting**

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| 100 | Examine conflict between DOE energy policy and EPA hierarchy | 7 |
| 90 | Compare effects of MSW technologies to governmental priorities | 3 |
| 90 | Minimize time, space, and energy requirements by maximizing microbe activity | 13 |
| 85 | Health and environmental risk assessment | 18 |
| 81 | Investigate microbial conditions causing odors and emissions | 10 |
| 80 | Establish a state-of-the-art demonstration facility | 1 |
| 80 | Transfer information and technology to industry and public | 2 |
| 80 | Relate knowledge gained from sludge composting experience | 5 |
| 80 | Define and establish standards of compost quality | 15 |
| 75 | Develop preprocessing methods and source-separation options | 8 |
| 72 | Optimize control factors through input-output relationships | 11 |
| 72 | Characterize nutrient availability and toxic content of MSW compost | 16 |
| 70 | Design efficient MSW composting systems | 14 |
| 65 | Identify and develop compost markets | 21 |
| 64 | Develop standardized methods of characterizing the waste stream | 9 |
| 56 | Investigate the use of MSW compost as a soil conditioner | 17 |
| 55 | Establish a clearinghouse of MSW composting information | 6 |
| 50 | Characterize related composting work from Europe | 4 |
| 40 | Evaluate the net energy benefits of composting | 19 |
| 36 | Investigate the treatment or utilization of leachate | 12 |
| 35 | Compare energy, conservation, economical, and environmental factors | 20 |

relevance of sludge experience to MSW composting research needs should be evaluated and made available (No. 5).

Effective marketing of MSW compost will require defining and establishing standards for product quality (No. 15). This is critical for developing confidence in the compost product and establishing long-term contractual agreements. Efficient, cost-effective preprocessing of MSW to separate non-compostables and heavy metals/toxics from the MSW substrate is crucial to ensuring a high quality compost. Practical preprocessing methods for use at the source and/or at the facility should be developed and evaluated (No. 8).

Studies assessing the potentially beneficial uses of compost for soil improvement, erosion reduction, weed control, moisture control, and as an aid in the establishment of vegetated soil cover are needed to identify and develop new compost markets (No. 21). The experience gained from many existing facilities has not been systematically collected and analyzed (No. 6). There are many anecdotes in trade publications, but no one has been putting it all together. There is also much misinformation and disinformation available so care

must be taken to avoid transfer of bad information. The panel felt that an objective characterization of composting research done in other countries would be nice to have, but is not critical (No. 4).

Panel members expressed a concern that DOE does not favor composting because they do not think that composting can provide a greater energy benefit than incineration of MSW. This assumption has not yet been validated by studies. A study examining the net energy benefit of both technologies could resolve this issue (No. 19). This study should look at all potential uses for the compost and assess cost-benefit criteria for each option.

## 6.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate MSW composting with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The panel could not estimate the full cost of the proposed RD&D program. The panel, however, estimated that a demonstration facility of 10 to 20 tons per day would cost about $1.0 to 2.0 million. This amount includes a significant up-front source-separation component.

### Difficulty of Technology Development

The panel rated the technology as not posing development difficulties because sufficient knowledge is currently available for successful implementation. Research on the biomass and microbiological processes can provide improvements in the technology, but it is not required for implementation.

### Commercial Development Risk

The technology currently enjoys a favorable public image. There are problems, however, with offensive odors experienced by people living near composting facilities that must be mitigated.

### Flexibility

The panel estimated that 40 to 60 percent of the raw MSW waste stream can be composted. Even after significant recycling has occurred and reject material has been removed, it is estimated that 35 to 40 percent of the raw MSW waste stream will still be available for composting.

### Net Energy Benefit

Composting requires energy and does not produce energy directly, but may provide a net energy benefit by serving as a substitute for materials that otherwise would require energy to produce.

### Occupational Health and Safety

Panel members did not agree on the potential human health and occupational safety effects of MSW composting. Fungal spores and gaseous emissions may be a problem at composting facilities that would require protection for workers. Composting poses a higher risk than anaerobic digestion, but probably less risk that many of the other MSW technologies.

### Human Health and the Environment

The panel rated the technology as having little environmental impact. Offensive odor generation is the biggest problem. The panel felt that leachate from the biomass could be prevented.

### Appropriateness for Government Funding

The panel considers that MSW composting is consistent with EPA policies and DOE's long-term goals, but may not be consistent with the apparent DOE policy on energy recovery.

# 7. GASIFICATION

## 7.1 Technology Description

Gasification is generally defined as the thermal decomposition of a material to produce primarily a gaseous product. Gasification often involves the partial oxidation of the feed (e.g., air-blown and oxygen-blown gasifiers) but may be carried out with steam and heat alone. While some pyrolysis processes (e.g., low-pressure fast pyrolysis) produce products in vapor form, these products become liquids as they cool. Gasification, on the other hand, seeks to maximize carbon monoxide and hydrogen-rich mixtures that remain in the gaseous state. The gaseous products can be used directly as fuel gas (e.g., in boilers or kilns), or as synthesis gas to be upgraded to value-added products such as ammonia, methanol, or other alcohols. Char, and sometimes liquid tar, are also produced in the gasification process. A distinguishing characteristic of gasification from other thermal technologies is that such by-products are of low-yield and limited economic significance.

Gasification can produce gases with a wide range of compositions depending on the thermal conversion process used. The DOE program in the 80's emphasized those that produce a medium-Btu gas (Biofuels and Municipal Waste Technology Program, 1988). Research on gasification in the United States has focused on the use of wood as the feedstock, rather than MSW, although interesting work has been done in crop residues. Of the four medium Btu processes that have received the most attention in the United States, only the process developed by Battelle Columbus Institute has been tried with MSW (Hopper et al., 1983, Onischak et al., 1988).

- The process developed by Battelle Columbus Institute uses two fluidized beds in so-called indirect gasification. The feedstock is gasified in the first bed using hot sand as the heat source. Hot char from the gasification process is sent to the second bed where it is burned to heat the sand, which is then cycled to the first fluidized bed to serve as a heat source. (Feldmann and Paisley, 1988; Biofuels and Municipal Waste Technology Program, 1988; Walter, 1990)

- The second process, developed at the University of Missouri-Rolla, is an indirectly-heated, fluidized bed reactor that uses an internal, fire-tube heat exchanger as a heat source, and feedstock such as mixed paper, plastic, wood, and demolition waste (Diebold and Stevens, 1990; Walter, 1990; Biofuels and Municipal Waste Technology Program, 1988). MTCI has researched improving the heat transfer in this design by using a pulse combustor to increase combustion gas velocity (Durai-Swamy et al., 1988; Diebold and Stevens, 1990).

- The third process, developed by the Institute of Gas Technology, utilizes a directly heated, pressurized fluidized bed reactor that can use air or pure oxygen as a partial combustion atmosphere (Biofuels and Municipal Waste Technology Program, 1988; Walter, 1990). This research was conducted using woody biomass as the primary feedstock.

This reactor is to be scaled up to 50-100 tons/day for the purpose of an integrated- gasification, combined-cycle turbine demonstration.

- The fourth process, developed by the Solar Energy Research Institute (now the National Renewable Energy Laboratory) and SynGas, Inc., uses a high-pressure, moving-bed gasifier, known as a downdraft gasifier, because oxygen or air enters from the top to burn volatile oils and push gas downwards (Reed, 1984; Biofuels and Municipal Waste Technology Program, 1988; Walter, 1990).

One other process, in an early stage of scale-up, uses a catalyst in an autoclave reactor to gasify high-moisture feedstock (Butner et al., 1988; Biofuels and Municipal Waste Technology Program, 1988). Numerous studies of air gasification, many by private companies, have aimed at small-scale, low-Btu gas for use in boilers, kilns, driers and internal combustion engines. (Reed & Das, 1988)

All gasification products are contaminated with various levels of tar, oil, char or ash particles, and condensed organics. These impurities can interfere with many of the uses of the produced gas. However, equipment such as scrubbers or cyclones may be used to remove tars and particulate matter. Another method for destroying these impurities is the catalytic partial oxidation of the gas in a fluidized bed combustor (Mudge et al., 1988; Biofuels and Municipal Waste Technology Program, 1988; Walter, 1990), or steam reforming in line.

## 7.2 Technology Status

Most of the applications of gasification technology have been developed in research projects that focused on the gasification of woody or other biomass, rather than MSW (Garg et al., 1988; Stevenson and Johnston, 1990; Solantausta and Kurkela, 1989; Bulpitt and Rittenhouse, 1989). One reason MSW has not been as popular as other forms of biomass is the inherent difficulty of handling, conveying, storing, and shredding MSW (Buekens and Schoeters, 1986). Nonetheless, pilot projects utilizing municipal refuse as a fuel source in fluidized bed gasifiers are being considered (Larson and Rundstrom, 1989). The DOE sponsored research on the production of fuels through its Biomass and Municipal Waste Technology Division (Diebold and Stevens, 1990). Gasification of biomass to produce medium-energy gases for methanol synthesis and a fuel gas for combustion turbines is still being researched by the new Offices of Utility Technologies and Transportation Technologies. A pilot plant demonstration project is planned in which the DOE will share the cost of development with a private firm (Diebold and Stevens, 1990). A number of gasification projects have been started around the world, including European countries, Japan, and the United States.

A Japanese company has commercially developed the PUROX system of gasification, a technology originally developed by Union Carbide Corporation. This process thermally decomposes refuse by use of partial combustion in oxygen, recovers the purified gas, and collects the inorganic residue in the form of slag. The system can be operated under two designs: wet process and dry process. The wet process recovers the gas after purification by means of a scrubber, electrostatic precipitator and condensor. The dry process burns the gas and vaporizes and oxidizes the wastewater from the refuse by utilizing the combustion heat of the gas. (Yasui and Masuda, 1981)

## 7.3 Description of RD&D Needs

Sections 7.3.1 through 7.3.7 describe the RD&D needs for gasification that were identified by the panel of technical experts (listed in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 27) that is used in later sections when the RD&D needs are prioritized and discussed. Section 7.3.8 describes RD&D issues that were identified in the literature review, but were not subsequently accepted by the panel of technical experts. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs in Section 7.3.8 are not prioritized or discussed further.

### 7.3.1 General

As new approaches are conceived for improving gasification technology, it is essential to have a comprehensive historical context in which to place the likelihood of success or failure. It is also important to juxtapose gasification with other technologies commonly viewed as more viable. Research is needed to:

1. Compare gasification and combustion and document history of gasification efforts.

### 7.3.2 Feeder Systems

MSW is commonly pre-processed before undergoing gasification. Work continues, however, to modify fuel handling capabilities for less pre-treated MSW rather than RDF pellets (Rensfelt and Ekström, 1989). The influence of short-term feed variation on process control in relation to various RDF feedstocks needs study (Onischak et al., 1988). Further research on feeder systems is needed to:

2. Develop reliable high pressure feeding systems;

3. Develop reliable low pressure feeding systems; and

4. Develop feedstock preparation systems for gasification.

### 7.3.3 Gasifier Design

Gasifier system design is critical to the efficient recovery of gas from waste. Across the industry, the development of more efficient, more durable industrial gasifiers will improve the cost-effectiveness of this technology (Miles and Miles Jr., 1989). Although the literature has reported that gasification has helped solve slagging and emission problems from biomass combustion in fluidized-bed systems, many design improvements can still be made. Research into the actual mechanisms involved in the gasification of biomass and pelletized RDF is being performed at the National Renewable Energy Laboratory (NREL) and the University of Washington (Diebold and Stevens, 1990). Understanding is still weak in the development of pressurized RDF gasification, where little is known about gas cleanup and ash disposal. Research is needed to:

5. Conduct fundamental gasification design studies.

Additional gasification process research has centered around optimizing the combination of pressure, temperature, and feed rate during gasification, but little understanding yet exists on the relationships between gasification efficiency and temperature and pressure (Onischak et al., 1988). Such an understanding is significant because residence times at various temperature ranges will alter the character of vapor condensates (Diebold and Stevens, 1990). Research into these relationships is being conducted to produce more precise energy balances and increase unit output (Larson and Rundstrom, 1989). Additional gasifier design research is needed to:

6. Study mineral matter behavior (e.g., catalytic effects,corrosion, erosion, deposition, phase behavior, agglomeration); and

7. Conduct process development studies at an intermediate scale.

With the fluidized bed design, one of the major issues has been how to transfer the heat required to pyrolize the biomass into the bed (Diebold and Stevens, 1990). Fluidized bed research has also involved indirect heating through heat-exchange surfaces immersed in the bed (Diebold and Stevens, 1990). A promising gasification technique is an indirectly heated, fluidized-bed, steam gasification process employing pulse-enhanced (resonating gaseous) heat transfer (Durai-Swamy et al., 1990; Durai-Swamy et al., 1989). Data in the literature suggest that an order of magnitude increase in heat transfer over that attained with conventional turbulent flow can be achieved through the use of pulsed combustion (Diebold and Stevens, 1990).

Research also is continuing in developing the best bed configuration in the fluidized-bed design. For the single-stage, fluidized-bed gasifier, further investigation into optimizing operating conditions has been recommended to achieve complete carbon conversion (Onischak et al., 1988). Multiple fluidized beds are being developed to burn and catalytically crack tars and hydrocarbons (Buekens and Schoeters, 1986). Research is also being conducted on a circulating fluidized bed gasification system (Rensfelt and Ekström, 1989).

Research into improvement of vertical shaft gasifiers continues, but progress has been limited. Despite careful calibration of the feedstock, vertical gasifiers experience problems with channeling, bridging, slag accretions, blowhole formation and peripheral fire. These problems become more severe and reduce the gas quality when the diameter of the shaft increases. Additionally, the mixing of unreacted hot air and gas causes small explosions. Heterogeneous materials such as unshredded refuse compound these problems. Research is needed to improve the partial combustion of MSW in vertical shaft gasifiers (Miles and Miles Jr., 1989; Buekens and Schoeters, 1986). Research is needed to:

8. Characterize a large-scale (100 tpd) cost-shared demonstration project;

9. Develop improved evaluation and measurement procedures; and

10. Develop and evaluate materials of construction.

### 7.3.4 Gas Processing

There is a strong need to improve the Btu value and quality of the off-gas generated from gasification. A better gasification reactor and gas conditioner need to be developed to produce a cleaned gas that can be used in boilers and other process heat equipment without risk of damage to either the equipment or the process (Temple-Pediani, 1983; Miles and Miles Jr., 1989). Research continues on improving the Btu content of the gas by employing such technologies as fluidized bed design (Koontz et al., 1984). There is also a need to better monitor partial combustion conditions in the gasifier to minimize fluctuations in off-gas calorific value and yield (Temple-Pediani, 1983). Further gas processing research is needed to:

11. Improve purity, uniformity and composition of product gases.

The use of catalysts in fluidized-beds is being investigated to cleanse generated gas (i.e., remove tars and particulate matter) and produce higher Btu product gases (Diebold and Stevens, 1990; Walter, 1989). Research also has been planned to evaluate the durability of selected catalysts in gas clean-up applications. Successful demonstration has been performed for the catalytic conversion of tars and ammonia simultaneously with absorption of hydrogen chloride at about 800° C using dolomite as a catalytic and absorbing agent (Rensfelt and Ekström, 1989). It has been reported that research is needed on maintaining the proper temperature, in the BKMI tar cracking process, because efficient tar cracking in has an adverse effect the heating value of the product gas by adding air to destroy tar (Buekens and Schoeters, 1986). NREL has initiated a study to screen different catalysts for the reduction of residual pyrolytic tars (Diebold and Stevens, 1990). Research into multiple fluidized beds is being conducted to determine whether they are the most effective means to burn and catalytically crack tars and hydrocarbons (Buekens and Schoeters, 1986). Other gas-cleaning technologies may be more technically and economically feasible. Thus, further research is needed to:

12. Develop catalysts to crack tars and hydrocarbons;

13. Develop and improve particulate removal systems (high and low temperature);

14. Develop methods to control nitrogen and chlorine containing compounds; and

15. Evaluate conventional gas clean-up methods.

### 7.3.5 End Use Applications

To become commercially viable, a market must exist for gasification products (Buekens and Schoeters, 1986). All potential application avenues should be pursued, which leads to the following list of research needs:

16. Evaluate use of product gas in fuel gas burners;

17. Evaluate use of product gas in gas turbines;

18. Evaluate use of product gas in internal combustion engines;

19. Evaluate use of product gas in industrial pipelines;

20. Evaluate use of product gas for chemical synthesis; and

21. Evaluate use of product gas for fuel cells.

### 7.3.6 Environmental Considerations

To meet changing air quality standards, gasification systems must more efficiently and more completely control emissions of fine particulate matter, nitrogen oxides, carbon monoxide, and organics (Miles and Miles Jr., 1989; Buekens and Schoeters, 1986). Issues involving all aspects of discharges and residue management need full attention to avoid even the perception of potential danger to human health or the environment. Thus, research regarding environmental risks is needed to:

22. Study residual solids management;

23. Investigate controlling air emissions;

24. Study waste water management; and

25. Study waste gas disposal (e.g., chlorides, nitrogen and sulfur compounds, and volatile organics).

### 7.3.7 Technology Transfer

Published studies of the technical and economic feasibility can have a significant impact on the success of gasification. These studies can be taken a step further and be used as decision-making tools. Research is needed to:

26. Conduct process integration systems analysis; and

27. Conduct economic analysis for end use applications.

### 7.3.8 Other Potential RD&D Topics

The following RD&D needs were identified in the literature review, but were not subsequently accepted by the panel of technical experts.

Better characterization of the feedstock and its gasification kinetics may be necessary to make accurate design assumptions. For example, because of the heterogeneous nature of MSW, and thus of RDF, the full range of RDF char reactivities for proper gasifier design could be investigated (Onischak et al., 1988).

The fuel source used for gasification affects the entire processing system design. A possible key feedstock need is to develop feedstock with higher energy density (more lignin) and less moisture (Walter, 1989). Although MSW may generate more toxic emissions than

other forms of biomass and contain a greater amount of noncombustible material that can cause slagging, the availability of MSW and the cost of its disposal may make it an attractive gasification fuel (Temple-Pediani, 1983; Miles and Miles Jr., 1989). Other potential RD&D topics identified in the literature review include the following:

- Continued development of a microprocessor-controlled gasifier has been recommended to better respond to fluctuations in the feedstock that can yield variable off-gas (Temple-Pediani, 1983);

- More efficient and accurate methods of designing and developing a facility/process could be developed (Buekens and Schoeters, 1986);

- More research could be directed towards optimizing updraft and downdraft gasifier configurations (Temple-Pediani, 1983).

## 7.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on gasification (listed in Appendix A) are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making gasification technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. After a final priority had been assigned to each RD&D need, the gasification panel members categorized the needs as being essential, high priority, medium priority, or low priority. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 7-1, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 7.3 is in the right-hand column. The rationale discussed by the panel of technical experts is summarized below. The rationale tend to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

### Essential RD&D Needs

The panel judged documenting the developmental history of this technology and comparing it to other technologies (No. 1) an essential item because it has a low cost that would provide high benefit. One major focus of such a comparison would be why gasification is preferable to combustion. The group felt that, without proving the merits of gasification over combustion, it would be difficult to justify requests for further RD&D spending on gasification.

### High Priority RD&D Needs

The high priority needs were viewed as such in the belief that they represented the foundation for further RD&D activities. They emphasize gas processing. According to the panel, it is more important initially to get a gasifier that produces the type of desired products, rather than cleaning up the product. Over the 5-10 year period, the panel felt that MSW would continue to yield a gas product that is too dirty for synthesis of value-added products. The

## Exhibit 7-1. Prioritized RD&D Needs for Gasification

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **Essential** | |
| 100 | Compare gasification and combustion and document history of gasification efforts | 1 |
| | **High Priority** | |
| 95 | Conduct process development studies (intermediate scale) | 7 |
| 90 | Develop reliable high pressure feeding systems | 2 |
| 80 | Fund large-scale (100 tpd) cost-shared demonstration project | 8 |
| 70 | Conduct fundamental gasification studies | 5 |
| | **Medium Priority** | |
| 65 | Develop and improve particulate removal systems (high and low temperature) | 13 |
| 65 | Develop methods to control nitrogen, chloride, and alkali compounds | 14 |
| 60 | Conduct economic analysis for end use applications | 27 |
| 50 | Develop catalysts to crack tars and hydrocarbons | 12 |
| 50 | Conduct process integration systems analysis | 26 |
| 50 | Study residual solids management | 22 |
| 50 | Study mineral matter behavior | 6 |
| 45 | Evaluate use of product gas in gas turbines | 17 |
| 45 | Study waste water management | 24 |
| 40 | Improve purity, uniformity, and composition of product gases | 11 |
| 40 | Evaluate use of product gas for chemical synthesis | 20 |
| 40 | Study waste gas disposal (e.g., chlorides, nitrogen, sulfur, VOCs) | 25 |
| 35 | Evaluate use of product gas in fuel gas burners | 16 |
| 35 | Control air emissions | 23 |
| | **Low Priority** | |
| 30 | Develop improved evaluation and measurement procedures | 9 |
| 30 | Develop feedstock preparation systems for gasification | 4 |
| 30 | Develop and evaluate materials of construction | 10 |
| 30 | Develop reliable low pressure feeding systems | 3 |
| 25 | Evaluate use of product gas in internal combustion engines | 18 |
| 25 | Evaluate use of product gas for fuel cells | 21 |
| 25 | Evaluate conventional gas clean-up methods | 15 |
| 20 | Evaluate use of product gas in industrial pipelines | 19 |

panel also felt that the major application is likely to be electricity generation. The panel also suggested that small to moderate-scale process development (No. 7) studies are needed before a large-scale demonstration project (No. 8) should be attempted. A subsequent large-scale demonstration project (on the order of 100 tpd) could then be built to encourage investment in gasification. According to one panelist, had more investment in feeder systems (No. 2) been made years ago, gasification would be much further along today. The panel emphasized the benefits of high pressure feeder systems over low pressure feeder systems. Fundamental gasification studies (No. 5) should include kinetics, thermodynamics, tar destruction, pyrolysis properties, etc.

**Medium Priority RD&D Needs**

The panel felt that all of the medium priority issues had considerable merit and were legitimate RD&D needs in making gasification technologically viable. They were not considered as important as the essential or high priority items, but were still worthy of funding. The use of catalysts to crack tars and hydrocarbons (No. 12) was viewed as far from commercial use at this time. The panel determined that catalyst research should move forward, but not at the cost of other needs that may show more benefit. The group agreed that more remains to be understood about mineral matter behavior in gasification (No. 6), stating that compounds thought to be volatile may not be, while other compounds may have catalytic properties. Most of the end-use application projects (Nos. 16, 17, and 20) were rated medium-to-low since their scope is difficult to define now when the technology is not fully developed. This is likely to change in the future.

The group did see an incentive to better develop end-use applications, to demonstrate beneficial waste recovery methods other than direct combustion. The technology transfer issues (Nos. 26 and 27) are important since the results of these studies, particularly the economic feasibility studies, can be used as decision-making tools. The group felt that other process issues ranked higher than gas processing (Nos. 11, 13, and 14) because it is most important initially to get a gasifier that produces a desired product rather than cleaning up the product. Environmental issues (Nos. 22 to 25) were seen as higher priority by some panel members who felt that waste management systems could become a critical factor in facility siting issues. In general, however, the group felt that environmental concerns were not a highly significant problem.

**Low Priority RD&D Needs**

Many of these items were considered low priority because they dealt with end uses of gas created by gasification (Nos. 18, 19, and 21). The panel members felt it was more important to perform RD&D on the actual gasification process itself, before starting RD&D on the products of the process. Feedstock preparation (Nos. 4 and 3) was not rated highly because it is being researched in some form by virtually all of the other technologies. Improvements in gasifier construction materials and design (Nos. 9 and 10) were not viewed as high priority relative to improving other process areas. Cleaning up the gas product (No. 15) was not as important as producing the gas.

## 7.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate gasification with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of RD&D Program

The panel predicted that the RD&D program cost would be on the order of $15 to $20 million for a 100 tpd demonstration project and $250 to $500 million for a pioneer commercial project (the size of the facility was not discussed).

### Difficulty of Technology Development

While the technical process itself has a relatively low risk, there is significant overall risk. There are major problems in the areas of feedstock, conversion technologies, and product quality. There is little likelihood for any large unit development in the near term, with nothing major expected before the year 2000. It will be at least five years before a demonstration project is produced.[1]

### Commercial Development Risk

The panel viewed commercial development risk as very high. The greatest commercial development opportunities will spring from any environmental advantages that gasification will have rather than its potential as a competitive energy source. Although the technical risks are low, the public image and political acceptability are also very low (not much better than combustion) as a result of current emissions problems. On a competitive market basis, it will be very difficult to compete with pipeline gas. There is a potential, however, for large markets with a specific product niche. Development of these niches would require significant investment beyond RD&D, probably double that of combustion (although after the second, it may be cheaper than new combustors with emissions controls). A commercially viable facility would be "high tech" with a very high throughput per ton produced.

### Flexibility

Gasification is very flexible, but not to the same degree that mass-burn is. It may be compatible with large parts of the MSW input stream, but gasification cannot handle items such as car batteries, refrigerators, etcetera. This technology would not be practical on a small scale, with 150 tpd being an absolute minimum for viability.[2]

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[1] One reviewer stated that there is a 200 ton/day gasification facility in Greve, Italy, a larger gasification facility operating in Japan, and a gasification facility being planned in California.

[2] One reviewer believes that this is unsubstantiated and that smaller gasifiers make more sense than small incinerators.

### Cost of the Energy Produced

The potential exists that gasification would be incrementally cheaper than some other technologies, such as mass-burn combustion, with respect to energy production costs.

### Net Energy Benefit

The panel believes that gasification could be 1.5 times more efficient than mass-burn combustion at extracting energy from given amount of MSW.

### Human Health and the Environment

The panel expected that gasification poses an equally low, or even less of a human health risk than mass-burn combustion. The panel believed that gasification would be better environmentally than mass-burn combustion because there are fewer dioxins, everything can be cleaned before it is burned, there is less air pollution since cleaner gas goes into burners, and there should be less of a particulate and flue gas problem.

### Occupational Health and Safety

The panel felt that gasification would compare similarly with mass-burn combustion in terms of occupational health and safety.

### Appropriateness for Government Funding

Gasification was viewed by the panel as very compatible with existing regulations and appropriate for DOE funding.

# 8. LANDFILL GAS

## 8.1 Technology Description

The natural process of anaerobic microbial degradation converts the organic fraction of MSW to methane gas ($CH_4$) and carbon dioxide ($CO_2$). This gas may be captured and utilized as a fuel, either directly or following purification. Section 8.1 discusses the natural process through which landfill gas is produced and then describes technologies to recover and purify this gas.

### 8.1.1 Microbiology of Landfill Gas Generation

The anaerobic decomposition of complex organic material is generally described as a three-stage process. Rather, complex organic material is hydrolyzed. Cellulose, fats, proteins, and carbohydrates are hydrolyzed. These end products are usually organic fatty acids. The second stage of methane fermentation involves consumption of the organic fatty acids facilitative acedogenic bacteria to aectif acid, CO and $H_2$. Then methanogenic bacteria, which are strictly anaerobic, convert the acids into methane and carbon dioxide.

The phases of methanogenesis in a landfill were described by Farquhar and Rovers in 1973 and modified by Rees in 1980. These five phases are as follows: (1) the aerobic phase (lasting several days to weeks) in which oxygen is present from the time of waste placement and carbon dioxide is the primary gas produced; (2) anaerobic nonmethanogenic phase existing once the oxygen has been depleted with significant amounts of carbon dioxide and some hydrogen is produced; (3) anaerobic methanogenic unsteady phase in which methane production is initiated and carbon dioxide production decreases; (4) methanogenic steady state phase in which the greatest quantity of high quality methane gas is produced and the composition and rate of gas production remain essentially constant under constant conditions; and (5) transition from anaerobic back to aerobic. (U.S. EPA, 1991)

The process of landfill gas production is dynamic; the success of any one phase depends on the creation of a suitable microbiological environment for the change to occur. Many landfills are capable of producing commercially recoverable quantities of methane gas without enhancement measures being taken. Landfill conditions, such as pH, moisture level, and waste density, may be modified, however, in order enhance the rate and quantity of methane generation.

### 8.1.2 Landfill Gas Recovery and Pretreatment

Methane gas is typically removed from landfills using methods similar to those used in extracting ground water. Wells, typically lined with a perforated casing and packed with sieved gravel, are drilled into the landfill or installed during landfill construction. Pumps are manifolded to the wells, creating a pressure gradient within the landfill which draws the gas into a collection system. The collection system brings the recovered gas to a common collection point where the gas may be utilized or stored for upgrading. (Scaramelli, 1979)

Extracted gas can be burned to generate process or space heat, steam, and electricity; fuel suitably modified gas engines or turbines to produce electricity; or can be purified and upgraded to pipeline quality gas for sale to the pipeline system. Purification, or pretreatment,

generally consists of drying the gas and removing carbon dioxide, hydrogen sulfide (if present is in trace amounts) and other gases from the methane. Exhibit 8-1 shows a process schematic for a typical landfill gas removal and upgrading system. The type and level of treatment necessary is determined by the characteristics of the gas, which tend to vary among individual landfills. (Scaramelli, 1979; Krol and Dent, 1989)

## 8.2 Technology Status

There are landfill gas recovery facilities throughout the world; most, however, are located in the United States, Germany, and the United Kingdom (Fletcher, 1989). According to a recent study by Government Advisory Associates Inc., 157 U.S. landfills now recover or plan to recover landfill gas. Of these 157 landfills, about 82 percent (129 landfills) have operational landfill gas collection systems and 69 percent (108 landfills) in 32 states have operational energy recovery systems (ENR, 1991). Exhibit 8-2 summarizes the status of landfill gas collection systems in the U.S.

Most landfill gas recovery systems are in the western states (38 percent), while the fewest systems are in the north central states (17 percent). California leads all states with 50 facilities. Over half of the landfill gas recovery projects in the U.S. are owned by public-sector entities. (ENR, 1991)

More than 67 percent of all facilities generate or plan to generate electricity, while the remainder collect and refine medium Btu gas and sell it to a direct user, produce near pipeline quality gas, co-produce electricity and medium Btu gas, and make synthetic fuels. The projects reporting data to Government Advisory Associates Inc. process a total of 381.4 million cubic feet per day of landfill gas (ENR, 1991).

There has been extensive research in the area of landfill gas recovery both in the United States and in several European countries. The U.S. Department of Energy has funded landfill gas recovery research since 1978, and the U.S. Environmental Protection Agency has funded research relating to landfill gas for more than 25 years. Internationally, the United Kingdom Departments of Energy and Environment have had large programs in landfill gas research for the last six to seven years, including a full-scale field test cell project. In Sweden, there are currently three full-scale field test cell projects and numerous smaller-scale research activities. West Germany has over 50 commercial landfill gas recovery facilities supported by 15 years of research. The United Kingdom Department of Energy counted 242 commercial landfill gas recovery facilities worldwide in 1989. (Bogner, 1991)

## 8.3 Description of RD&D Needs

As in the past, much of the recent and current research on landfill gas technology has focused on enhancing the production and recovery of gas from landfills while controlling potential health and environmental effects of landfill gas exploitation. RD&D needs in landfill gas technology have been identified in four major areas: (1) gas generation; (2) gas extraction; (3) pretreatment; and (4) health and environmental protection. Sections 8.3.1 through 8.3.4 describe the RD&D needs for landfill gas that were identified by the panel of technical experts (listed in Appendix A). Each RD&D need has been assigned a reference number for easy identification. Section 8.3.5 describes an RD&D topic that was identified in

**Exhibit 8-1. Process Options for a Typical Landfill Gas Recovery System**

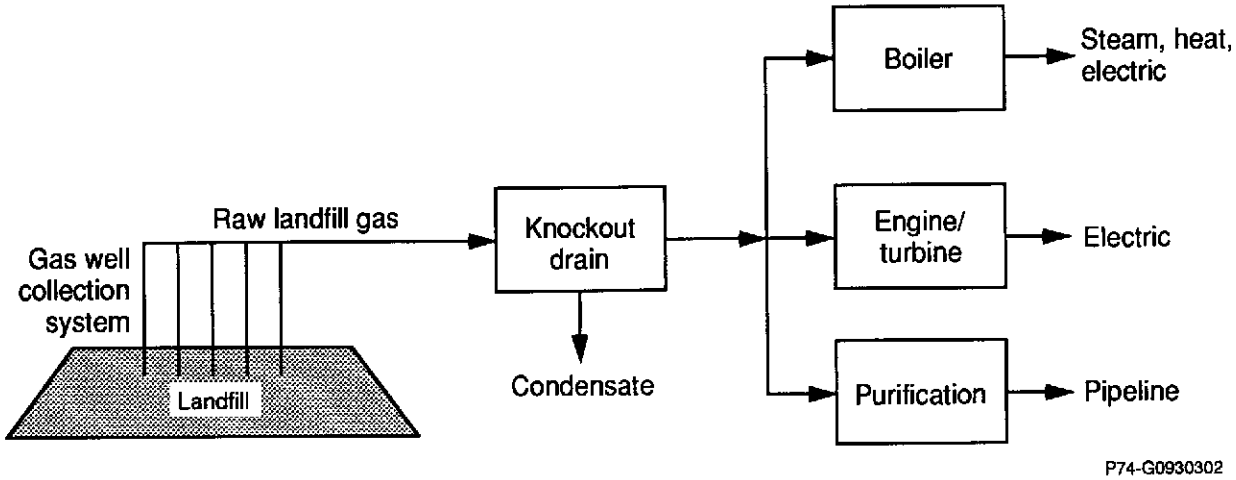


**Exhibit 8-2. Status of U.S. Landfill Gas (LFG) Collection and Recovery Systems**

| | Landfill Gas Collection Systems | Landfill Gas Energy Recovery Systems |
|---|---|---|
| **Operating** | 129 | 108 |
| **Planned** | 18 | 49 |
| **Total** | 157 | 157 |

Source: (ENR, 1991)

the literature review (see the introduction chapter), but was not subsequently accepted by the panel of technical experts. This topic is not prioritized or discussed further.

### 8.3.1 Gas Generation

A number of researchers have identified a need for further study of the landfill gas generation process in order to determine the maximum rate of gas production in the field and to evaluate measures for enhancing gas production.

**Understanding Gas Generation and Methane Oxidation**

Significant work has been done toward understanding the landfill gas generation process. For example, the Food Research Institute of the United Kingdom, in collaboration with the University of Oregon, planned to investigate the potential for enhanced gas production through optimizing degradation of the lignocellulosic (woody cell) fraction of MSW. This work was viewed as a forerunner to further fundamental studies of the degradation process (Krol and Dent, 1989). A basic understanding of the microbial ecology of landfills is generally lacking (Bogner et al., 1988). This further understanding of the gas generation process would require a field demonstration process with associated laboratory support and would include studies of the effects of moisture content, waste density, and pH on methane generation and yield from a landfill. Thus, there is a need to

1. Conduct long-term research to develop a basic understanding of the gas generation process.

Methane oxidation by indigenous methanotrophic bacteria in aerated cover materials can reduce the amount of methane available to a gas recovery system as well as the amount of methane emissions. The stoichiometric equation for this process is

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

However, estimates of the amount of methane that can be oxidized by methanotrophic bacteria vary widely. According to one panelist, field and laboratory work conducted by Hoeks (1972) suggests that virtually all methane in soil gas in the vicinity of a leaking natural gas line

can be converted to carbon dioxide by indigenous microbes. Laboratory work by Mancinelli and McKay (1985), however, indicates that a maximum of about 10 percent of the methane in a simulated landfill gas mixture is consumed by methanotrophic bacteria. Previous work (Mancinelli, et al., 1981) has shown that the number of methanol-oxidizing bacteria in landfill soils are proportional to the $CH_4$ concentration up to about 50 percent methane. The role of limiting variables, such as moisture, oxygen, and nutrients upon methanotrophic activity in soils needs to be better understood. RD&D is needed to

2. Develop a basic understanding of methane oxidation.

Additional work is also needed to assess the effects of changes in the waste stream on the quality and quantity of landfill gas generated. For example, if present in sufficient concentrations, certain trace components of landfill gas may produce corrosive or abrasive effects in the gas extraction and combustion equipment or have negative human health and environmental effects. (Dent et al., 1986) Also, changes in the composition of the waste stream affect the presence of minor components of landfill gas and the methane generation potential of a landfill. Thus, the research is needed to:

3. Identify the source and composition of minor components of landfill gas and define their corrosive and abrasive potential as well as their environmental effects (including their effect on human health and global warming); and

4. Determine the effect of waste stream composition changes (due to such practices as recycling and composting of various components of the waste stream) on methane generation potential.

**Evaluating Landfill Gas Production and Potential Production**

Very little information is available regarding the potential yield of landfill gas in practical situations, primarily because no gas recovery schemes have been continued through to the end of the degradation process. Little work has been done toward determining the maximum rate of gas production that may be achieved in the field. (Fletcher, 1989) Thus, research needs include the following:

5. Develop field techniques for evaluating actual gas generation and the percentage of gas that is recoverable; and

6. Develop field techniques for evaluating potential gas generation from a landfill.

Researching actual and potential landfill gas generation will require a field demonstration project with associated laboratory support. The results of this work will be valuable in providing guidance for the development of gas recovery systems (Bogner et al., 1988).

Several models are currently available for evaluating the gas generation rate for a landfill using site-specific input parameters. These models include the Palos Verdes, Sheldon-Arleta, and the Scholl Canyon models (simple, first order kinetic models) and the GTLEACH-I

model (a more complex model). There is a significant amount of landfill gas generation modeling being done, but the results of this modeling have not been collected and analyzed as a whole. Thus there is a need to:

7. Synthesize existing landfill gas generation modeling results into a comprehensive report.

**Enhancing Landfill Gas Generation**

Experiments have shown that controlled addition of moisture or sludge can enhance the rate of landfill gas generation. Many other techniques may also enhance landfill gas generation. Research into other areas of landfill gas generation enhancement is still needed. Research needs in this area include the following:

8. Conduct small-scale laboratory work to understand the effects of aeration and waste type on gas generation;

9. Determine optimal municipal solid waste management techniques in consideration of energy potential as well as environmental impacts (e.g., landfilling and landfill gas recovery versus recycling, landfilling and landfill gas recovery versus incineration, and alternative landfill design and operation requirements); and

10. Develop operational strategies for landfill gas generation management and assess the operational and environmental implications of applying these strategies (e.g., rapidly initiating gas generation, ensuring high methane content in landfill gas, stabilizing production rates over time to meet user demands, and changing leachate composition).

In addition to these enhancement strategies, leachate recirculation technologies could accelerate the rate of gas production at existing and future landfills and shorten the period in which a given quantity of gas could be recovered. Recycling leachate back into a landfill can replace lost organic acids and gas-producing bacteria, add moisture, and create a more uniform distribution of the essential ingredients throughout the landfill. (Frank et al., 1983) Development of these technologies would improve the economic feasibility of recovering and utilizing gas from smaller landfills. The recovered gas might be used on-site to produce electricity to meet the energy demand of landfill leachate treatment requirements, which could be minimized since leachate recirculation leads to chemical oxygen demand (COD) reduction. Some work has been done in New York to demonstrate landfill leachate recirculation that would accelerate methane production and reduce the need for external treatment. (Mathusa, 1989) Nevertheless, research is still needed to:

11. Demonstrate leachate recirculation techniques for enhancing landfill gas generation through a field demonstration with associated laboratory support.

### 8.3.2 Gas Extraction

Engineering designs for landfill gas extraction systems are based upon broad

engineering principles, but in many cases, these designs are not entirely satisfactory. Current landfill gas extraction system designs may be improved through the following research and technology transfer projects:

12. Study and evaluate gas extraction techniques for various landfill designs (e.g., encapsulated landfills);

13. Advance the field of hydraulic modeling of landfill gas as it relates to gas extraction (e.g., location of wells, percent capture, effect of adding a well on capture rate); and

14. Document the current state of practice in landfill gas extraction system design and operation for the purpose of technology transfer among landfill gas recovery facility operators.

### 8.3.3 Pretreatment

Landfill gas may require different levels of pretreatment depending upon the end use of the product. In addition, pretreatment requirements for energy conversion may differ from pretreatment requirements for emission control after burning. Thus, landfill gas pretreatment RD&D needs include the following:

15. Define pretreatment needs for energy conversion, including: (1) technologies to produce high quality gas; (2) technologies to produce medium Btu gas with little or no pretreatment; and (3) technologies to produce medium Btu gas with significant pretreatment; and

16. Define pretreatment needs for emission control after burning.

Both of these needs would require reviewing research and case studies on pretreatment in order to define the state of the art in pretreatment for energy conversion and emissions control and to define future pretreatment research needs.

On-going research efforts in this area include investigating technologies for converting raw gas into pipeline quality (high Btu) gas via adsorption, absorption, membrane separation, or cryogenic separation (Lailas, 1986). Current technologies to separate methane from landfill gas are commercially available and economically attractive only for very large volumes of gas. To create more viable options for smaller landfills and to achieve higher efficiencies and reduce costs, alternative gas clean-up systems may need to be developed and tested.

### 8.3.4 Health and Environmental Protection

In the past, a major concern associated with landfill gas production has been reducing the explosive hazards of laterally migrating methane (Bogardus, 1986). More recently the scope of concern for health and environmental protection has expanded to include odor and toxicity problems from volatile organic compounds (VOCs) and other organic constituents of landfill gas. MSW landfill gas contains a wide variety of trace organic compounds. More than 80 VOCs have already been identified, the most predominant being benzene, toluene, xylene, vinyl chloride, and chloroethylenes. Research is needed to identify and develop appropriate

methods to control the VOC emissions from landfills and the associated odor and toxicity problems. (Lailas, 1986)

Landfill gas emissions control is the subject of regulations proposed by the U.S. Environmental Protection Agency. EPA's Office of Air Quality Planning and Standards has recently proposed standards and guidelines for new and existing MSW landfills under provisions of the Clean Air Act. (56 Federal Register 24468, May 30, 1991) EPA's proposed rule addresses the health and environmental hazards posed by both the methane and non-methane fractions of landfill gas emissions. Landfills emitting more than 150 tons per year of non-methane organic compounds (NMOCs) would be required to design and install gas collection systems and emission control systems that achieve recovery or destruction of the NMOCs by at least 98 percent by weight. (EPA's proposed standards and guidelines attempt to avoid the administrative burden and expense of measuring all components of MSW landfill emissions by using NMOC concentration as a surrogate measure). Research needs in the area of health and environmental protection include the following:

17. Assess the environmental impact of emitted and burned landfill gas;[1]

18. Assess and document the destruction removal efficiency of, and emissions from, power generation equipment and flares;

19. Assess the environmental effects of increasing landfill gas generation rates, including effects such as changes in the quantity and composition of leachate produced;

20. Research alternate methods for control and utilization of landfill gas components (e.g., carbon dioxide); and

21. Identify sampling techniques for addressing various regulatory concerns that are easier and less expensive than current sampling techniques for non-methane organic carbons, total organics, and other organic and inorganic constituents of landfill gas (e.g., identify potential surrogate measurements for measuring one or more components of landfill gas).

### 8.3.5 Other Potential RD&D Topics

The following landfill research need was identified in the literature, but was not subsequently accepted by the panel of technical experts.

Characterize major variables affecting landfill gas movement and model gas migration. Landfill gas migration poses potentially serious threats to the environment and to human health and safety. Landfill gas can create anoxic conditions in the root zones of plants adjacent to a landfill site. Also, methane migration from disposal sites into adjacent structures, such as basements, crawl-spaces, or utility closets, has been detected and, in

[1] One reviewer believes that RD&D to quantify uncontrolled emissions from landfills with methane recovery should be given the highest priority because this information is needed to determine if enhancing degradation in landfills is environmentally desirable.

some cases, has apparently caused explosions. In order to assess the extent of problems with gas migration and prevent gas migration problems, it is important to understand how and to what extent landfill gas is transported through soil materials. (Bogner, 1988)

## 8.4 Prioritized RD&D Needs

This section presents and discusses the priorities assigned to the RD&D needs by the panel of technical experts on landfill gas (listed in Appendix A). The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need toward making landfill gas recovery technically and economically feasible as well as commercially viable. The panel reviewed, discussed, and sometimes modified the prioritized list of RD&D needs. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 8-3, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 8.3 is in the right-hand column. The rationale discussed by the panel members for ranking the high and medium priority needs is summarized below. Discussion of rationale was constrained by the limited amount of time available to the panel.

### High Priority RD&D Needs

The panel members ranked fundamental research to determine optimal municipal solid waste management techniques (No. 9) as the top RD&D need. This need is aimed at finding tho most efficient ways to manage wastes considering both energy potential and environmental impacts. The panel members felt that this kind of research may yield criteria for landfill design and operation that are more encompassing than current criteria. In many cases, current criteria are driven by the desire to minimize liability and maximize environmental protection. New research could attempt to balance energy and environmental concerns in landfill design and operation. Most of the panel members felt the results of the research could also have significant national implications, perhaps on future solid waste management regulations, and that the research is very appropriate for U.S. Department of Energy funding.

The panel members also indicated the importance of demonstrating leachate recirculation techniques for enhancing landfill gas generation (No. 11). Although much research has already been done, the panelists believed that there is a strong need for a demonstration project in this area with associated laboratory support. Some panel members felt that leachate recirculation research has a high probability of success and that a demonstration project would drive other research needs. Panelists disagreed about whether a landfill existed where the research could be done, since not many municipal landfills have been designed for leachate collection.

Determining the effect of waste composition changes (e.g. from recycling and composting) on the methane generation potential of a landfill (No. 4) is an important issue in integrated solid waste management. Understanding which segments of the waste stream are most important for methane generation from landfill will help solid waste managers determine what waste management strategies will provide the greatest energy and environmental benefits.

Finally, the panelists felt that it is important to develop field techniques for evaluating actual gas generation from a landfill and the percentage of gas recoverable (No. 5). Most of the work on landfill gas will be in retrofitting existing landfills for gas recovery. Some workshop participants believed that few new landfills would be developed in the future.

**Exhibit 8-3. Prioritized RD&D Needs for Landfill Gas**

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **High Priority** | |
| 100 | Determine optimal municipal solid waste management techniques | 9 |
| 95 | Demonstrate leachate recirculation techniques for enhancing landfill gas generation | 11 |
| 90 | Determine effect of waste stream composition changes on gas generation potential | 4 |
| 85 | Develop field techniques for evaluating actual generation and percent recoverable | 5 |
| | **Medium Priority** | |
| 80 | Develop field techniques for evaluating potential gas generation | 6 |
| 80 | Develop strategies for landfill gas generation management and assess the impacts | 10 |
| 75 | Conduct long-term research to understand basic landfill gas generation process | 1 |
| 60 | Conduct lab work on effects of aeration and waste type on landfill gas generation | 8 |
| 60 | Identify source and composition of minor landfill components and define effects | 3 |
| | **Low Priority** | |
| 55 | Document the current state of practice in landfill gas system design and operation | 14 |
| 55 | Assess the environmental effects of increasing landfill gas generation rates | 19 |
| 45 | Define pretreatment needs for energy conversion | 15 |
| 45 | Identify alternative sampling techniques to address regulatory concerns | 21 |
| 40 | Define pretreatment needs for emission control | 16 |
| 35 | Advance the field of hydraulic modeling of landfill gas as it relates gas extraction | 13 |
| 35 | Assess the environmental impact of emitted and burned landfill gas | 17 |
| 30 | Develop a basic understanding of methane oxidation | 2 |
| 30 | Study and evaluate gas extraction techniques for various landfill designs | 12 |
| 25 | Synthesize existing landfill gas generation modeling results | 7 |
| 25 | Research alternate methods for control and utilization of landfill gas components | 20 |
| 15 | Assess and document destruction removal efficiency and emissions | 18 |

### Medium Priority RD&D Needs

The panel members identified the need to develop field techniques for estimating potential gas generation from a landfill (No. 6) as a medium priority, only slightly less important than developing techniques for estimating actual landfill gas generation. Panelists

ranked the need to develop strategies for gas generation management (No. 10) in the same position as need No. 6., despite disagreement among panel members about its importance. Some panelists felt that specific operational decisions are made on a case-by-case basis in the field, thus limiting the value of this research. Other panel members, however, believed that little effort has been made to develop and disseminate information on enhancement management and felt that this work could have a substantial benefit.

The panelists felt that conducting long-term research to understand the basic landfill gas generation process (No. 1) is a long-term project that will not yield quick results. However, most panel members saw the research as creating a foundation for other landfill gas research.

The panel members gave a wide range of scores to conducting laboratory work on the effects of aeration and waste type on gas generation (No. 8). Some panelists assigned this need a low priority because they believe a lot of studies have already been completed in this area. Despite this work, other panelists felt that more field studies are needed. Similarly, panel members believed that the source and composition of minor landfill gas components and their corrosive, abrasive, and environmental effects (No. 3) had already been researched to some extent, but there was room for additional work to be done.

### Low Priority Needs

The panel assigned scores of 55 or less to 12 needs. The low priority assigned to these needs was based, in general, on (1) the fact that work on the subject was already completed or underway; (2) the low probability of successful research in the area; or (3) the inappropriateness of the research for Department of Energy funding.

## 8.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate landfill gas recovery with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The panelists for the landfill gas workshop provided rough cost estimates for a field demonstration project and a laboratory research project (encompassing the RD&D needs identified as requiring field and laboratory work). The field demonstration would be a 5 to 10 year project costing $1 to $3 million. First year construction costs would be a major component of the overall cost of the project. In years two through five, the program's monitoring costs would be likely to decrease. If a 10-year demonstration project were undertaken, it would include additional replacement and repair costs. The laboratory research program would be a two-year project costing approximately $100,000 to $125,000 per year.

### Difficulty of Technology Development

The panel members believed that a research program in the landfill gas recovery area is timely because the waste stream is changing and solid waste management decisions are being made now by cities and states without regard to research into energy recovery. For example, landfill cover requirements are creating drier landfills and driving landfill gas generation rates down, but the impact of drier landfills on potential for landfill gas recovery on the entire waste management system is not considered in the development of cover requirements.

In addition, assessing the timeliness of the RD&D program, the panel members characterized the technology risk for this program as low.

### Net Energy Benefit

Panel members believe that pursuing landfill gas enhancement RD&D may yield significant net energy benefits.

### Human Health and the Environment

An RD&D program in the landfill gas area may have significant benefits to human health and the environment. These benefits include reduction of methane -- a greenhouse gas -- through improved collection processes, reduction of odor due to odor controls, improved leachate control, shortened time for waste decomposition due to gas generation enhancement, reduced leachate strength, improved groundwater quality, and landfill life extension through volume reduction.

### Appropriateness for Government Funding

The panelists agreed that a landfill gas RD&D program is very appropriate for U.S. Department of Energy funding.

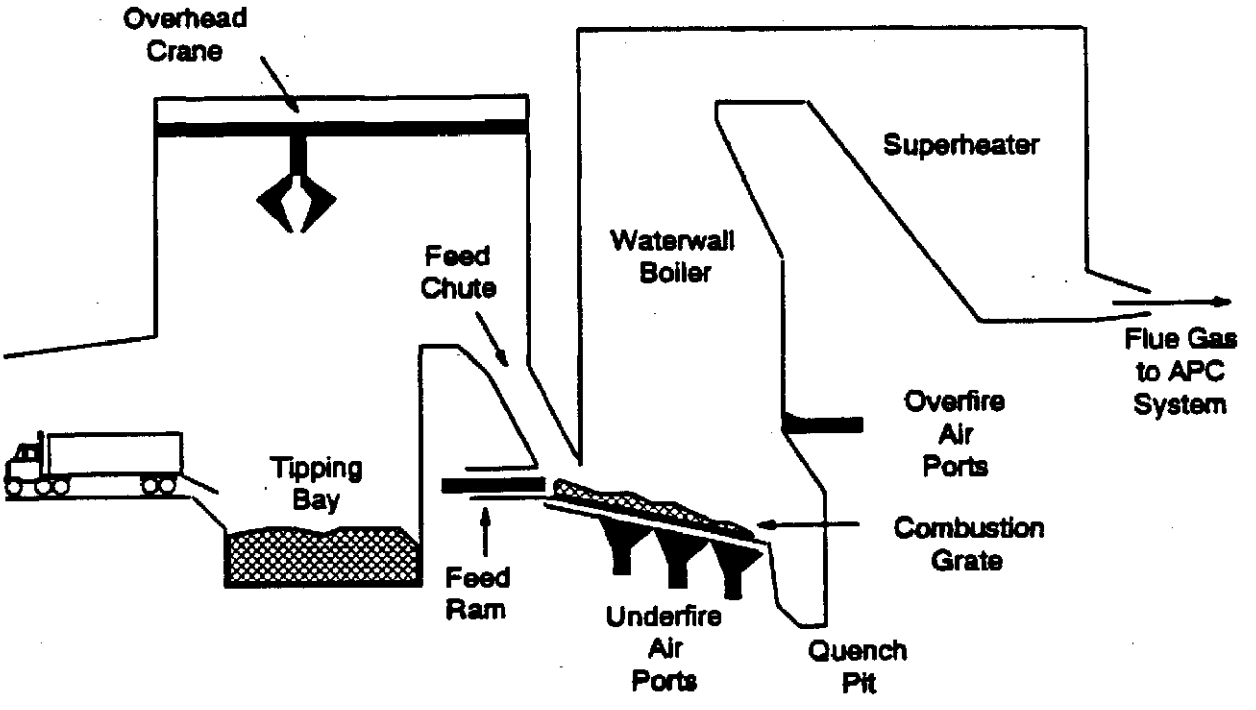
# 9. MASS-BURN COMBUSTION SYSTEMS

## 9.1 Technology Description

Mass-burn waste-to-energy systems* accept refuse that has typically undergone little preprocessing other than the removal of oversized items and whatever source separation activities the community undertakes. To recover energy in the form of steam, these facilities burn the refuse in a single combustion chamber under conditions of excess air (i.e., more air than is needed for complete combustion. Most modern mass-burn combustors burn refuse on an inclined, moving grate system which mixes the waste with air. Some systems, however, utilize a rotary kiln rather than a grate system to accomplish this agitation.

In a typical modern mass-burn combustor (see Exhibit 9-1), MSW is dumped directly into a receiving pit or tipping bay. This area is usually enclosed to eliminate flying debris and odors. An overhead crane (or cranes) mixes the MSW to more even distribute combustible materials and moisture, and to remove oversized items. The crane then moves MSW from the receiving pit into a furnace feed (charging) chute or hopper. From the feed chute, MSW is continuously fed to the grate system, typically using a hydraulic ram. The purpose of the grate system, for which there are a number of designs, is to move MSW through the combustion chamber with a tumbling motion that encourages more rapid ignition, more complete combustion, and transformation of the MSW to ash.

**Exhibit 9-1. Schematic of a Typical Mass-Burn Combustor**




*There are two types of mass-burn systems: modular, which is fabricated in a factory, and field-erected.

Air is introduced to the chamber from above and below the grate system. Underfire or combustion air, introduced below the grate system, initiates combustion and keeps the grate system cool. Overfire or secondary air, introduced above the grate system and fuel (MSW) bed, helps mix the gases emitted and continue their combustion. Noncombustible material and residual ash fall from the grate system and are transferred into a residue or quench pit where they are water-quenched.

Energy is recovered from the hot combustion flue gases in a waterwall boiler. Boilers are often combined with superheaters and economizers in order to increase energy recovery efficiency. The waterwalls are made of steel tubes welded together to form a continuous, gas-tight chamber. The boiler system transfers thermal energy from the hot flue gases to the water circulating in the waterwall tubes and superheater, generating hot water, generating steam and cooling the flue gases. Generated steam can be used to turn a turbine and generate electricity, or it can be used directly in a heating/cooling system. Cooled flue gases pass through air pollution control equipment and are exhausted to the atmosphere through a stack. Typical air pollution control systems include scrubbers, electrostatic precipitators (ESPs), and fabric filters.

## 9.2 Technology Status

Mass-burn facilities make up a significant portion of the conceptual, developmental, and existing waste-to-energy projects in the U.S. According to data compiled in September 1990, 53 mass-burn facilities were operating in the U.S. with a combined daily processing capacity of 49,086 tons (see Exhibit 9-2). These facilities most often use electrostatic precipitators and scrubber/fabric filter combinations as air pollution control devices (Kiser, 1990; Alvarez, 1988), and utilize continuous emissions monitoring.

**Exhibit 9-2. Mass-Burn Facility Status**

| FACILITY STATUS | NO. OF MASS-BURN FACILITIES | DAILY DESIGN CAPACITY (tpd) |
|---|---|---|
| Planned | 37 (35%) | 49,913 (42.7%) |
| Under Construction | 15 (14%) | 17,510 (15.2%) |
| Operational | 53 (50.1%) | 49,086 (42%) |
| Inactive | 1 (0.9%) | 185 (0.1%) |
| Total Number (Total Percentage) | 105 (100%) | 116,694 (100%) |

Of the 91 facilities identified in the advanced planning stage or under construction, 63 (69 percent) were designed to utilize mass-burn technologies, with the majority using waterwall incineration. (Berenyi and Gould, 1988)

The northeast region of the country had the greatest share of waste-to-energy facilities, while the West had relatively few. Most (62.2 percent) of the advance-planned and existing facilities in the Northeast were mass-burn facilities. From 1984 to 1988, planners shifted toward mass-burn combustors that generated electricity and away from steam generation, which had a higher financial risk. Steam generation facilities, however, were still planned in areas where the economics and demographics permitted. As of 1988, the majority (66 percent) of advance-planned and existing mass-burn facilities in the U.S. generate electricity as their primary energy product, as opposed to steam or co-generation of electricity (Berenyi and Gould, 1988).

As of 1988, 27 waste-to-energy facilities had been permanently closed in a total of 19 states, mainly in the South. These facilities most often cited equipment problems (35 percent) as the reason for the shut downs, followed by unfavorable economics (25 percent), environmental problems (13 percent), and explosions and fires (6 percent each). Only 3 (11 percent) of the facilities that had been shut down utilized mass-burn technologies. Equipment-related problems were generally the cause for the closure of mass-burn units, and modification or rebuilding of the units cost facilities an average of $16 million, the highest of all facilities using MSW combustion technologies. (Berenyi and Gould, 1988) Private sector ownership of waste-to-energy facilities has levelled off and may be decreasing. Capital funding efforts have shifted slightly toward the public sector due to changes in the U.S. tax code limiting the use of tax-exempt bonds for private financing of waste-to-energy projects (Berenyi and Gould, 1988).

As of September 1990, in addition to the 53 operational facilities, 15 mass-burn facilities were under construction and 37 facilities were in the planning stages as shown in Exhibit 9-2 (Kiser, 1990; Alvarez, 1988). Data from 1988 identified 81 (69.8 percent) of the 139 waste-to-energy facilities in the conceptual stage of planning in the U.S. would utilize mass-burn technologies including waterwall incineration, rotary combustion, and refractory furnaces. Mass-burn projects accounted for 76 percent of conceptually planned facilities in the South and approximately two-thirds of planned facilities in the northeast, northcentral, and western regions. (Berenyi and Gould, 1988)

A number of other countries are utilizing mass-burn technology in waste-to-energy projects, including the United Kingdom, Sweden, and Canada. These countries, however, have quite different patterns of waste and energy management and have focused their waste-to-energy efforts in different areas. For example, Sweden depends on energy imports, while both the United Kingdom and Canada are net energy exporters. Because of these and other political, environmental, and institutional factors, Sweden treats MSW as an energy source more than the other two countries do. Sweden has 25 mass-burn facilities with energy recovery capabilities that process approximately 50 percent of all MSW generated in the country. In contrast, Canada and the United Kingdom each have only five commercially operating mass-burn facilities (Krol and Dent, 1989; Dent and Krol, 1990).

## 9.3 Description of RD&D Needs

Mass-burn combustion is a relatively mature technology. Its primary RD&D needs are associated with the need to gain public acceptance of the technology; reduce the cost of air pollution control devices; increase energy recovery efficiency; monitor an increasing number of air pollutants; and control $NO_X$ emissions. Other RD&D needs are associated with the disposal of ash from mass-burn combustion systems are addressed separately in the chapter on ash disposal and utilization.

Sections 9.3.1 through 9.3.7 describe the RD&D needs for mass-burn combustion that were identified by the panel of technical experts (listed in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 25) that is used in later sections where the RD&D needs are prioritized. Section 9.3.8 describes RD&D needs that were identified during the literature review (see the introduction chapter), but were not subsequently identified by the panel of technical experts. The RD&D needs in Section 9.3.8 are not prioritized or discussed further.

### 9.3.1 Waste Preprocessing

The presence of steel, glass, and other non-combustible materials in MSW reduces the heating value of the waste and contributes to a variety of problems that may include slagging, fouling, clinker formation, and air emissions. As a result, waste preprocessing to remove portions of the MSW that are non-combustible or otherwise undesirable can have a significant impact on system performance. Discussions of the RD&D needs associated with source separation and mechanical on-site separation, the two most common approaches to preprocessing, can be found in the chapters on source separation and material recovery facilities. Research needs associated with the application of source separation to mass-burn combustion are discussed in this section.

While source separation does not generally have much effect on the heat content of MSW, it may have an effect on ash composition. Past studies of the impacts of source separation on ash composition have not been conclusive, and additional research is needed to:

1. Evaluate the impacts of source separation on the economics and air emissions of mass-burn combustion systems, and confirm these impacts with a demonstration project.

Mechanical on-site separation can, like source separation, affect air emissions and ash composition. Achieving a level of separation that has a significant effect on air emissions and ash composition will be both expensive and technically difficult, though the technology probably does exist. While a more detailed description of the RD&D needs for this technology can be found in the chapter on materials recovery facilities, research is needed to:

2. Evaluate the impact of mechanical separation on economics and air emissions.

### 9.3.2 Combustion Chamber Design and Operating Conditions

Combustion chamber design and operating conditions are interrelated and can affect system efficiency and air emissions (e.g., polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzo-furan (PCDFs), and other organic pollutants). As many of the organic constituents found in the air emissions result from incomplete combustion, changes in operating parameters and/or furnace design can substantially reduce such emissions (Schindler and Nelson, 1989; Finkelstein, 1991; Donnelly, 1991). To ensure that mass-burn combustors will comply with increasingly stringent emission standards and that this information is communicated effectively, work is needed to:

3. Determine the relationships among combustion chamber design, operating conditions, and air emissions, and identify the parameters with the greatest influence (Zimmerman and Isaacson, 1989; Landrum, et al., 1989; Buekens, 1989; Finkelstein, 1991; Dent and Krol, 1990; Energy and Environmental Research Corp., 1987);

4. Establish a database containing information on combustion chamber designs and the relationships between combustion chamber design, operating conditions, and air emissions; and

5. Evaluate the use of oxygen enrichment to improve combustor performance.

### 9.3.3 Slagging and Fouling

Heat transfer can be adversely affected by slagging and fouling. Slagging occurs when the ash reaches the temperature at which it starts to fuse and adhere to boiler-tube surfaces. Fouling occurs when ash particles bind together (possibly caused by the condensation of materials vaporized in the furnace) and adhere to convection-pass tubes. Research is needed to:

6. Determine the slagging points of different waste constituents so that the waste stream can be screened to remove materials that result in slagging or the furnace can be operated at temperature that minimizes slagging (see Section 9.3.1);

7. Study the chemical and physical mechanisms of slagging and fouling to help develop methods, equipment, and chemicals to prevent and/or treat the effects of slagging and fouling;

8. Determine operating practices and furnace conditions that minimize slagging and fouling (Scaramelli, 1979) and disseminate this information;

9. Improve equipment and chemicals for cleaning surfaces in the furnace and air pollution control devices;

10. Evaluate the environmental impacts of operating methods, equipment, and cleaning chemicals developed to prevent and/or treat the effects of slagging and fouling; and

11. Establish a system for disseminating information and technology about slagging and fouling, and investigate recent research performed in other countries, especially Europe.

### 9.3.4 Energy Recovery Efficiency

The energy recovery efficiency of mass-burn facilities is relatively low when compared to coal-fired power plants. This lower efficiency is due primarily to the lower temperature and pressure of the steam generated by the mass-burn facilities: 1,400-1,800 degrees Fahrenheit and over 900 pounds per square inch as compared to 1,900-2,200 degrees Fahrenheit and over 3,500 pounds per square inch in coal-fired plants (Barrett et al., 1989). Factors that keep mass-burn facilities from producing steam at higher temperatures and pressures are (1) corrosion problems associated with contaminants, particularly chloride, found in MSW that increase with temperature and (2) the high moisture content of the refuse. Research is needed to:

12. Develop mass-burn combustion systems that produce steam at a higher temperature and pressure, possibly through the development of superheaters and dual-fluid systems (Scaramelli, 1979);

13. Develop materials that allow higher operating temperatures (e.g., materials with greater resistance to corrosion) (see Section 9.3.5);

14. Evaluate the value and trade-offs of using supplemental fuels (e.g., coal, gas, waste oil, and solvents) to produce higher furnace temperatures; and

15. Develop methods to recover additional heat from furnace exit gases.

### 9.3.5 Corrosion

Both mass-burn combustion boilers and air pollution control devices experience problems with corrosion, though boilers tend to have more problems because of their higher temperature. While methods to control the corrosion of metal surfaces in mass-burn combustion systems have been developed, these methods have some disadvantages and have not been completely successful. Specifically, refractory coatings such as silicon carbide reduce corrosion, but require frequent maintenance; corrosion resistance metals such as Incoloy® and Inconel® are available, but are expensive; and the furnace can be run at a lower temperature to reduce corrosion, but this reduces the system's energy recovery efficiency (see Section 9.3.4). Research is needed to:

16. Develop boilers that are more resistant to corrosion, particularly corrosion caused by chlorine; and

17. Develop air pollution control devices that are more resistant to corrosion.

### 9.3.6 Characterization and Control of Air Emissions

The U.S. Environmental Protection Agency has recently promulgated standards for new municipal waste combustors (MWCs) and emission guidelines for existing MWCs that burn more than 250 tpd MSW (see 56 Federal Register 5488, February 11, 1991). These standards include good combustion practices and emission limits for nitrogen oxides (not applicable to existing MWCs), total dioxins and furans (i.e., PCDDs and PCDFs), sulfur dioxide, hydrochloric acid, particulate matter, and opacity. Research is needed in a variety of areas to ensure compliance with the new standards and to address issues related to air emissions from mass-burn combustion units (U.S. Environmental Protection Agency, 1991).

Bioassays, which can be used to evaluate the potency of different biological effects of a chemical or mixture of chemicals (e.g., toxicity, carcinogenicity, and mutagenicity), may be useful for characterizing MWC air emissions. More research, however, is needed to investigate how bioassays may be applied to MWC air emissions. In particular, methods are needed to separate toxic constituents from the samples that interfere with the mutagenicity assay (Watts, et al., 1989).

Stack emissions need to be sampled for pollutants such as CO, $SO_2$, $NO_x$, HCl, and trace toxins in order to satisfy regulatory requirements. For example, stack samplers able to assess the mutagenic potency of organic and particulate emissions and collect samples for carcinogenicity assays have been developed. They require, however, improvements to reduce costs, simplify their use, and to solve problems with corrosion of the samplers caused by emission gases (see No. 17 in Section 9.3.5) (Watts, et al., 1989). Research is needed to:

18. Develop simple low-cost stack sampling methods and evaluate the available sampling methods with respect to their practicality.

The use of surrogates to monitor air emissions can be very effective. Research is needed to:

19. Improve and demonstrate surrogate monitoring equipment and techniques.

Continuous monitoring methods for both criteria and toxic pollutants (e.g., PCDDs and PCDFs) is important to satisfy public concerns and regulatory requirements. For example, despite their low concentrations, PCDDs and PCDFs pose a potential hazard and need to be monitored. Research is needed to:

20. Develop less expensive conventional and innovative methods for the continuous collection and analysis of air emissions for both criteria and toxic pollutants (Rappe, et al., 1989; Finkelstein, 1991).

While technology is available for controlling the emission of particulates and sulfur dioxide, this technology could be improved. In addition, the technology for controlling the emission of other pollutants is less developed. Research is needed to:

21. Reduce the cost of acid gas air pollution control devices (e.g., less expensive substitutes for lime as an acid gas sorbent);

22. Develop and demonstrate methods for controlling $NO_x$ (e.g., selective catalytic reduction); and

23. Develop methods for controlling mercury emissions.

### 9.3.7 Assessment of Health Risks

Public acceptance could have a large influence on the viability of mass-burn combustion technology. Since MSW must be managed one way or another, public acceptance of a particular technology depends heavily on how its risks and costs compare with those of the alternative technologies. In order to make these comparisons, research is needed to:

24. Estimate and compare the health risks associated with mass-burn combustion to those associated with other MSW technologies; and

25. Estimate the marginal reduction of risk to human health resulting from small reductions in air emissions in order to evaluate the trade-offs between control costs and risks to human health.

### 9.3.8 Other Potential RD&D Topics

The following RD&D topics were identified in the literature review, but were not subsequently accepted by the panel of technical experts (listed in Appendix A).

Determine the relationships between operating parameters and air emissions. Research could determine the thermodynamics and reaction pathways involved in the formation and degradation of PCDDs and PCDFs. The results of this research may help design mass-burn combustion systems and operating procedures that discourage the formation of PCDDs and PCDFs (Dent and Krol, 1990; Energy and Environmental Research Corp., 1987).

Investigate the use of sulfur as an MSW additive to control chloride corrosion. This topic was identified by Scaramelli (1979).

Develop methods to sample and characterize air emissions containing complex mixtures of organics. The air emissions from municipal waste combustors may contain thousands of different organic constituents, some of which are potentially hazardous (e.g., toxic, carcinogenic, and mutagenic). While it is important to characterize and monitor the stack air emissions to determine if they pose a risk to human health or the environment, the large number of potential constituents makes it impractical to routinely test for each constituent.

Establish sources of and background levels for PCDDs and PCDFs. A variety of combustion sources (e.g., steel mills, copper smelters, and motor vehicles) other than MWCs emit significant quantities of PCDDs and PCDFs (Hattemer-Frey and Travis, 1989). Given the concern about PCDDs and PCDFs in general, and about MWCs as a potential source of these chemicals in particular, new research could determine whether MWCs are a significant source of PCDDs and PCDFs in the environment relative to other sources (Hattemer-Frey and Travis,

1989). Specifically, data would be needed to (1) determine the background concentrations of PCDDs and PCDFs in air, soil, and vegetation; (2) assess background human exposure to PCDDs and PCDFs; (3) quantify PCDD and PCDF levels in environmental samples collected near facilities known to emit PCDDs and PCDFs; and (4) quantify PCDD and PCDF emissions from vehicles that use unleaded gasoline and diesel fuel (Hattemer-Frey and Travis, 1989). Similarly, new data could be developed to determine and compare mutagen concentrations in air samples collected upwind and downwind from incinerators (Watts, et al., 1989).

Develop and improve flue gas cleaning technology. While the technology for controlling the emission of particulates and sulfur dioxide in flue gas works reasonably well, operational problems have been encountered that require additional research and development. For example, semi-dry scrubbing systems have had problems with scaling; dry scrubbing systems have had problems with the air pollution control residue solidifying; and wet scrubbing systems have had problems with both corrosion and fouling (Buekens, 1989).

Develop methods to characterize and screen MSW before combustion. The composition and physical characteristics of MSW have a major impact on boiler performance and the characteristics of air emissions and ash. By monitoring and screening the MSW being fed to a furnace, boiler performance can be improved and potentially hazardous air emissions can be reduced (Hayes, 1990; Dent and Krol, 1990). Instrumentation needs to be developed to monitor the composition and physical characteristics of MSW that influence combustion and the characteristics of air emissions and ash (Tinning, 1985). Also, it would be useful to those designing mass-burn combustion systems if the available information on existing monitoring and screening techniques was compiled and evaluated (Dent and Krol, 1990).

## 9.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on mass-burn combustion (listed in Appendix A) are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making mass-burn combustion technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 9-3, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 9.3 is in the right-hand column. The rationale discussed by the panel of technical experts is presented after Exhibit 9-3. The rationale tend to focus on RD&D needs where panel members had widely differing opinions on the priority and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

The expert panel assigned the highest priority to assessment of the health risks (No. 24) associated with mass-burn combustion because it is important to change the public perception that mass-burn combustion poses a serious risk to human health. Without a change in this negative image, the financial risks may be too high for potential investors. Some panel members, however, believe that research to assess the health risks would be a

**Exhibit 9-3. Prioritized RD&D Needs for Mass-Burn Combustion**

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| 90 | Estimate and compare health risks of mass-burn with other MSW technologies | 24 |
| 85 | Reduce the cost of acid gas air control pollution devices (e.g., lime substitutes) | 21 |
| 80 | Develop systems that generate steam at a higher temperature and pressure | 12 |
| 70 | Develop simple low-cost stack sampling methods and evaluate their practicality | 18 |
| 68 | Develop and demonstrate methods for controlling $NO_x$ | 22 |
| 64 | Develop materials that allow higher operating temperatures without corrosion | 13 |
| 63 | Develop less expensive continuous air emission collection and analysis methods | 20 |
| 60 | Determine relationships among design, operating conditions, and air emissions | 3 |
| 50 | Develop boilers that are more resistant to corrosion | 16 |
| 50 | Evaluate the impact of source separation on the economics of mass-burn units | 1 |
| 45 | Estimate the marginal reduction of risk to human health for air emission reductions | 25 |
| 43 | Develop methods for controlling mercury emissions | 23 |
| 30 | Study the chemical and physical mechanisms of slagging and fouling | 7 |
| 30 | Establish a system for disseminating information about slagging and fouling | 11 |
| 21 | Improve and demonstrate surrogate monitoring equipment and techniques | 19 |
| 15 | Establish database with data on design, operating conditions and air emissions | 4 |
| 12 | Determine the slagging points of different waste constituents | 6 |
| 12 | Determine operating practices & furnace conditions to minimize slagging & fouling | 8 |
| 10 | Develop air pollution control devices that are more resistant to corrosion | 17 |
| 10 | Evaluate the impact of mechanical separation on economics and air emissions | 2 |
| 9 | Evaluate the use of oxygen enrichment to improve combustor performance | 5 |
| 8 | Develop methods to recover additional heat from furnace exit gases | 15 |
| 6 | Improve equipment and chemicals for cleaning furnace and APC surfaces | 9 |
| 4 | Evaluate the use of supplemental fuels to produce higher furnace temperatures | 14 |
| 2 | Evaluate the environmental impacts of methods to control slagging and fouling | 10 |

waste of time because a large amount of money could be spent without producing conclusive results.

Research on methods for controlling $NO_x$ is needed because of uncertainty about the feasibility of retrofitting existing mass-burn combustion systems (No. 22).

The development of less expensive methods for continuous collection and analysis of air emissions is ranked highly for two reasons: (1) the need to reduce operating costs, and (2) the ability to tell the public that air emissions are continuously monitored for pollutants

ofconcern could be an important factor in gaining public acceptance of mass-burn combustion (No. 20).

Determining the relationships among combustion chamber design, operating conditions, and air emissions (No. 3) may help design mass-burn combustion chambers that discourage the formation of PCDDs, PCDFs, and other pollutants of concern (Dent and Krol, 1990; Energy and Environmental Research Corp., 1987; Scaramelli, 1979). The panel was divided on the importance of this research. The panelists from the commercial sector believe that the need has already been fulfilled by past research, whereas the panelists from the academic community believe that a more systematic understanding is needed.

The development of methods to control mercury emissions (No. 23) is given a relatively low priority for research by DOE because industry expects to have solved the problem in the near future.

Even though the measurement of pollutant surrogates can be a very effective method of monitoring air emissions (No. 19), this approach is somewhat controversial and does not appear to be politically acceptable. Given its lack of political acceptability, the panel members believe that additional research would have no impact on its use.

Establishing a database with information on combustion chamber design, operating conditions, and air emissions (No. 4) is important because much of what is learned is site specific and is not shared among practitioners. No means to routinely disseminate such information is available.

## 9.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate mass-burn combustion with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The cost of implementing an RD&D program that consists of the prioritized RD&D needs should be less than most of the eleven other MSW technologies being considered in this report. Construction of a demonstration facility, however, is expected to cost between $50 and $400 million.**

### Difficulty of Technology Development

While mass-burn technology is still evolving, it is already being used on a widespread basis; more than 50 mass-burn combustion facilities currently operating in the United States.

** One reviewer believes that $400 million for the construction of a demonstration facility seems excessive.

The panel was divided on whether most of the technical problems associated with mass-burn combustion have been solved. Panel members from the research community believe that considerable work remains to be done on the relationships between source separation and air emissions and on air pollution control devices. On the other hand, panel members involved with commercial operations believe that public education and cost-benefit demonstrations are the primary need.

**Commercial Development Risk**

The primary sources of risk for commercial development appear to be public and political acceptance, both of which vary significantly.

**Flexibility**

Mass-burn combustion facilities tend to be very flexible with respect to the chemical and physical composition of the waste they utilize.

**Net Energy Benefit**

Waste-to-energy technologies currently supply about 0.25 percent of the nation's energy.

**Human Health and the Environment**

Due to the mature nature of this technology, all of the environmental impacts are regulated and the relationships between these impacts and combustor operations are relatively well understood.

**Appropriateness for Government Funding**

Given the need for impartiality, an assessment of the health risks associated with mass-burn combustion is viewed as a project that would be appropriate for funding by DOE. In addition, some panel members believe that DOE should keep abreast of the research being done by approximately five vendors, and aid it when possible. Reducing the cost of acid gas air pollution devices, however, may not be an appropriate project for funding by DOE. DOE funding is probably not needed to develop methods of controlling mercury emissions, since industry appears to be already working on the problem.

# 10. MATERIALS RECOVERY FACILITIES AND PREPROCESSING

## 10.1 Technology Description

A materials recovery facility (MRF) is a centralized facility where recyclable materials are recovered from MSW or some portion of a MSW stream (e.g., mixed containers) and prepared for marketing. MRFs are also known as intermediate processing facilities or centers (IPFs or IPCs). Facilities where little or no processing of materials takes place, for example drop-off centers where generators place recyclables into separate containers by material, are generally not considered MRFs.

### 10.1.1 MRF Feed Streams and Products

MRFs may be designed to accept MSW feed streams that have undergone varying degrees of pre-sorting. Some MRFs accept MSW as-generated, in the same form as it would be received at a landfill or a mass-burn combustor. Other MRFs accept MSW that has been pre-sorted, either by source separation or in the collection process. The degree of pre-sorting will affect the technology that the MRF utilizes. MRFs that receive pre-sorted materials tend to be less mechanized facilities.

MRFs may be designed to recover a variety of materials from MSW including paper, glass, metals, and plastic. These materials may be further separated into subcategories or grades, such as the following:

- **Paper** materials such as mixed paper, newspaper, computer or office paper, cardboard, and magazines
- **Glass** materials such as mixed glass, clear (or flint) glass, brown glass, and green glass
- **Metals** such as aluminum, ferrous scrap, steel cans, and bi-metal cans
- **Plastics** such as mixed plastics, polyethylene terephthalate (PET) plastics (mixed or separated by color), polystyrene foam, high-density polyethylene (HDPE) plastics (mixed or separated by color), and polyvinyl chloride (PVC) plastics

MRFs may also be designed to separate out organic materials for use in composting, combustible materials for use in RDF production, or to remove hazardous wastes (e.g., lead batteries) from the waste before it is landfilled. The products targeted will influence the level of technology that the MRF utilizes. Some materials are more amenable to mechanical separation processes, while others generally require hand sorting (various colored glass bottles, for example).

### 10.1.2 MRF Technology

Separation techniques employed by MRFs include hand sorting as well as higher technology mechanical methods. MRFs also often employ mechanical preparation equipment

such as shredders, hammermills, and balers to process separated recyclables into more marketable forms. The combination of processes used by an individual MRF and the order in which these processes are implemented will depend on the type of feed received and the specific materials recovered. As an example, Exhibit 10-1 shows the design of a MRF that accepts mixed recyclables and recovers aluminum, steel, various colors of glass, and three types of plastic.

At the front end, MRFs often use machinery such as air classifiers, air knives, and vibrating screens to separate MSW by weight or size. Ferrous metals are typically recovered with a magnetic separator or series of magnetic separators. Aluminum may be recovered using various types of eddy current separators, differential screening, density separation, or hand sorting. Separating glass into different colors usually requires hand sorting, although some facilities have employed mechanical separation using photocells . Alternatively, mixed color glass may be obtained through crushing, screening, and froth flotation. Plastics are generally recovered through hand sorting, although density separation may be used. If paper is to be recovered in dry form it usually must arrive at the MRF pre-separated or be hand separated at the start of the process. Systems do exist, however, that separate paper later in the recovery process in the form of fiber or pulp. Paper can also be included in an organic fraction to be utilized in composting or combustion (Berenyi and Gould, 1990; Robinson, 1986; U.S. Congress, 1989).

## 10.2 Technology Status

Of the 35 materials recovery facilities operating in the United States in July 1990, 1 was undergoing shakedown, and 4 were temporarily shut down for repair or retrofitting (see Exhibit 10-2). Twenty-two of these MRFs utilized an equipment-intensive "high-tech" process while 17 utilized a "low-tech" (i.e., labor-intensive) process, and one MRF was using a process that did not fit in either category. Twenty-seven MRFs commenced operation in 1988-1989. As of 1990, existing facilities had design capacities ranging from 2 to 470 tpd with an average capacity of 89.43 tpd. These facilities reclaimed approximately 3,577 tpd (939,444 tpy) of recyclables and generated 211 tpd of residue which must be landfilled, incinerated, or marketed in some other form such as "glassphalt" (Gould, March 1990; Gould, July 1990; Berenyi and Gould, 1990).

The number of MRFs in the U.S. appears to be increasing rapidly. As of July 1990, 64 MRFs were in either the conceptual planning, advanced development, or construction stages. Thirty-five facilities were scheduled to open in 1990 and an additional 24 in 1991. If all 64 facilities are completed and begin processing recyclables, they will create an additional 10,362 tpd capacity (2,895,199 tpy) and generate an additional 784 tpd of residue. The average capacity of the planned facilities (162 tpd) is higher than for existing facilities which accounts, in part, for the greater average residue generation from planned facilities (20 versus 6 tpd). A slightly higher percentage of the planned facilities will utilize "low-tech" processes, although process information was unavailable for 26 of the planned MRFs. (Gould, March 1990; Gould, July 1990; Berenyi and Gould, 1990)

There is almost an even split between public and private ownership of planned and existing MRFs. Private firms, however, own only 38 percent of planned facilities versus 65 percent of existing facilities, which indicates that many future projects will be developed by

**Exhibit 10-1. Sample Design of a Large-Scale MRF**

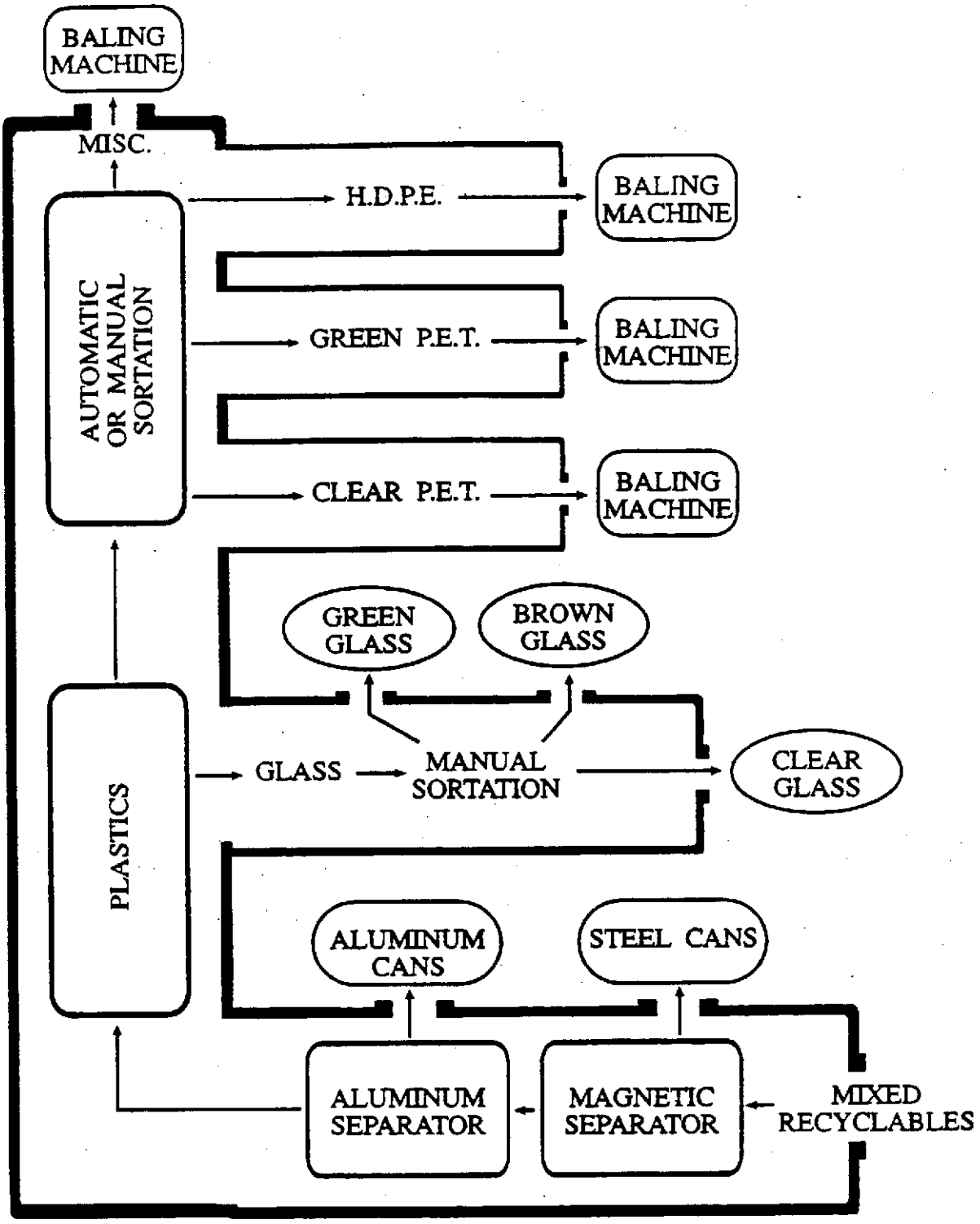


**Exhibit 10-2. Status and Degree of Mechanization of MRFs by Design Capacity**

| Design Capacity (tpd) | Status | | Degree of Mechanization[a] | |
|---|---|---|---|---|
| | Planned | Existing | Low-Tech | High-Tech |
| 1-99 | 17 (27%) | 30 (75%) | 26 (65%) | 11 (35%) |
| 100-199 | 27 (42%) | 5 (12.5%) | 11 (52%) | 10 (48%) |
| OVER 200 | 20 (31%) | 5 (12.5%) | 4 (21%) | 15 (79%) |
| TOTAL | 64 (100%) | 40 (100%) | 41 (53%) | 36 (47%) |

Source: (Berenyi and Gould, 1990)

[a] Information was unavailable for some planned facilities.

government entities. The northeast region of the U.S. has the highest percentage (55 percent) of planned and existing MRFs. It contains three of the four states with the highest number of MRFs: New York (20), New Jersey (15), and Pennsylvania (13). The other state is California with 14. Of the remaining facilities, the northcentral U.S. has 18 percent, the West 17 percent, and the South 10 percent ("Directory of Materials Recovery Facilities," 1990; Gould, March 1990; Gould, July 1990; Berenyi and Gould, 1990).

## 10.3 Description of RD&D Needs

As the role of MRFs in local and regional waste management programs continues to grow, there will be a greater need for RD&D projects aimed at improving the performance of MRFs and adapting them to growing and changing recycling programs. There may be some overlap among research needs in the areas of source separation, RDF, and MRF. The degree of overlap depends largely upon which definition of a MRF is applied. Some expert panel members felt that the definition of a MRF should include facilities that accept both mixed waste and source separated materials. Other panel members believed that the definition of a MRF should include only facilities accepting source separated materials. Panelists agreed that RD&D needs for mixed (i.e., unseparated) waste processing facilities may be covered to some extent by the RD&D needs identified in the chapters dealing with RDF production and combustion. Thus, the panel agreed that for purposes of identifying and prioritizing RD&D needs the broadest definition of a MRF would be used. MRFs within this definition include facilities receiving source separated or mixed waste for materials recovery but not for recovery of a fuel product.

The expert panel agreed that as the role of MRFs expands, interest will increase in recovering materials in addition to those traditionally targeted by MRFs (e.g., paper, glass, plastic). The group believed that it may be desirable to design the MRF of the future with

some or all of the following capabilities: battery separation and processing; bulky waste processing; improved aluminum capture (e.g., from foil); processing infrequently generated wastes with high energy value (e.g., waste oil); magazine separation and processing; mixed waste paper processing; yard waste and food waste processing; textiles processing including fiber, rags, and clothing; and construction and demolition waste processing including substandard material. Many of the research needs described in this section relate to developing, evaluating, and designing a MRF of the future with these capabilities.

The remainder of this section is devoted to describing each of the RD&D needs that has been identified for MRFs. The RD&D needs have been assigned a reference number (i.e., 1, 2, 3, ... 25) that is used in later sections of this chapter when the RD&D need is discussed.

### 10.3.1 Preprocessing and Separation Technology

As recycling gains popularity across the country, both new and existing MRFs should continue to develop and improve technologies for preprocessing and separating the recyclable portion of the MSW stream. In some areas, state recycling goals will force more types of materials into MRFs. In addition, new and more complex waste streams accepted by the MRF of the future are going to require more complex separation technologies.

Monitoring and detection devices need to be developed for use as precursors to the separation process. These detectors are needed to detect small quantities of contaminants in incoming waste streams. Example contaminants include PVCs mingled with PET plastic, small amounts of ceramics in glass, staples in magazines, and toxics in waste oils including chlorinated hydrocarbons such as PCBs. Good detection mechanisms for PCBs and ceramics do not currently exist. Research is needed to:

1. Develop detection and monitoring devices.

New separation needs created by the non-traditional waste streams accepted by the MRF of the future should be examined in the near term. Separation requirements for materials such as fabrics and mixed commercial waste must be defined before technology can be developed. Studies of these separation requirements should be material specific. Related research will be needed to decide what kinds of materials the MRF of the future should accept. In keeping with this goal, a system study for the MRF of the future should forecast preprocessing and separation capabilities and examine costs and benefits of accepting various wastes. Research needs are:

2. Define separation requirements for new materials; and

3. Conduct system study for MRF of the future forecasting pre-processing and separation capabilities and examining costs and benefits.

Some researchers have identified a need to develop a primary sorting device that separates paper products from container materials, such as plastic, aluminum, and glass, and leaves glass essentially unbroken (Smith, 1989). Similarly, devices are needed to identify and separate different fibers in mixed textile waste streams (fibers, clothing, and rags). Synthetic fibers cannot go to paper mills, so cotton fibers must be separated. Some states have started collection programs for separated batteries. Therefore, systems are needed to separate

batteries from commingled containers and from each other. In particular, a separation system to isolate mercury batteries is needed. RD&D is needed in each of these three areas:

4. Develop device to separate paper products from commingled containers;

5. Develop systems to separate textile fibers (cotton and synthetic); and

6. Develop systems to separate batteries.

An efficient optical or other automated system to identify and sort bags or other containers of pre-separated waste by their contents is needed. An improved automated system to break open bags is also needed for facilities accepting mixed waste. Current bag breaking methods cause a lot of commingling. An improved system would liberate bag contents without breaking glass and without commingling contents. RD&D in this area would:

7. Develop an efficient automated bag sorting system; and

8. Develop improved automated bag opening systems.

In the 1970s, a colored glass sorting technology was developed that might be useful in present-day MRFs. Similarly, industrial processing technologies, from the food industry, for example, might be adapted to MRF use. Research should:

9. Evaluate past waste sorting systems and technologies from other industries for applicability to MRFs.

### 10.3.2 Quality and Market Issues

As more secondary materials become available for recycling and industry is able to be more selective about the secondary materials it accepts, the contamination and the quality of materials emerging from MRFs will be of greater concern. Quantitative market specifications for the quality of recycled materials emerging from MRFs need to be established. Standard sampling methods for quality control checks also need to be developed so that MRF operators can demonstrate that their products meet these specifications.

Markets for MRF products must be expanded. Some public sector intervention may be necessary in order for such secondary materials to be competitive with virgin materials. Policy analysis on methods to enhance markets would be appropriate. Research in this area could lead to the development of a national secondary materials policy. Markets for products recovered from specific waste streams should also be developed. For example, construction and demolition wastes make up a large portion of the waste stream. Operating facilities that handle construction and demolition wastes have shown that there is economic value and energy benefit in processing these streams. Research in this area should focus on removing impediments to marketing these streams and developing beneficial product uses. The following research needs cover product quality and market issues:

10. Develop quantitative standardized product specifications and standardized quality sampling methods;

11. Conduct policy analysis on methods to enhance markets for secondary materials versus virgin materials; and

12. Research marketing of construction and demolition wastes.

### 10.3.3 Environmental and Health Issues

MRFs can have both environmental and health impacts. Potential environmental impacts, such as emissions and residuals generation, associated with MRFs and MRF processes should be studied. Also, future research should address health concerns related to the MRF working environment. RD&D work may be conducted to evaluate potential environmental impacts of solid waste recycling processes. This work should focus on the environmental implications of expanding the types of materials accepted by MRFs, particularly to commercial and industrial waste. In the expanded MRF of the future, it may also be necessary to handle quantities of hazardous materials received with the input waste streams. Research should address the environmental impacts of hazardous materials in MRFs and develop handling practices. Additional research should investigate the characteristics of solid and liquid residues from recyclables processing and methods to minimize environmental impacts from the residue stream. This research could also focus on developing methods of utilizing process residuals. (Mathusa, 1989) Similar research should characterize air emissions of metals and bacteria from MRFs. Cadmium pigments released during plastic shredding, particulates from glass crushing, and lead from paper processing may cause air emission problems. Research should also cover assessing the need for methods to control emissions and developing these methods. The following RD&D needs are associated with the external environmental effects of MRFs:

13. Investigate the pollution control implications of expanding MRFs;

14. Define, characterize, mitigate impacts from, and develop utilization methods for MRF process residues;

15. Characterize air emissions from MRFs, assess control needs, and develop control methods; and

16. Assess environmental impacts of hazardous materials in MRFs and develop handling practices.

In many instances, the working environment at MRFs is unpleasant, with excessive noise and dust, an absence of temperature controls, and a lack of adequate lighting. MRF developers should design a working environment such that most of the human work force will be housed in a sorting room separate from the mechanical equipment. This arrangement would ease control of lighting. Dust and noise should be controlled by a combination of walls and ventilation systems. By using hoods, blowers, and a central baghouse, dusty environments can be confined to a portion of the tipping floor and the immediate surroundings of the size-reduction devices (Smith, 1989). Research should investigate the most technically and economically effective methods of creating a safe and pleasant working environment for MRF workers, including worker health and safety training. The research should also address any additional health and safety issues created by the expanded MRF of the future. To summarize, there is a need to:

17. Identify and mitigate occupational health and safety problems associated with MRFs.

### 10.3.4 Economics

Some technologies are better suited to small scale MRFs while others are better for large size MRFs. Research should be done to address this issue. Specifically, research should:

18. Weigh the costs and benefits of various separation devices as a function of MRF size and the types of materials received.

Several other studies could be done in the area of MRF economics. Research should assess energy use throughout the MSW system and compare the net energy savings associated with MRFs in comparison to other waste management methods. Another study should address the use of recovered materials in various production processes and compare the economics of this use to the use of virgin materials. A related research project would study the physical properties of materials as they are repeatedly recycled and determine the number of times individual materials can be recycled. Individual RD&D needs are associated with each of these topics:

19. Compare net energy savings of MRFs to other waste management methods;

20. Examine the economic impacts of using secondary materials in the production process in comparison to using virgin materials; and

21. Determine the number of times individual materials can be recycled.

In addition to these broad needs, specific research could be done on the economics of plastics recycling. A considerable investment is being put into research on plastic recycling, but this research is focusing on producing low-quality, mixed plastic products.[1] The private sector has invested in this technology sometimes for public relations purposes rather than economics. It might be more profitable, in terms of energy and economics, to recover high-quality, separated plastics from the waste stream to substitute for virgin resins. In order to decide whether waste-derived resins will be competitive, research should:

22. Develop a database on the economic and energy costs and benefits of waste-derived resin substitutes.

### 10.3.5 Technology Development

The technical panel indicated that a pilot plant (possibly of one ton per day capacity) is needed to demonstrate the selective solvent dissolution process of recovering resins from mixed plastics. Commercialization of this technology would eliminate the need for separating

[1] One reviewer commented that "lots of R&D is underway on PET methanolysis and glycolysis to make food-grade plastic from post-consumer [plastic]," but did not identify specific R&D projects.

plastics at an MRF. The success of selective solvent dissolution, however, will depend upon the competitiveness of high-quality resin substitutes (see Section 10.3.4). Research is also needed to improve end-user technology to utilize recovered products. If end-users have greater flexibility in the feeds they can accept, many preprocessing problems will be eliminated. The primary market for mixed paper is overseas, where cheap labor can be used to separate it into various grades. New uses for mixed paper should be developed. For example, it could be used as fuel, in fiber, or as a feedstock for bioprocessing (e.g., anaerobic digestion, composting). The RD&D needs for technology development are:

23. Build a pilot plant to demonstrate selective solvent dissolution;

24. Improve the flexibility of end-user technology to utilize recovered materials; and

25. Develop new uses for mixed paper.

### 10.3.6 Other Potential RD&D Topics

A number of RD&D needs were identified in the literature review, but not accepted by the expert panel. Over the past 20 years, researchers have made numerous attempts to retrieve recyclables from MSW and simultaneously prepare refuse-derived fuel or a material that could be composted and sold. Each scheme has succeeded technically, to some degree. Only one or two systems have lasted, however, and in the long-lasting cases the only material recovered for its recyclable value, and actually sold on any regular basis, has been iron. Capital and operating costs for these projects have been greater than the sum of materials and energy revenues. Despite the lack of success in the past, some researchers contend that further work may create technically and economically feasible schemes for retrieving clean recyclables directly from MSW and avoiding the extra step of source separation of recyclables.

Plastic bottles have become an important component of community recycling programs in recent years. Research could be conducted to develop an automatic separation system for plastic bottles. The Center for Plastics Recycling Research at Rutgers University has done considerable work in conceptualizing and developing such a system. In this system, a sensor or a battery of sensors would recognize various types of plastic containers using light transmission, infra-red analysis, bar code recognition, image recognition, or laser sensing. The system would be able to detect different types of plastic containers without regard to their shape, presence of labels, or degree of dirtiness. Currently, however, automatic sorting works only for relatively undamaged, uncrushed plastic bottles. Automatic sorting systems for crushed bottles must be developed if automatic sorting is to be viable, because consumers are urged to crush their plastic bottles to reduce the volume of plastics collected and the costs of collection. (Fernandes and Alex, 1990)

Domestic processing capability for post-consumer plastic film is generally lacking. Almost all plastic film is discarded after a single use. The capability of regenerating film-grade resin from post-consumer plastic film has been demonstrated. Further work could be needed to develop commercial facilities to recover and reprocess post-consumer plastic film. (Nutter, 1990)

Existing shredders, flails, or hammer mills do not adequately size or condition municipal solid waste for effective separation or end use in waste-to-energy applications. RD&D efforts may improve these devices and the quality of the material they produce. (U.S. DOE, 1986)

MRFs need to pay more attention to quality standards. MRF developers could improve separation technology and provide better worker training so that MRFs consistently meet high quality standards for recyclables. For example, magnetic separation devices could be improved so that bi-metal cans are not able to "sneak" through the separation process along with aluminum. Similarly, the air classification process could be improved so that plastics do not remain with aluminum. Also, problems with contamination of aluminum cans with dirt or glass should be reduced. Research efforts should also focus on reducing glass breakage and color mixing and on eliminating contamination of glass with ceramics. (Apotheker, 1990)

MRFs with multiple processing capabilities that allow flexible responses to changing market demands could be designed and demonstrated. For example, because of the volatile nature of the waste-paper market, MRFs could include refuse-derived fuel production from wastepaper and possibly other materials and, in some cases, preparation of paper for composting in addition to material recovery processes. (Grogan, 1989)

## 10.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts (listed in Appendix A) on MRFs are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making MRFs more technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 10-3, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 10.3 is in the right-hand column.

The rationale used by the panel of technical experts is discussed below. The rationale reflects the brief deliberations of the panel; for example, it tends to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus.

The panel gave improving end-user technology (No. 24) the highest ranking because this research was considered to be the most comprehensive. Improvements to end-user flexibility have the greatest potential for increasing markets for secondary materials, which is a critical issue for MRFs. The panel also gave defining separation requirements (No. 2) a high priority.

Research on automated bag identification, sorting, and opening (Nos. 7 and 8) also has great potential benefits, especially for MRFs processing mixed waste streams. The commercial risk in developing these technologies is low. The cost of the research will be relatively low. The impacts of the technology will be realized in the short-term. The automated systems will allow yard waste processing at MRFs and reduce the energy cost associated with waste collection. Some panelists disagreed that these needs should be high

**Exhibit 10-3. Prioritized RD&D Needs for MRFs**

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| 100 | Improve the flexibility of end-user technology to utilize recovered materials | 24 |
| 98 | Define separation requirements for new materials | 2 |
| 98 | Develop an efficient automated bag sorting system | 7 |
| 98 | Develop improved automated bag opening systems | 8 |
| 80 | Develop new uses for mixed paper | 25 |
| 78 | Evaluate past waste and other industry technologies for applicability to MRFs | 9 |
| 75 | Develop standardized product specifications and quality sampling methods | 10 |
| 70 | Build a pilot plant to demonstrate selective solvent dissolution | 23 |
| 69 | Develop detection and monitoring devices | 1 |
| 69 | Identify and mitigate occupational health and safety problems | 17 |
| 60 | Weigh costs/benefits of separation devices as a function of MRF size and type | 18 |
| 56 | Research marketing of construction and demolition wastes | 12 |
| 49 | Develop systems to separate batteries | 6 |
| 45 | Conduct policy analysis to enhance markets for secondary vs. virgin materials | 11 |
| 42 | Characterize air emissions, assess control needs, and develop control methods | 15 |
| 40 | Conduct system study for MRF of the future on capabilities and costs/benefits | 3 |
| 40 | Develop device to separate paper products from commingled containers | 4 |
| 31 | Investigate the pollution control implications of expanding MRFs | 13 |
| 30 | Compare net energy savings of MRFs to other waste management methods | 19 |
| 30 | Develop database on costs and benefits of waste-derived resins | 22 |
| 29 | Develop systems to separate textile fibers (cotton and synthetic) | 5 |
| 27 | Define, characterize, mitigate impacts from, and utilize MRF process residues | 14 |
| 27 | Determine the number of times individual materials can be recycled | 21 |
| 24 | Examine the economic impacts of using secondary materials vs. virgin materials | 20 |
| 18 | Assess impacts of hazardous materials in MRFs and develop handling practices | 16 |

priority, because manual sorting may achieve a higher quality product. However, other panelists gave this need a high priority because it is difficult to get a large enough, reliable labor force to do this work efficiently and consistently. Manual sorting may be especially demanding at facilities processing a large volume of waste.

The panel gave developing new uses for mixed paper (No. 25) a high priority because paper represents such a substantial portion of the waste stream. The panel also considered developing standardized product specifications and quality control sampling methods (No. 10) a major RD&D need because of its potential market stabilizing effects.

The need to demonstrate selective solvent dissolution (No. 23) would have ranked high because of its potential energy benefits. However, some panelists believed that it was too specific an approach to solving the problem of resin recovery and that the technology would not have a widespread impact. Furthermore, some research is currently being done on the process, albeit at a basic level.

Panelists believed that development of devices to detect contamination (No. 1) would be a risky research investment. The development could be costly with a low probability of success. However, the potential benefits of such research are high and the technology, if successful, would be flexible with a wide range of applications.

Although the panel noted that research on beneficial uses for construction and demolition wastes (No. 12) is important because it addresses critical market issues, this need did not rank very high because it focuses specifically on one waste stream. There was disagreement about the importance of policies to make secondary materials competitive with virgin materials (No. 11). Some panelists gave it a high priority because of its source reduction potential. Others believed that this RD&D need was not appropriate under a research program dedicated to MRFs.

Air emissions (No. 15) were not considered a serious problem, although RD&D in this area was ranked higher by those who believe it would contribute to research on occupational health and safety (No. 10). The panel considered the system study to forecast capabilities for the MRF of the future (No. 3) a risky research investment. Panelists were skeptical about the possibility of accurately predicting future trends. The recycling infrastructure would probably be in place before the study could effect its development.

The panel gave separating co-mingled paper from co-mingled containers (No. 17) a low priority. Source separation of paper before reaching the MRF was considered to be a much more effective approach. Automated approaches would probably involve pulping paper and would make MRF operations more difficult and complex. Comparison of the net energy benefits of MRFs to other waste technologies was ranked low for two reasons: its focus on energy alone is too narrow and it is not a need unique to MRFs. Systems to separate cotton from other fibers (No. 5) were given low priority because cotton is a small percentage of waste stream and it is a renewable resource so the value of recovering it is limited. Furthermore, textiles are combustible so it may be more efficient to burn this waste stream for energy recovery. The panel believed that the economic impacts on production of substituting secondary materials for virgin materials (No. 20) was probably not an RD&D need appropriate to a research program focused on MRFs.

Research on hazardous materials in MRFs (No. 16) got the lowest priority. The panel believed that this was not a research issue, but rather a problem to be dealt with by operators on a site-specific basis as it arises.

## 10.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate MRF research with respect to some of the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for

the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

A national research program on MRFs would cost approximately $5 million per year. The end-user work (No. 24) would be the most expensive component.

### Commercial Development Risk

There is no real commercial development risk associated with MRFs. Availability of markets is the only big concern. Many observers believe that the lack of markets will limit the continued development of MRFs. Although there have been problems in siting specific facilities, overall public acceptance is good.

### Flexibility

Currently, MRFs process a small percentage of MSW. But if market goals are reached, MRFs could handle much more of the waste stream, at least 30 percent.

### Net Energy Benefit

The amount of energy conserved through MRF use is unknown. There is significant energy conserved in manufacturing with materials recovered by a MRF, but it is not known how this balances with energy consumed in extracting materials.

### Appropriateness for Government Funding

While research on the environmental and health and safety aspects of MRFs may not be appropriate for DOE funding, DOE is already conducting research in other areas, specifically economics.

# 11. MODULAR MASS-BURN COMBUSTION SYSTEMS

## 11.1 Technology Description

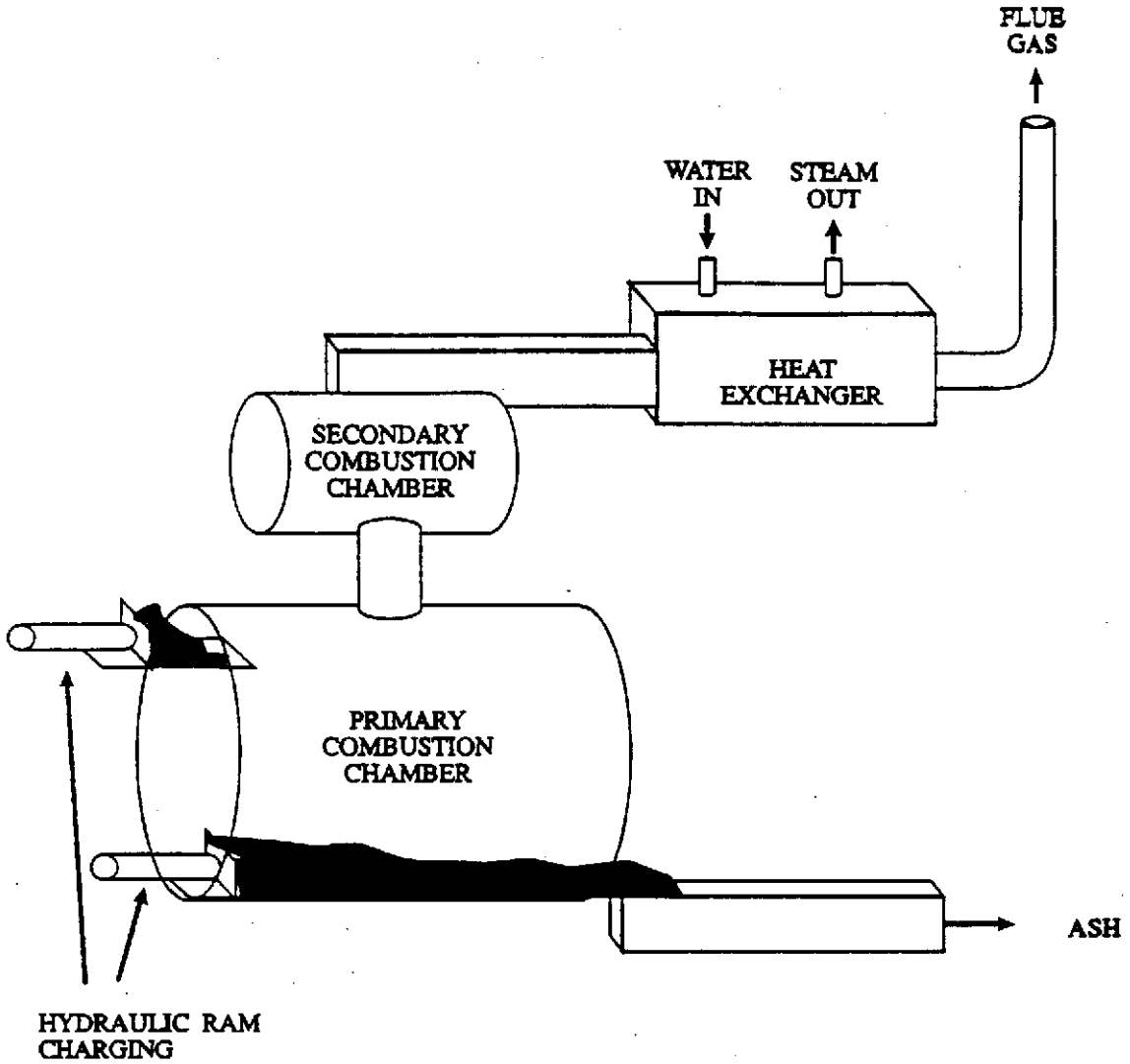
Modular combustors, a subset of mass-burn combustors, burn municipal solid waste to recover energy in the form of steam. Modular combustors differ from other types of mass-burn technologies, primarily in being manufactured on an assemby line rather than erected in the field. Most of them have two refractory-lined combustion chanbers, with the first chamber operated at substoichiometric conditions and low gas flows and the secondary chamber providing excess air to complete combustion. Also, modular combustors have tended to be prefabricated, small capacity units, with lower development costs than mass-burn combustion systems. Many of the units were designed to take advantage of the old Federal Clean Air Act regulations that exempted units burning up to 50 tpd of MSW from the new stationary source emission requirements. Thus, the capacity of a single modular unit is usually less than 50 tons per day of MSW (with some exceptions), although more than one unit may operate at an individual site (Scaramelli, 1979; Robinson, 1986). The MSW that is fed to modular units usually undergoes little or no preprocessing. Because of their small capacity, modular combustors are often used for MSW combustion in smaller communities, commercial applications (e.g., at hospitals for medical waste), and industrial operations.

In a typical modular combustor, MSW is stored on a flat tipping floor at ground level. Front-end loaders or bulldozers feed MSW into floor-level hoppers at the front of the combustor. As shown in Exhibit 11-1, feed rams move the waste into the primary combustion chamber resulting in a cyclic or semi-continuous, rather than continuous, operation. This semi-continuous feed system results in cyclic variations in temperature and combustion atmosphere (e.g., from reducing to oxidizing conditions) that wear out equipment and refractory lining and generally reduce the useful life of a modular combustion system prior to major repair. Once in the primary combustion chamber, a series of transfer rams or a moving grate system moves the MSW through the furnace while it is burned. Most of the systems that transport MSW through the primary chamber agitate the waste in order to expose the maximum amount of surface area for combustion (Robinson, 1986; Siddens, 1990).

The primary combustion chambers are classified as either "starved air" or "controlled air". "Starved air" combustors limit the amount of air entering the chamber, which reduces peak combustion rates and reduces the magnitude of temperature fluctuations and thermal stress in the system. Limiting the amount of air causes the MSW to undergo partial pyrolysis, releasing gases and particulates that then enter the secondary combustion chamber (Robinson, 1986; Siddens, 1990). This partial pyrolysis also results in an incompletely burned residue, which causes modular combustion units to commonly generate more bottom ash per ton of waste burned than the other types of waste-to-energy facilities (Berenyi and Gould, 1988; Robinson, 1986; U.S. Congress, 1989). "Controlled air" systems have better combustion efficiency (i.e., they burn waste more completely) than "starved air" modular systems because they do not limit the amount of air entering the primary combustion chamber. Combustion efficiency, however, is still less than that achieved by other mass-burn technologies (Robinson, 1986).

Gases generated from burning MSW in the primary chamber flow into an upper, secondary combustion chamber. Additional air is added to complete combustion. The secondary chamber may be equipped with auxiliary burners to maintain adequate combustion

**Exhibit 11-1. Schematic of a Typical Modular Combustion System**



temperatures and to ensure that the waste undergoes complete combustion (Robinson, 1986; Scaramelli, 1979; Siddens, 1990). Hot combustion gases exit the secondary chamber into a waste heat boiler that generates steam. A superheater section is sometimes used to produce high-quality steam (Robinson, 1986; Siddens, 1990).

Vendors of modular combustors sometimes claim that the units do not require air pollution control equipment (Robinson, 1986; Scaramelli, 1979). Currently, units burning up to 250 tpd are effectively exempt from stationary source performance standards other than particulate standards. However, the U.S. EPA is mandated under the Clean Air Act Amendments to promulgate new standards for new municipal waste combustors (MWCs) and emission guidelines for existing MWCs that burn less than 250 tpd of MSW at the end of 1992. Uncontrolled particulate emissions from modular combustors may be lower than those from other types of mass-burn combustors because the limited air intake of modular units reduces air velocity in the primary chamber, thereby reducing the entrainment of ash in the flue gas (Scaramelli, 1979).

## 11.2 Technology Status

As of September 1990, 50 modular combustion facilities were operating in the United States, comprising approximately 35 percent (by number) of the waste-to-energy facilities in the United States (Klass, 1990; Science Appl. Intl. Corp., 1986; Kiser, 1990). The U.S. facilities were located in 41 states and Puerto Rico and had a combined annual capacity of 1.8 millon tons MSW. Six facilities were operating in Canada at this time; they were distributed across three provinces and had a combined annual capacity of 0.2 million tons MSW (Klass, 1990; Science Appl. Intl. Corp., 1986; Kiser, 1990).

As of 1990, 32 of the 50 operating modular facilities were equipped with air pollution control equipment, the majority of which were using electrostatic precipitators (ESPs) (16) and scrubbers, and/or fabric filters (11), while the remainder utilized scrubber/ESP combinations (2), lime injection (1), continuous emissions monitoring (1), and cyclone separation (1). Only four existing modular facilities process their waste stream (i.e., recover recyclable materials) before combustion. The majority of owners (79 percent) and operators (65 percent) of modular facilities are public entities. (Klass, 1990; Science Appl. Intl. Corp., 1986; Kiser, 1990)

As of 1990, nine modular facilities were inactive, in the planning stages, or under construction in the U.S. If all these facilities were to commence operations, they would increase the annual modular combustion capacity by about 0.35 million tons of MSW (or 20 percent) (Kiser, 1990). As of 1988, the majority of existing modular facilities were situated in the north central and southern regions of the U.S., while most of the facilities now being planned are in the north central and northeast regions. On average, the planned modular facilities have slightly higher design capacity than the existing facilities (Berenyi and Gould, 1988). In contrast to the existing facilities, as of 1988, only 33 percent of the planned modular facilities in the U.S. were projected to produce steam as their sole energy project, while a much higher percentage, 50 percent, were designed to generate only electricity. (In 1988, 60 percent of the U.S. modular combustion facilities generated steam as their sole energy product.) (Berenyi and Gould, 1988)

## 11.3 Description of RD&D Needs

The primary RD&D needs for modular combustion systems are associated with the need to gain public acceptance of the technology, waste preprocessing, and determining the relationships among combustion chamber design, operating conditions, and air emissions. The RD&D needs associated with the disposal of ash from modular combustion systems are addressed separately in the chapter on ash disposal and utilization. In general, the RD&D needs for modular combustion systems are very similar to those for other types of mass-burn combustion systems. The priority of the RD&D needs are different, however, and the RD&D needs for modular combustion tend to be less-well defined than those for other types of mass-burn combustion systems.

Sections 11.3.1 through 11.3.8 describe the RD&D needs for modular combustion that were identified by the panel of technical experts (listed in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 30) that is used in later Section 11.4 where the RD&D needs are prioritized. Section 11.3.9 describes RD&D needs that were identified by the literature review (see Section 1.2 on methodology), but were not subsequently accepted by the panel of technical experts. The RD&D needs in Section 11.3.9 are not prioritized or discussed further.

### 11.3.1 Waste Preprocessing

The presence of steel, glass, and other non-combustible materials in MSW reduces the heating value of the waste and contributes to problems with slagging, fouling, clinker formation, and air emissions (Science Appl. Intl. Corp., 1986). As a result, waste preprocessing to remove portions of the MSW that are non-combustible or otherwise undesirable can have a significant impact on system performance and cost. Discussions of the RD&D needs associated with source separation and mechanical on-site separation, the two most common approaches to preprocessing, can be found in the chapters source separation and material recovery facilities. Research needs associated with the application of source separation to modular combustion are discussed in this section.

While source separation does not generally have much effect on the heat content of MSW, it can have a significant effect on ash composition and air emissions. Also, since modular combustion systems are often used to burn the waste from a single organization, there are greater opportunities to employ source separation. Past studies of the impact of source separation on ash composition, however, have not been conclusive and additional research is needed to:

1. Evaluate the impact of source separation on the economics and ash composition for modular combustion systems, and confirm this impact with a demonstration project.

Mechanical on-site separation can, like source separation, affect air emissions and ash composition. Achieving a level of separation that has a significant effect on air emissions and ash composition is both expensive and technically difficult, though the technology does exist. While a more detailed description of the RD&D needs for this technology can be found in the chapter on materials recovery facilities, research is needed to:

2. Develop inexpensive and reliable technologies to remove the non-combustible components of MSW (Science Appl. Intl. Corp., 1986), and evaluate their impact on economics and ash composition.

### 11.3.2 MSW Feed Systems

Most modular combustion systems feed MSW to the combustion chamber in batches with a hydraulic ram or trap door mechanism. This intermittent charging of waste to the combustion chamber coupled with small combustion chambers results in a cyclic combustion process that makes it difficult to maintain steady-state operating conditions. The resultant variations in the operating conditions (e.g., temperature, combustion rate, and moisture) make it difficult for system operators to control both the thermal performance of the system and the air emissions that are influenced by the operating conditions. The constantly changing operating conditions also increase maintenance costs and decrease the operating life of the system (see Section 11.3.4). Research is needed to:

3. Develop mechanisms for feeding a continuous stream of MSW to modular combustion systems (Science Appl. Intl. Corp., 1986);

4. Develop dual MSW feed systems (e.g., two sets of rams that feed waste to the same combustion chamber) to approximate a continuous feed stream; and

5. Improve methods for controlling fugitive emissions from the tipping floor and feed system.

### 11.3.3 Combustion Chamber Design

In modular combustion units it is important to maximize the mixing of air in order to maintain an adequate combustion rate, while minimizing turbulence in the combustion chamber, which can increase particulate air emissions. At the same time, furnace temperatures must be kept low enough to keep slagging and corrosion at acceptable levels (Science Appl. Intl. Corp., 1986; Scaramelli, 1979). Research is needed to:

6. Determine the relationships among combustion chamber design, operating conditions, and air emissions, and identify the parameters with the greatest influence (Zimmerman and Isaacson, 1989; Landrum, et al., 1989; Buekens, 1989; Finkelstein, 1991; Dent and Krol, 1990; Energy and Environmental Research Corp., 1987);

7. Establish a database containing information on combustion chamber designs and the relationships between combustion chamber design, operating conditions, and air emissions;

8. Study the relationships among furnace geometry (e.g., number of stages), volume, temperature, and residence time;

9. Improve systems for automatically monitoring and controlling combustion parameters; and

10. Develop grates that improve combustion through better air circulation (Science Appl. Intl. Corp., 1986).

The refractory lining and the steel anchors used to attach the lining to the furnace walls tend to have a shorter life in modular combustion systems than in other types of mass-burn systems. This shorter life is due to the combination of mechanical vibrations caused by the mechanisms: usually hydraulic rams or vibrating grates, used to move waste into and through the combustion chamber; thermal stresses from temperature variations within the combustion chamber; and a combustion atmosphere that alternates from being reducing to oxidizing because of the semi-continuous feed system. Research is needed to:

11. Develop more durable refractory materials or other methods of increasing refractory life (Science Appl. Intl. Corp., 1986; Scaramelli, 1979; Robinson, 1986); and

12. Evaluate the advantages and disadvantages of using waterwalls instead of refractory lining.

### 11.3.4 Slagging and Fouling

Slagging and fouling can adversely affect heat transfer. Slagging occurs when the ash reaches the temperature at which it starts to fuse and adhere to boiler-tube surfaces. Fouling occurs when ash particles bind together (possibly caused by the condensation of materials vaporized in the furnace) and adhere to convection-pass tubes. Research is needed to:

13. Determine the slagging points (i.e., fusion temperature) of different waste constituents so that the waste stream can be screened to remove materials that result in slagging or the furnace can be operated at temperature that minimizes slagging (see Section 11.3.1);

14. Study the chemical and physical mechanisms of slagging and fouling to help develop methods, equipment, and chemicals to prevent and/or treat the effects of slagging and fouling;

15. Determine operating practices and furnace conditions that minimize slagging and fouling (Scaramelli, 1979; Science Appl. Intl. Corp., 1986), and then disseminate this information;

16. Improve equipment and chemicals for cleaning surfaces in the furnace and air pollution control devices;

17. Evaluate the environmental impacts of operating methods, equipment, and cleaning chemicals developed to prevent and/or treat the effects of slagging and fouling; and

18. Establish a system for disseminating information and technology about slagging and fouling, and investigate recent research performed in other countries, especially Europe.

### 11.3.5 Energy Recovery Efficiency

The energy recovery efficiency of modular combustion facilities is relatively low when compared to both coal-fired power plants and other types of mass-burn facilities. This lower efficiency is due primarily to the greater amount of excess air used in modular systems: 150-200 percent in modular mass-burn combustion systems versus 70-80 percent in other mass-burn combustion systems. Therefore, for flue gas leaving the boiler system at a given temperature, more heat will be lost in a modular system than a mass-burn system.
As with other types of mass-burn combustion systems, modular systems are less efficient than coal-fired systems because of the lower temperature and pressure of the steam generated. Factors that keep modular mass-burn facilities from producing steam at higher temperatures and pressures are (1) corrosion problems associated with contaminants, particularly chloride, found in MSW that increase with temperature and (2) the high moisture content of the refuse. Research is needed to:

19. Develop systems able to operate at higher temperatures in order to generate steam at higher temperatures and pressures (Science Appl. Intl. Corp., 1986; Scaramelli, 1979), that utilize superheaters or dual-fluid systems (Scaramelli, 1979), and/or recover additional heat from furnace exit gases; and

20. Evaluate the value and trade-offs of using supplemental fuels (e.g., coal, gas, waste oil, and solvents) to produce higher furnace temperatures, while considering the effect of MSW moisture content on temperature.

### 11.3.6 Boiler Tube Corrosion

While methods to control the corrosion of metal surfaces in modular combustion units have been developed, these methods have some disadvantages and have not been completely successful. Specifically, refractory coatings such as silicon carbide reduce corrosion, but require frequent maintenance; corrosion resistant metals such as Incoloy® and Inconel are available, but are expensive and not always readily available. While the furnace can be run at a lower temperature to reduce corrosion, this reduces the system's energy recovery efficiency (see Section 11.3.6). Research is needed to:

21. Develop boilers that are more resistant to corrosion, particularly corrosion caused by chlorine; and

22. Develop air pollution control devices that are more resistant to corrosion.

### 11.3.7 Characterization and Control of Air Emissions

Until recently, MSW combustors with a capacity of 50 tpd or less were exempt from the Clean Air Act emission requirements for new stationary sources. Since many modular combustion systems have a capacity of 50 tpd or less, the control of air emissions from modular combustion systems has received less attention than it might otherwise have. However, the recently promulgated air standards for new municipal waste combustors (MWCs) and the emission guidelines for existing MWCs (see 56 Federal Register 5488, February 11, 1991) have had the effect of raising the exemption cut-off from 50 to 250 tpd. While facilities

that burn up to 250 tpd MSW have a de facto exemption from air emission standards except for particulate standards until EPA issues standards (mandated by late 1992), research is needed on a variety of topics to ensure that modular combustion systems will be able to meet future standards.

Stack emissions need to be sampled for pollutants such as CO, $SO_2$, $NO_x$, HCl, and trace toxins in order to satisfy regulatory requirements. For example, stack samplers able to assess the mutagenic potency of organic and particulate emissions and to collect samples for carcinogenicity assays have been developed. They require, however, improvements to reduce costs, simplify their use, and to solve problems with their corrosion caused by emission gases (see No. 22 in Section 11.3.6) (Watts, et al., 1989). Research is needed to:

23. Develop simple low-cost stack sampling methods and evaluate the available sampling methods with respect to their practicality.

The use of surrogates to monitor air emissions can be very effective. Research is needed to:

24. Improve and demonstrate surrogate monitoring equipment and techniques.

Continuous monitoring methods for both criteria and toxic pollutants (e.g., PCDDs and PCDFs) is important to satisfy public concerns and regulatory requirements. For example, despite their low concentrations, PCDDs and PCDFs pose a potential hazard and need to be monitored. Research is needed to:

25. Develop less expensive conventional and innovative methods for the continuous collection and analysis of air emissions for both criteria and toxic pollutants (Rappe, et al., 1989; Finkelstein, 1991).

While technology is available for controlling the emission of particulates and sulfur dioxide, this technology could be improved. In addition, the technology for controlling the emission of other pollutants is less developed. Thus, research is needed to:

26. Reduce the cost of acid gas air pollution control devices (e.g., less expensive substitutes for lime as an acid gas sorbent);

27. Develop methods for controlling mercury emissions (U.S. Environmental Protection Agency, 1991); and

28. Develop methods for controlling chromium and cadmium emissions.

### 11.3.8 Assessment of Health Risks

Public acceptance could have a large influence on the viability of modular combustion technology. Since MSW must be managed one way or another, public acceptance of a particular technology depends heavily on how its risks and costs compare with those of the alternative technologies. In order to make these comparisons, research is needed to:

29. Estimate and compare the health risks associated with modular combustion to those associated with other MSW technologies; and

30. Estimate the marginal reduction of risk to human health resulting from small reductions in air emissions in order to evaluate the trade-offs between control costs and risks to human health.

### 11.3.9 Other Potential RD&D Topics

The following RD&D topics were identified in the literature review, but were not subsequently accepted by the panel of technical experts.

Determine the relationships between operating parameters and air emissions. Research could determine the thermodynamics and reaction pathways involved in the formation and degradation of PCDDs and PCDFs. The results of this research may help design modular combustion systems and operating procedures that discourage the formation of PCDDs and PCDFs (Dent and Krol, 1990; Energy and Environmental Research Corp., 1987).

Develop methods to sample and characterize air emissions containing complex mixtures of organics. The air emissions from municipal waste combustors (MWCs) may contain thousands of different organic constituents, some of which are potentially hazardous (e.g., toxic, carcinogenic, and mutagenic). While it is important to characterize and monitor the stack air emissions to determine if they pose a risk to human health or the environment, the large number of potential constituents makes it impractical to routinely test for each constituent.

Bioassays, which can be used to evaluate the potency of different biological effects of a chemical or mixture of chemicals (e.g., toxicity, carcinogenicity, and mutagenicity), may be useful for characterizing MWC air emissions. More research, however, is needed to investigate how bioassays may be applied to MWC air emissions. In particular, methods are needed to separate toxic constituents from the samples that interfere with the mutagenicity assay (Watts, et al., 1989).

Establish sources of and background levels for PCDDs and PCDFs. A variety of combustion sources (e.g., steel mills, copper smelters, and motor vehicles) other than MWCs emit significant quantities of PCDDs and PCDFs (Hattemer-Frey and Travis, 1989). Given the concern about PCDDs and PCDFs in general, and about MWCs as a potential source of these chemicals in particular, new research could determine whether MWCs are a significant source of PCDDs and PCDFs in the environment relative to other sources (Hattemer-Frey and Travis, 1989). Specifically, data would be needed to (1) determine the background concentrations of PCDDs and PCDFs in air, soil, and vegetation; (2) assess background human exposure to PCDDs and PCDFs; (3) quantify PCDD and PCDF levels in environmental samples collected near facilities known to emit PCDDs and PCDFs; and (4) quantify PCDD and PCDF emissions from vehicles that use unleaded gasoline and diesel fuel (Hattemer-Frey and Travis, 1989). Similarly, new data could be developed to determine and compare mutagen concentrations in air samples collected upwind and downwind from incinerators (Watts, et al., 1989).

Develop and improve flue gas cleaning technology. While the technology for controlling the emission of particulates and sulfur dioxide in flue gas works reasonably well, operational problems have been encountered that require additional research and development. For example, semi-dry scrubbing systems have had problems with scaling; dry scrubbing systems have had problems with the air pollution control residue solidifying; and wet scrubbing systems have had problems with both corrosion and fouling (Buekens, 1989).

Develop methods to characterize and screen MSW before combustion. The composition and physical characteristics of MSW have a major impact on boiler performance and the characteristics of air emissions and ash. By monitoring and screening the MSW being fed to a furnace, boiler performance can be improved and potentially hazardous air emissions can be reduced (Hayes, 1990; Dent and Krol, 1990). Instrumentation needs to be developed to monitor the composition and physical characteristics of MSW that influence combustion and the characteristics of air emissions and ash (Tinning, 1985). Also, it would be useful to those designing modular combustion systems if the available information on existing monitoring and screening techniques were compiled and evaluated (Dent and Krol, 1990).

## 11.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on modular combustion (listed in Appendix A) are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making modular combustion technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 11-2, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 11.3 is in the right-hand column. The rationale discussed by the panel of technical experts is summarized below. The rationale tend to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

The expert panel assigned the highest priority to assessment of the health risks associated with modular combustion (No. 30) because it is important to change the public perception that modular combustion poses a serious risk to human health. Without a change in this negative image, the financial risks may be too high for potential investors. Some panel members, however, believe that research to assess the health risks would be a waste of time because a large amount of money could be spent without producing conclusive results.

Evaluating the impacts of source separation on economics and ash composition (No. 1) was given a high priority, much higher than it was given for mass-burn combustion, because modular combustion systems are often used to burn waste from a single organization. Within a single organization, the task of creating an effective source separation program is relatively simple. Thus, there are significant opportunities to improve combustor performance and reduce the concentration of pollutants in the ash through source separation.

## Exhibit 11-2. Prioritized RD&D Needs for Modular Combustion

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| 100 | Estimate and compare health risks of modular with other MSW technologies | 29 |
| 100 | Evaluate the impact of source separation on the economics of modular units | 1 |
| 90 | Determine the relationships among design, operating conditions, & air emissions | 6 |
| 80 | Develop boilers that are more resistant to corrosion | 21 |
| 80 | Reduce the cost of acid gas air control pollution devices (e.g., lime substitutes) | 26 |
| 75 | Estimate the marginal reduction of risk to human health for air emission reductions | 30 |
| 75 | Develop simple low-cost stack sampling methods and evaluate their practicality | 23 |
| 70 | Develop mechanisms able to feed a continuous stream of MSW to the combustor | 3 |
| 63 | Study relationships among furnace geometry, volume, temp., & residence time | 8 |
| 63 | Improve systems for automatically monitoring and controlling combustion | 9 |
| 60 | Develop methods for controlling mercury emissions | 27 |
| 60 | Develop air pollution control devices that are more resistant to corrosion | 22 |
| 60 | Develop methods for controlling chromium and cadmium emissions | 28 |
| 60 | Develop systems that generate have a higher energy recovery efficiency | 19 |
| 54 | Evaluate the use of supplemental fuels to produce higher furnace temperatures | 20 |
| 45 | Improve and demonstrate surrogate monitoring equipment and techniques | 24 |
| 45 | Develop more durable refractory materials | 11 |
| 45 | Establish a database with data on design, operating conditions, and air emissions | 7 |
| 45 | Develop less expensive continuous air emission collection and analysis methods | 25 |
| 41 | Develop grates that improve combustion through better air circulation | 10 |
| 35 | Study the chemical and physical mechanisms of slagging and fouling | 14 |
| 35 | Develop dual MSW feed systems to approximate a continuous feed stream | 4 |
| 14 | Determine operating practices & furnace conditions to minimize slagging & fouling | 15 |
| 14 | Establish a system for disseminating information about slagging and fouling | 18 |
| 14 | Determine the slagging points of different waste constituents | 13 |
| 9 | Evaluate using waterwalls vs. refractory lining | 12 |
| 7 | Improve equipment and chemicals for cleaning furnace and APC surfaces | 16 |
| 7 | Improve methods to control fugitive emissions from the tipping floor & feed system | 5 |
| 2 | Evaluate the environmental impacts of methods to control slagging and fouling | 17 |
| 0 | Evaluate the impact of mechanical separation on economics and air emissions | 2 |

Determining the relationships among combustion chamber design, operating conditions, and air emissions (No. 6) may help design modular mass-burn combustion chambers that discourage the formation of PCDDs, PCDFs, and other pollutants of concern (Dent and Krol, 1990; Energy and Environmental Research Corp., 1987; Scaramelli, 1979). The panel was divided on the importance of this research. The panelists from the commercial sector believe that the need has already been fulfilled by past research, whereas the panelists from the academic community believe that a more systematic understanding is required.[1]

The RD&D needs pertaining to the characterization and control of air emissions (Nos. 23-28) (see Section 11.3.7) were given high to medium priorities, primarily because of their potential influence on public acceptance of modular combustion. The development of methods to control mercury emissions (No. 27) is given a high priority because the waste from hospitals, a typical user of modular combustion systems, is expected to contain a relatively high proportion of mercury containing batteries. The development of less expensive methods for continuous collection and analysis of air emissions has a medium priority for two reasons: (1) the need to reduce operating costs, and (2) the ability to tell the public that air emissions are continuously monitored for pollutants of concern could be an important factor in gaining public acceptance of modular combustion (No. 25).

Developing systems to feed a continuous stream of MSW to the combustor (No. 3) and to automatically monitor and control combustion (No. 9) are given a high priority because the cyclic operation of modular combustors has an adverse impact on air emissions and maintenance costs.

Establishing a database with information on combustion chamber design, operating conditions, and air emissions (No. 7) is given a medium priority because many of the problems with modular combustion systems are site-specific and much of what is learned is not shared among operators. No means to routinely disseminate such information is available.

## 11.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate modular combustion with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The cost of implementing an RD&D program that consists of the prioritized RD&D needs should be less than most of the 11 other MSW technologies being considered in this report.

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[1] One reviewer believes that it is more important to focus future RD&D on developing affordable and more effective flue gas cleaning systems than it is to study the relationship between operating conditions and air emissions.

### Difficulty of Technology Development

The panel was divided on whether most of the technical problems associated with modular combustion have been solved. Panel members from the research community tend to believe that considerable work remains to be done on the relationships between source separation and air emissions and on air pollution control devices. On the other hand, panel members involved with commercial operations tend to believe that many of the technical problems have been solved and that public education and cost-benefit demonstrations are the primary need.

### Commercial Development Risk

The primary sources of risk for commercial development appear to be public and political acceptance, both of which vary significantly.

### Net Energy Benefit

Waste-to-energy technologies currently supply about 0.25 percent of the nation's energy.

### Human Health and the Environment

Due to the mature nature of this technology, all of the environmental impacts are regulated and the relationships between these impacts and combustor operations are relatively well understood.

### Appropriateness for Government Funding

Given the need for impartiality, an assessment of the health risks associated with modular combustion is viewed as a project that would be appropriate for funding by DOE. In addition, the panel members believe that DOE should keep abreast of the research being done by vendors and aid it when possible. Reducing the cost of acid gas air pollution devices, however, may not be an appropriate project for funding by DOE. DOE funding is probably not needed to develop methods of controlling mercury emissions, since industry appears to be already working on the problem.

# 12. PYROLYSIS

## 12.1 Technology Description

Pyrolysis is generally defined as the thermal decomposition of a material in an oxygen free atmosphere to maximize liquid and/or solid product. Over the last century, pyrolysis processes have been applied commercially to produce fuels and chemicals, such as charcoal, methanol, turpentine, coke, acetic acid, and acetone, from materials including wood, peat, coal, and heavy oils. More recently there has been interest in using pyrolysis to convert prepared MSW into storable fuel oils (Reed, 1988; Robinson, 1986).

Pyrolysis systems that use MSW as feed usually accept waste that has undergone substantial preprocessing, including shredding and removal of non-organics, the equivalent of fine or powdered RDF (see the chapter on RDF production and co-fired combustion). Most pyrolysis processes generate a carbonaceous residue, known as char, along with the liquid tar or oil that is the primary product. There are a variety of pyrolysis systems. Pyrolysis may occur in a vertical shaft reactor (with a fixed bed or a fluidized/entrained bed), a horizontal (eg. cyclonic) reactor, or a rotary kiln. Reactors may be heated indirectly, with heat applied through a sealed medium, wall, or through recirculating hot solids.

The raw liquid product of ligno-cellulosic pyrolysis is often referred to as biocrude oil or pyrolysis oil. In some cases, the oil may be used directly as fuel without refining. However, because MSW and biomass have a high oxygen content, their pyrolysis products also tend to have a high oxygen content, limiting their heating value (Diebold and Stevens, 1990; Brooks, 1984; Helt, et al., 1984). The oil formed by fast pyrolysis, in particular, tends to have a very high oxygen content (essentially identical to the feed) (Diebold and Stevens, 1990). Furthermore, MSW pyrolysis oil may be corrosive and unstable during storage due to the presence of constituents such as acids and phenols. Exposure to air may cause constituents in the oil to polymerize and cause the oil to become more viscous with time (Helt, et al., 1984). Because of these characteristics, MSW pyrolysis products usually require upgrading to improve their storage life and heat content (Diebold and Stevens, 1990; Helt, et al., 1984; Robinson, 1986). Two methods for upgrading pyrolysis oil are catalytic hydrogenation and zeolite catalysis.

- Catalytic hydrogenation utilizes hydrogen gas and a metallic catalyst (e.g., cobalt-molybdenum) to deoxygenate pyrolysis oil. Catalytic hydrogenation may also crack the heavy fraction of the oil into molecules with lower molecular weight similar to those found in gasoline. The process typically occurs at high pressure in two stages. The first stage partially deoxygenates the oil and stabilizes it to prevent polymerization, and the second stage completes the deoxygenation. Catalytic hydrogenation may be applied to the products of both catalytic high pressure pyrolysis and low pressure fast pyrolysis. (Diebold and Stevens, 1990; "Petroleum," 1982; Helt, et al., 1984)

- Pyrolysis oil may also be upgraded at atmospheric pressure without added hydrogen through the use of zeolite catalysts. The purpose of this process is to crack heavy molecules in the oil and convert them to smaller, lower molecular weight molecules while rejecting oxygen as CO and $CO_2$. Zeolite catalysis is best used on pyrolysis products in vapor form, therefore it is applicable mainly in combination with fast pyrolysis. Pyrolysis vapors from fast pyrolysis are passed through a catalytic cracking reactor before they are cooled and condensed, resulting in an upgraded final product. (Diebold and Stevens, 1990; "Catalysis," 1979)

## 12.2 Technology Status

There are no full-scale commercial MSW pyrolysis facilities currently operating in the United States. In the early 1970s several important pyrolysis initiatives were started in the United States and Japan. The work on MSW pyrolysis systems that has been done in the United States was confined to pilot projects and research facilities in the mid to late 1970s. Nearly all of the recent RD&D on pyrolysis in the United States has focused on the use of wood as a feedstock. The densely populated portions of Western Europe, which were already utilizing modern incinerator plants, did not follow as quickly in the investigation of alternative technologies such as pyrolysis (Hainsworth et al., 1983; Hasselriis, 1983; Hickman, 1983; Hopper et al., 1983; Keuster, 1983; Leeper et al., 1982; Pfeffer and Isaacson, 1983; Ridzon et al., 1983; Trezek, 1983; Turner, 1983; Zimmerman et al., 1983).

A variety of MSW pyrolysis processes have been successfully demonstrated in laboratory-scale systems using hand-picked waste. When full-scale MSW pyrolysis systems were tested in the 1970s, however, they generally failed because of mechanical problems with MSW automatic feed mechanisms, difficulties with oil recovery, high costs relative to competing technologies. The panel generally felt that the pyrolysis process itself was not the primary cause of failure in the attempts to operate full-scale MSW pyrolysis systems. In the United States, large-scale pyrolysis plants for the conversion of refuse derived fuel (RDF) to fuel oil have been designed and built, but they failed to meet initial expectations. During the 1970s, with the assistance of the U.S. EPA, both Monsanto and Garrett Research and Development constructed MSW pyrolysis facilities. Their performance, however, was disappointing (Diaz, 1985). One of the facilities, built in El Cajon, California, was designed to utilize low pressure flash pyrolysis on the organic fraction of MSW to produce liquid boiler fuel. A series of mechanical and operational problems plagued the facility, however, and it was eventually closed (Scahill and Diebold, 1988). In recent years, progress in converting biomass to oil using solid convective heat transfer techniques has raised expectations for the successful application of these techniques in RDF pyrolysis (Scahill and Diebold, 1988).

As of 1984, a number of Japanese firms had performed extensive research, development, and demonstration on the pyrolysis of MSW. Tsukishima Kikai Co., Ltd. operated a pilot facility for two years in the late 1970s, and, in 1979, Funabashi City decided to build a commercial scale MSW pyrolysis facility processing 450 tons per day of municipal wastes. While construction was completed in 1981, the facility became operational well after the projected start-up date. Ebara Corporation conducted laboratory-scale pyrolysis research and constructed a 30 ton per day pyrolysis demonstration plant in Yokohama, Japan for performance analysis (Kuester, 1984).

In 1986, the main activity in pyrolysis research and development in Europe could be divided into two areas:

- Pyrolysis of household refuse and industrial wastes in a rotary kiln, operating at low to medium temperatures; and

- Specialized pyrolysis processes to recover chemicals from rubber and other wastes or metals from composite waste.

In 1988, an analysis of waste-to-energy research and applications in the United Kingdom, Sweden, and Canada identified no commercial pyrolysis facilities operating in any of these countries (Dent and Krol, 1990). Several European MSW pyrolysis initiatives have been abandoned or stopped, though there is strong current interest in biomass pyrolysis (Bridgwater, 1992).

## 12.3 Description of RD&D Needs

Each of the RD&D needs associated with pyrolysis tends to focus on the generation and compilation of fundamental data that can be used to identify new pyrolysis processes, scale up existing processes, or design equipment to upgrade pyrolysis products. Due to the scarcity of full-scale pyrolysis facilities, very little is reported in the relevant technical literature about the need for RD&D on such topics as fuel preparation, the control of air emissions, or the disposal of residues. It is likely that additional RD&D needs in these areas will be identified if and when the development of full-scale facilities begins.

Sections 12.3.1 through 12.3.8 describe the RD&D needs for MSW pyrolysis that were identified by the panel of technical experts (listed in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 28) that is used in section 12.4 where the RD&D needs are prioritized.

### 12.3.1 Basic Research on Pyrolysis Processes

The characterization of chemical reactions that occur during pyrolysis and the mechanisms of these reactions play an important role in the identification and subsequent development of pyrolysis processes. One method that has been used to develop this knowledge is real-time monitoring of operating conditions and pyrolysis product composition by molecular beam mass spectrometry, followed by multivariate statistical analysis. The results of this analysis have been useful for identifying mechanisms of pyrolysis and the effects of process variables on product yield and composition (Diebold, et al., 1990; Evans and Milne, 1988; Evans, et al., 1988).

While some work has already been done to characterize selected pyrolysis processes, a substantial amount of research remains to be done. Research is needed to:

1. Establish reliable mass and energy balances for potential pyrolysis processes;

2. Refine the use of techniques for real-time monitoring of pyrolysis product composition (e.g., molecular beam mass spectrometry);

3. Generate data on MSW pyrolysis and its products over a broad range of operating conditions (e.g., temperature, pressure, and reactor residence time), and determine the relationships between pyrolysis product composition and the properties relevant to product upgrading and utilization;

4. Develop a better understanding of the kinetics and mechanisms of the vapor-phase and solid-phase pyrolysis reactions; and

5. Develop computer models that can be used to simulate and study pyrolysis processes.

In addition, compiling this information in a single database would be useful to researchers trying to identify potential pyrolysis processes, relate changes in product composition to reaction conditions, or design scaled up pyrolysis systems (Diebold, et al., 1990; Evans and Milne, 1988; Walter and Wallace, 1988; Tinning, 1985) (see Section 12.3.3).

### 12.3.2 Feedstock Preparation

The failure of MSW automatic feed mechanisms was one of the primary reasons that full-scale MSW pyrolysis facilities were unsuccessful in the 1970s. While present day MSW preprocessing equipment is better able to deal with the diversity and variability of MSW, this issue continues to pose a significant problem. Before the manufacturers of MSW preprocessing equipment are to develop the necessary equipment, however, they need to know what kind of feedstock will be required by pyrolysis systems. Therefore, research is needed to:

6. Develop, for each promising pyrolysis system, feedstock specification and standards (e.g., moisture content, size, and organic material content).

### 12.3.3 Development of Pyrolysis Processes

Laboratory experiments with catalytic high pressure pyrolysis and wood feedstock have achieved an energy efficiency of about 0.5. Research is needed to determine if this level of energy recovery can be achieved in a full-scale system using MSW as a feedstock. In particular, research is needed to:

7. Increase catalyst performance and operating life;

8. Decrease reactor residence time; and

9. Improve methods for upgrading the pyrolysis products (Elliott, et al., 1990) (see Section 12.3.5).

The few full-scale low pressure fast pyrolysis facilities -- most of which used wood as a feedstock -- built in the United States were closed because of poor performance. One of the few facilities to use MSW as a feedstock was built by Occidental Research Corporation and Garrett Research in El Cajon, California. This facility experienced numerous operational and

mechanical problems with the equipment used to process the pyrolysis products. Many of these problems resulted from an incomplete understanding of the pyrolysis product characteristics and the circumstances that would be experienced by conventional processing equipment. To ensure that future efforts enjoy more success, research is needed to:

10. Fully characterize the pyrolysis products to help design equipment better able to upgrade the pyrolysis products (Scahill and Diebold, 1988); and

11. Improve the methods and equipment for upgrading pyrolysis products.

Pyrolysis reactor design for both direct- and indirect-heated pyrolysis processes becomes increasingly important once the basic concepts of a pyrolysis process have been developed. Thus, to address the technical issues that may arise in a full-scale system (e.g., preprocessing of the feedstock, clogging and fouling, and problems with processing the pyrolysis products), larger systems must be built. The basic concepts of a pyrolysis process are generally developed and tested using bench-scale systems and laboratory apparatus that give the researcher comprehensive control of system conditions such as temperature, pressure, and mixing. When the process is implemented on a larger scale, the design and operation of the system must be responsible for creating the conditions needed to make the process occur. Increasing the size or changing the shape of a system can significantly change behavior. Therefore, it is important to know what conditions are necessary for the desired process to occur, and how variations in the conditions will affect the process. Research is needed to:

12. Generate the fundamental data needed to identify promising pyrolysis processes.

Such data will be valuable in developing larger scale systems and processing equipment. (Walter and Wallace, 1988; Nels, 1990; Scahill and Diebold, 1988)

Corrosion is a potential problem in many pyrolysis systems due to the following causes: acidic conditions, stress corrosion cracking from chlorides and alkali conditions, and steel embrittlement from the presence of hydrogen (Molton, et al., 1989; Brooks, 1984). Erosion is a potential problem in both fluidized bed and entrained bed reactor types, which utilize high velocity gases to mix the waste and ensure good heat transfer. Valve seals have been eroded by mineral particles in the high velocity gas flowing out of the reactor in some systems (Molton, et al., 1989; Brooks, 1984). Therefore, research is needed to:

13. Identify reactor materials of construction that are not susceptible to corrosion in pyrolysis systems, and develop designs for fluidized and entrained bed reactors that minimize erosion by the high velocity particles used in such reactors (Molton, et al., 1989).

### 12.3.4 Utilization of Pyrolysis Products

Unprocessed pyrolysis products tend to be reactive and over time may polymerize into viscous, tar-like substances that do not store well and are less suitable for use as fuel or chemicals. The pyrolysis oil can also be corrosive and have a relatively low heat content.

Since these properties will vary, depending on the pyrolysis process and feedstock being used, research is needed to:

14. Characterize the pyrolysis oil with respect to the relationships between feedstock composition and pyrolysis product characteristics, combustion, and the effect of storage conditions on shelf life.

### 12.3.5 Upgrading Pyrolysis Oil

Due to the typically reactive, corrosive, and viscous nature of MSW pyrolysis oil, it is generally unsuitable for direct use as a fuel or chemical feedstock. In addition, the pyrolysis oil has a relatively low heat content. These undesirable properties are largely due to the high oxygen content of the pyrolysis oil and, depending on the pyrolysis process, the large proportion of high molecular weight organic molecules. Consequently, pyrolysis products generally must be upgraded to reduce their oxygen content and to break the larger molecules into smaller molecules. Catalytic hydrogenation and zeolite catalyst upgrading are the two most promising methods for reducing the oxygen content and the molecular weight of the pyrolysis oil molecules (Helt, et al., 1984; Diebold and Stevens, 1990).

Catalytic hydrogenation can be applied to the pyrolysis oil from both high pressure catalytic pyrolysis or low pressure fast pyrolysis. Its goal is to saturate the pyrolysis oil, reduce its oxygen content, and to crack the oil into molecules with lower molecular weights that are less viscous. Catalytic hydrogenation uses hydrogen gas in combination with a metallic catalyst to reduce the oxygen content of the pyrolysis oil. Research is needed to determine the catalysts and operating conditions that yield the best results. The useful operating life of the catalysts is an area where research is needed to:

15. Determine the catalysts and operating conditions that yield the best results;

16. Identify substances in MSW that act as catalytic poisons and need to be removed from MSW before pyrolysis so that they do not degrade the catalyst; and

17. Develop methods for regenerating the catalysts so that they can be reused (Diebold and Stevens, 1990; Tinning, 1985; Helt, et al., 1984).

Zeolite catalyst upgrading can be used to treat pyrolysis oil while it is still a vapor, so that it applies primarily to low pressure fast pyrolysis which produces a pyrolysis vapor. The primary objective of zeolite catalyst upgrading is to break the large molecular weight molecules into the lower molecular weight molecules typically found in gasoline (Walter, 1990) and to reject the oxygen as $CO_2$ and CO. Zeolite catalysis is a technology that has been used to convert the heavy petroleum fraction to gasoline for about 30 years, and more recently to convert methanol to gasoline (Diebold and Stevens, 1990). Zeolite catalysts, however, are sensitive to the shape of the molecules to be converted, and the composition of pyrolysis oil vapors and petroleum are significantly different ("Catalysis," 1979). Therefore, if zeolite catalysts are to be used to upgrade pyrolysis vapors, research will be needed to:

18. Determine the relationships between major process variables, catalyst performance, and product yield; and develop methods to remove pyrolysis products that degrade or poison the zeolite catalyst (U.S. Dept. of Energy, 1986; Diebold and Stevens, 1990).

### 12.3.6 By-products and Waste

High production cost is one reason that MSW pyrolysis was not successful in the 1960s and 1970s. Therefore, reducing the costs and/or increasing the revenues associated with MSW pyrolysis will increase its commercial viability. It may be possible to reduce the cost of waste management by sharing disposal areas, or increase revenues by recovering heat or materials that are not being utilized by current systems. In order to realize these potential benefits research is needed to:

19. Evaluate the potential for using waste heat to generate electric power;

20. Demonstrate metals recovery from pyrolysis ash;

21. Evaluate the potential for selling by-products as industrial chemicals; and

22. Evaluate the feasibility of co-disposing pyrolysis wastes with waste coal or industrial wastes.

### 12.3.7 Environmental Assessment

The by-products and wastes generated by MSW pyrolysis generally consist of complex mixtures of organic compounds, some of which are hazardous or potentially hazardous (e.g., carcinogenic, teratogenic, or toxic). In addition, heavy metals and halogenated organic compounds in MSW are also a potential concern. Identifying and assessing the potential risks posed by pyrolysis by-products and wastes are important tasks from the perspectives of (1) meeting regulatory requirements, (2) protecting human health and the environment, and (3) gaining public acceptance of the technology. In order to address these potential risks, research is needed to:

23. Study the reactions and release of inorganic and organic halogens and heavy metals in both the primary and subsequent gas phase reactions in pyrolysis and oxidation;

24. Evaluate the health and environmental effects of the constituents found in pyrolysis by-products and wastes; and

25. Evaluate the mobility, transport, retention, and fate of hazardous constituents in pyrolysis by-products and wastes.

### 12.3.8 Feasibility Evaluation

Given the extensive, albeit unsuccessful efforts to develop and commercialize MSW pyrolysis in the 1960s and 1970s, a great deal could be learned by studying these past

efforts. For example, what approaches to commercialization were tried, what caused these approaches to fail, and were there any efforts to address the causes of failure? At the same time, it is important to look forward and develop a strategy for developing and commercializing MSW pyrolysis that is designed to overcome the barriers to MSW pyrolysis (e.g., regulatory constraints and public acceptance). In addition, some of the technical barriers to MSW pyrolysis are likely to remain unidentified, and therefore unsolved, until a full-scale MSW pyrolysis system is built and operated. In order to address these issues research is needed to:

26. Study the history of attempts to demonstrate and commercialize MSW pyrolysis systems;

27. Develop a strategy for commercializing and marketing MSW pyrolysis systems; and

28. Implement a full-scale demonstration of MSW pyrolysis.

#### 12.3.9 RD&D Topics Identified by Reviewers

One reviewer believes that RD&D is needed to determine the benefits that pyrolysis offers over other MSW technologies.

## 12.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on MSW pyrolysis (listed in Appendix A) are presented and discussed. The priorities are based upon an assessment by each panel member, of the potential contribution of each RD&D need towards making MSW pyrolysis technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. After a final priority had been assigned to each RD&D need, the panel members categorized the needs as being essential, high priority, medium priority, or low priority. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 12-1, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 12.3 is in the right-hand column. The rationale used by the panel of technical experts is discussed below. The rationale tend to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

#### Essential RD&D Needs

Both of these needs (Nos. 3 and 26) are seen as low cost, high benefit options. Also, many of the other RD&D needs would be able to use the information generated by fulfilling these two RD&D needs. One panel member, however, felt that a study of the history of MSW pyrolysis would show that a further investment of RD&D dollars on pyrolysis would not be worthwhile.

### High Priority RD&D Needs

Environmental concerns are of great importance because of significant public concerns about the safety of waste management in general; thus addressing these concerns would increase the political and social viability of the technology (No. 23). In some respects, the public's perception of pyrolysis is almost as important as the technical viability of the technology itself. The development of reliable mass and energy balances (No. 1) will be of great use to future research once the basic data have been generated. The development of feedstock specifications (No. 6) was given high priority because the failure of the MSW pyrolysis in the 1970s was due to problems with feedstock consistency and quality.

### Medium Priority RD&D Needs

The medium priority RD&D needs have considerable merit and will need to be fulfilled if MSW pyrolysis is to become commercially viable. There was some disagreement among the panel of technical experts about the value of real-time monitoring of product composition (No. 2). Some panel members considered it to be important because it provides a large volume of detailed data on a large number of variables; other panel members believe that computer simulations (No. 5) could be used to generate much of these data. There was little consensus among panel members on the importance of indirect-heated pyrolysis system development (No. 12).

### Low Priority RD&D Needs

The panel of technical experts believes that catalytic high pressure pyrolysis is a flawed technology and that RD&D on this technology should get low priority (Nos. 8, 9, and 10). The panel was divided on the usefulness of a full-scale MSW pyrolysis demonstration project (No. 28), with many panel members believing that a such a project would require a substantial sum of money to create something that might not work; money that should be used to address other RD&D needs. The panel members believe that a significant body of literature on the effects of analyzing the transport and fate of pyrolysis by-products and wastes (No. 25) already exists, although assessing the environmental concerns about pyrolysis was given a high priority.

## 12.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate MSW pyrolysis with respect to the evaluation criteria developed by the Advisory Committee. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The cost of implementing an RD&D program that consists of the prioritized RD&D needs could range from a low of $100 million to a high of $1.5 billion. This range reflects the opinions of two panel members. The $100 million figure came from a panel member who believes that MSW pyrolysis has already been shown to have fatal flaws, and that no more

## Exhibit 12-1. Prioritized RD&D Needs for MSW Pyrolysis

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **Essential** | |
| --- | Generate data on MSW pyrolysis and its products | 3 |
| --- | Study the history of past attempts to commercialize MSW pyrolysis | 26 |
| | **High Priority** | |
| 100 | Study the reactions and release of compounds with heavy metals and halogens | 23 |
| 97 | Establish reliable mass and energy balances for potential pyrolysis processes | 1 |
| 97 | Develop, for promising pyrolysis systems, feedstock specifications and standards | 6 |
| | **Medium Priority** | |
| 67 | Characterize the pyrolysis oil (i.e., composition, combustion, and shelf life) | 14 |
| 66 | Generate the fundamental data needed to identify promising pyrolysis processes | 12 |
| 62 | Develop a strategy for commercializing and marketing MSW pyrolysis systems | 27 |
| 50 | Evaluate the potential for selling pyrolysis by-products as industrial chemicals | 21 |
| 49 | Fully characterize pyrolysis oil to aid the design of equipment for upgrading the oil | 10 |
| 49 | Evaluate the health and environmental effects of pyrolysis by-products and wastes | 24 |
| 46 | Improve methods for upgrading pyrolysis oil | 11 |
| 45 | Demonstrate the recovery of metals from pyrolysis ash | 20 |
| 43 | Determine the catalysts and operating conditions that yield the best results | 15 |
| 42 | Determine the factors affecting zeolite catalyst performance and degradation | 18 |
| 40 | Develop a better understanding of the kinetics and mechanisms of pyrolysis | 4 |
| 40 | Identify substances in MSW that act as catalytic poisons in catalytic hydrogenation | 16 |
| 37 | Develop reactor materials and reactor designs that resist corrosion and erosion | 13 |
| 36 | Develop computer models that can be used to simulate and study pyrolysis | 5 |
| 30 | Refine the use of real-time techniques for monitoring pyrolysis product composition | 2 |
| 26 | Evaluate the co-disposing of pyrolysis wastes with waste coal or industrial wastes | 22 |
| | **Low Priority** | |
| 23 | Develop methods for regenerating the catalysts for catalytic hydrogenation | 17 |
| 23 | Evaluate the mobility, transport, retention, and fate of the by-products and wastes | 25 |
| 21 | Implement a full-scale demonstration of MSW pyrolysis | 28 |
| 16 | Evaluate the potential for using waste heat to generate electric power | 19 |
| 15 | Decrease reactor residence time of catalytic high pressure pyrolysis systems | 8 |
| 11 | Improve methods for upgrading catalytic high pressure (CHP) pyrolysis oil | 9 |
| 9 | Increase the performance and operating life of CHP catalysts | 7 |

money should be spent to develop it. The $1.5 billion figure came from a panelist who believes that a full-scale (i.e., 100 tpd) facility should be built to develop and demonstrate MSW pyrolysis. The estimates of the rest of the technical panel ranged from $200 to $500 million dollars.

**Difficulty of Technology Development**

The commercialization of MSW pyrolysis is expected to be very difficult. During the next five to ten years, three major technological areas will need to be addressed. First, and most important, feedstock issues will have to be resolved. Today it is not possible to produce a feedstock of sufficient quality for MSW pyrolysis, and be economically competitive with competing technologies. Second, methods and equipment for upgrading pyrolysis oil into the desired liquid fuel or chemical feedstock need to be developed. Finally, the quality and consistency of the pyrolysis products must be ensured.

**Commercial Development Risk**

Panel members have differing opinions on the levels of public and political acceptance of MSW pyrolysis. They felt that markets for this technology do exist, and the market for the product is very high. The capital investment requirements beyond RD&D were seen as approximately $200,000 per tpd which is twice as much as mass-burn combustion.

**Flexibility**

The panel members believe that MSW pyrolysis can handle specific portions of the waste stream very well, but that its ability to accept the full range of MSW is yet to be determined.

**Cost of the Energy Produced**

The panel members were unable to agree upon the cost impact of pyrolysis. Some panel members believe that the production of liquid fuel is expensive, while other members believe that the value of the fuel produced could outweigh production costs.

**Net Energy Benefit**

Using the figure of 10 million Btu in a ton of trash, the panel members believe that MSW pyrolysis could recover 40-50 percent of that energy. One panelist believes that MSW pyrolysis could only recover 10-20 percent of the energy. The liquid fuel recovered is storable and can be used as a chemical stock.

**Human Health and the Environment**

The panel did not achieve consensus on this issue. Opinions ranged from saying that the effect of pyrolysis on health were unknown to saying that they were beneficial compared to incinerators.

Release of MSW pyrolysis by-products or wastes into the environment is seen as having the potential for much greater impact than other technologies, because MSW pyrolysis

produces combustible materials containing known carcinogens. The effect of pyrolysis upon environmental pollution is currently unknown and would depend on how waste products were handled and managed. There are, however, no air emissions or scrubber effluents from MSW pyrolysis.

### Occupational Health and Safety

The panel members believe that occupational health and safety is a major issue due to the potentially hazardous nature of the MSW pyrolysis products, by-products, and wastes. There are, however, many unknowns about MSW pyrolysis that could affect occupational health and safety. The impact of this issue on the viability of MSW pyrolysis is likely to depend upon the type and stringency of regulatory controls.

### Appropriateness for Government Funding

The panel believes that MSW pyrolysis is an appropriate area for DOE to fund research, and that the technology is not yet ready for funding from the private sector. The panel also believes that MSW pyrolysis can be conducted within the existing regulatory framework.

# 13. RDF PRODUCTION AND DEDICATED COMBUSTION

This chapter addresses the RD&D issues associated with RDF (refuse derived fuel) production and dedicated combustion. Although there are unique circumstances particular to dedicated RDF combustion as compared to co-fired RDF, there are also similarities. In an effort to make the discussion of each technology an independent unit, there is some duplication of material in each chapter.

## 13.1 Technology Description

In a broad sense, refuse derived fuel refers to MSW in any form that may be used as fuel. For purposes of this discussion, however, RDF refers to MSW that has undergone mechanical processing to produce a more homogeneous fuel. Preprocessing of MSW is required for most waste-to-energy systems other than mass-burn or modular incineration because of the need for homogeneous fuel. This chapter addresses the combustion of RDF in boilers designed to burn RDF as the sole fuel. This differs from co-firing in which RDF is burned along with another fuel (typically coal) in existing or retrofitted boilers. A combustor that burns RDF as its sole fuel is known as a "dedicated" RDF combustor.

All RDF preparation processes reduce the size of the waste particles prior to burning. The specific size and form characteristics of RDF are determined by the processing system used to produce it. In general, RDF can be classified as coarse, fine, powdered, or densified. Coarse and fine RDF are sometimes classified together as fluff RDF or shredded RDF. The American Society for Testing and Materials (ASTM) has established an RDF classification system as shown in Exhibit 13-1.

This chapter is concerned with coarse, fine, and powdered RDF, which correspond, respectively, to RDF-2, RDF-3, and RDF-4. Processes that utilize unprocessed MSW (RDF-1) are discussed in the chapters on mass-burn and modular combustion. Processes that utilize densified RDF (RDF-5) are discussed in the chapter on RDF production and co-fired combustion.

Coarse RDF is produced by shredding MSW, usually in a hammermill. This may be followed by magnetic separation to recover ferrous metals or by air classification to reduce ash content. The resulting particle size is usually between 4 and 6 inches. Fine RDF is produced by adding an additional grinding or shredding step to reduce particle size along with additional screening, magnetic separation, or trommelling to remove metals, glass, and other inorganics (noncombustible materials). Powdered RDF is produced first by processing MSW in a system similar to those used to produce coarse or fine RDF. The shredded RDF is then dried and ground into a free-flowing powder. Sometimes treatments are used to embrittle the RDF. (Scaramelli, 1979; U.S. Congress, 1989; Donnelly, 1991)

An alternative method for producing RDF utilizes water as a suspension medium and conveyance mechanism. MSW is ground in a hydropulper (similar to a household blender) and the resulting slurry is sent to a cyclone separator that removes noncombustible materials (glass, metals, ceramic, stone) by centrifugal action. The organic fraction is then mechanically dewatered to produce a wet-pulped RDF with a moisture content of about 50 percent. (Scaramelli, 1979; U.S. Congress, 1989) While it is unclear how this type of RDF fits within the ASTM classification system, it is not very important since the process did not prove to be successful in full-scale plants.

**Exhibit 13-1. RDF Classification System**

| COMMON NAME | ASTM CLASS | DEFINITION |
|---|---|---|
| MSW | RDF-1 | MSW used as fuel in as-discarded form |
| Coarse RDF | RDF-2 | MSW processed to a coarse particle size with or without ferrous metal separation |
| Fine RDF | RDF-3 | MSW processed to a particle size such that 95 percent by weight passes through a 2 inch (50 mm) square mesh screen and from which most metals, glass, and other inorganics have been removed |
| Powdered RDF | RDF-4 | MSW processed into a powdered form such that 95 percent by weight passes through a 10-mesh wire screen and from which most metals, glass, and other inorganic materials have been removed |
| Densified RDF (dRDF) | RDF-5 | MSW that has been processed and densified (compressed) into the form of pellets, slugs, small cubes, or briquettes |

Sources: (Robinson, 1986)

Most modern dedicated RDF combustors operate similarly to mass-burn waterwall combustors. Both systems typically utilize moving grates and waterwall boilers with superheaters, economizers, and air pollution control equipment. Energy may be recovered from RDF combustors in the form of steam or electricity, just as with mass-burn combustors. The main differences between RDF combustors and mass-burn combustors are in the way that MSW is fed to the combustor and the design of the grate. In RDF combustors, the RDF is typically distributed by air swept feeders. RDF enters the combustion chamber high enough above the grate so that lighter particles burn in suspension. As much as 50 percent of the fuel never reaches the grate (Seeker et al., 1989). It has been claimed but not yet proven that the small particle size and homogeneity of RDF causes it to burn more evenly and efficiently than unprocessed MSW. However, the necessity for complex preprocessing systems tends to increase operating and maintenance costs and reduce reliability.

## 13.2 Technology Status

In 1991 it was reported that there were 33 operational RDF production and/or combustion facilities in the United States, and an additional 11 such facilities in a state of advanced planning, construction, or shakedown. Of these 44 facilities, 22 are used for the dedicated combustion of RDF, 14 only produce RDF for off-site use, and 7 co-fire RDF. (Ohlsson et al., 1991) As of 1990, 8 RDF production facilities conducted material separation and recycling activities, including recycling ferrous metals, nonferrous metals, glass, plastic, and corrugated paper.

All of the "first generation" RDF production facilities, which began operation in the U.S. through 1978, have either been closed or are currently inactive. Most of these earlier plants encountered operational problems, did not have their own dedicated boiler plant, or were unable to find a market for the RDF they produced. Consequently, most of the plants constructed since 1978 have been built with a combination of dedicated boilers and contracts guaranteeing fuel or energy customers. (Alvarez, 1988)

In order to control the emission of air pollutants 73 percent of the RDF combustion facilities use a baghouse, electrostatic precipitator (ESP), or scrubber system, while the remaining 27 percent of the facilities use an ESP/baghouse or ESP/scrubber combination (Ohlsson et al., 1991). Kiser (1990) reports that the majority of dedicated RDF facilities employ electrostatic precipitators alone or an ESP/scrubber combination.

Dedicated RDF facilities generate a combination of bottom ash and fly ash, nearly all of which is sent to landfills for disposal (Ohlsson, 1989). The ratio of ash residue to design capacity tonnage is 15-17 percent on a dry basis.

Outside the U.S., RDF technology has been applied commercially to some extent in at least three countries. Canada has two RDF production facilities and one facility utilizing a grate combustor to burn coarse RDF. In the United Kingdom, several existing facilities use solid fuel boilers to burn pelletized RDF and one facility burns coarse RDF. Sweden has a number of facilities that burn RDF utilizing various combustion technologies: three circulating fluidized bed combustors, five bubbling fluidized bed combustors, and four grate combustors. (Krol and Dent, 1989)

## 13.3 Description of RD&D Needs

RDF production and combustion is a relatively mature technology; its primary RD&D needs are associated with gaining wider public acceptance of the technology, improving air emissions controls, and increasing the economic efficiency of the technology. Additional RD&D needs associated with RDF are discussed in the chapters on RDF production and co-fired combustion and ash disposal and utilization.

Sections 13.3.1 through 13.3.8 describe the RD&D needs for dedicated RDF production and combustion that were identified by the panel of technical experts (listed in Appendix A). Each of the RD&D needs identified by the panel is assigned a reference number (i.e., 1, 2, 3, ... 33) that is used in later sections when the RD&D needs are prioritized and discussed. Section 13.3.9 describes RD&D topics that were identified in the literature review, but were not subsequently accepted by the panel of technical experts. (See the introduction chapter for a more detailed description of the prioritization process). The RD&D needs in Section 13.3.9 are not prioritized or discussed further.

### 13.3.1 Municipal Solid Waste Characterization

Many variable RDF characteristics can influence the quality of the feedstock and ultimate energy recovery. For example, high ash and moisture content in the RDF frequently reduces boiler efficiency (McGowin and Kohan, 1983). Other MSW characteristics can also impair combustor performance. The presence of noncombustible materials can cause slagging and fouling, large objects can damage equipment, and chlorides can cause corrosion. Improving RDF feedstock quality requires developing methods to better characterize the content of the refuse and to more selectively remove the hazardous and polluting components of refuse (Buekens, 1989). The consistency of the MSW received for processing also needs further attention (McGowin, 1989). In particular, research is needed to:

1. Develop methods/technologies to identify items in MSW that damage equipment, such as the shredder; these items include dense objects (i.e., greater than 50 pounds) such as metallic material, concrete, and tree stumps; and

2. Determine the components of MSW that contribute to combustion and environmental concerns.

The potential for explosions, harmful fumes, and other biohazards is a very real concern at dedicated RDF production and combustion facilities. Further research is needed to:

3. Develop methods/technologies to identify substances in MSW that can be hazardous to occupational health and safety.

Increasing community recycling programs and improvements in presorting technologies ensure that the MSW stream will change in the near future. Further research is needed to:

4. Study the economic effects of major changes in the composition of the MSW stream on RDF.

### 13.3.2 MSW Processing

RDF technologies can entail a higher capital cost than other MSW combustion technologies because of the preprocessing equipment that must accompany combustion equipment. Better fuel quality is seen as a significant factor to improving dedicated RDF combustor performance and reducing emissions. (Hayes, 1990) Investigations are continuing to develop a simpler, more energy efficient process for separating MSW (Kenny and Sommer, 1984).

Researchers have noted that processing MSW into RDF that can be stored and blended would reduce waste volume and increase energy recovery (Onischak et al., 1988). Argonne National Lab, among other institutions, has been actively researching RDF feedstock preparation (Ohlsson, 1989).

The primary RD&D goals for RDF preparation are to produce from MSW a homogeneous fuel with maximum Btu value through better shredding, presorting, and fuel feeding (Dent and Krol, 1990). Improvements in these processes require improved RDF characterization, more efficient removal of noncombustible materials, better RDF storage methods, and more effective RDF densification or powdering agents.

The most common problem encountered in primary shredding occurs when wires and stringy cloth objects wrap around and inhibit free movement of the shredder shaft. This problem is also frequently encountered during secondary shredding. Additionally, massive objects, such as packs of paper, can jam the shredder or break shredder components. This is a greater problem during secondary shredding, when RDF is more finely shredded than in primary shredding. Additionally, the potential for fires and explosions during shredding poses a significant hazard. Specifically, further research is needed to:

5. Develop technologies to handle objects in MSW that cannot be handled at present (Scaramelli, 1979); and

6. Develop technologies for converting items in MSW that are or are potentially hazardous to be nonhazardous.

Noncombustible materials such as glass and metal (e.g., ferrous, aluminum) in RDF increase slag and deposit formation (fouling) on furnace heat transfer surfaces (Massoudi, 1984; McGowin, 1989; Scaramelli, 1979; Seeker et al., 1989; Tinning, 1985; and Tweedale, 1988). Clinker formation from ash on the grate reaching temperatures sufficient to cause bonding is also a continuing problem. Another significant impact of noncombustible materials is that heavy metals can become an air emissions problem. Research is being conducted for RDF pretreatment methods to separate lead, cadmium, and mercury, primarily by removing dry cell batteries (Feindler, 1991). Further, a high chlorine content increases corrosion by hydrogen chloride (HCl) and chlorine on high temperature heat transfer surfaces (McGowin, 1989). The potential for improvement in the numerous stages and processes of separation warrants further attention:

- Air classification may be made more efficient in sorting out noncombustible materials by developing an air classifier that operates on particle density rather than aerodynamics (Walter, 1988). The benefits of air classification in contrast to the energy expended in this process are unclear. (Scaramelli, 1979)

- Magnetic separation effectively removes most ferrous materials, although low density items within a pile may not be extracted (Scaramelli, 1979).

- Aluminum should be removed because it can melt and foul grates. Development of low cost and/or high-throughput ways to remove aluminum are recommended (Scaramelli, 1979). Generally aluminum recovery is of limited success because waste streams of insufficient volume are treatable with the present technology, and because aluminum recovery units require excessive maintenance (Scaramelli, 1979; Kenny and Sommer, 1984).

Research is needed to:

7. Develop new or improved processes to minimize the input of noncombustible materials to the combustion train (Kenny and Sommer, 1984);

8. Develop new or improved processes to recover noncombustible materials;

9. Evaluate methods or technologies to remove elemental heavy metals and other constituents (e.g., chlorine and sulfur) from MSW; and

10. Develop a process to recover reusable combustible materials when warranted (e.g., plastics, tires, grades of paper).

### 13.3.3 RDF Storage

RDF storage entails a number of problems that require further attention (McGowin, 1989). For example, piled RDF can become compacted at thicknesses greater than about 20 feet. In addition, wet refuse produces wet RDF and exacerbates the problem of storing and recovering RDF. (Scaramelli, 1979) RDF in its coarse form may keep in storage for only three days or so before biodegradation makes it unmanageable (Onischak et al., 1988). Specifically, more research is needed to:

11. Conduct a laboratory analysis of the effects of long-term RDF storage on the Btu value of RDF; and

12. Conduct technology studies and a risk analysis of the regulatory, health, and other effects of extended storage of RDF.

### 13.3.4 Retrieval and RDF Feed

Many issues relating to RDF feed RD&D needs have been identified above. One issue is feed quality. Accurate instrumentation does not currently exist that can monitor in real time feedstock characteristics such as moisture content (Tinning, 1985). A computer model of RDF systems is being developed to allow specifications of the size and purity of components for a user-selected system configuration (Ohlsson, 1989).

RDF size and form requirements vary by the type of boiler or combustion process being used. For example, pelletized RDF works well for spreader-stoker boilers, which are common systems for co-firing. Suspension-fired units, which are sensitive to feedstock high in moisture, noncombustible materials, and varied particle sizes, benefit from an RDF preparation process involving two-stage shredding, reduced moisture, and the elimination of most metals, glass, sand, and grit. (Ohlsson, 1989) Conventional fluidized-bed shell boilers have been found to be unsuitable for pelletized RDF burning due to excessive boiler fouling and bed contamination (Dent and Krol, 1990). Unique problems are associated with the various RDF forms, including the following:

- Coarse RDF typically undergoes only primary shredding. It is possible with some combustion operations that large RDF particles with low densities can be entrained and carried out of the combustion chamber before the hydrocarbons are completely oxidized (Ohlsson, 1989). More effective primary shredding would help achieve more complete combustion.

- Research is being conducted into developing better embrittlement agents for further RDF processing via powdering (Walter, 1989; Ohlsson, 1989). This includes research into powdering MSW for a finely divided, low ash fuel that can substitute for oil in existing boilers (Walter, 1988).

These issues can be summarized by stating that additional research is needed to:

13. Study the distribution of material (both in terms of physical distribution and Btu value) (McGowin, 1989; Seeker et al., 1989) and the rate at which it is fed into boilers.

### 13.3.5 Combustion

The efficient combustion and energy recovery of RDF is a high priority because a significant amount of energy, as well as cost and effort, is invested in its preparation. For example, research is being conducted on the relation between trace metals in fly ash and RDF combustion efficiency (Hartman, 1991). Another problem is that existing methods for measuring the performance of heat recovery incinerators are subject to error (Fernandes, 1984). Boiler combustion efficiency has a significant influence on the quality of air emissions from the combustor. Research is needed to:

14. Determine the optimum combustion conditions (i.e., air, distribution, temperature, moisture) to recover energy from RDF (Hasselriis, 1984);

15. Develop boiler designs that allow higher temperature/pressure steam generation for RDF and develop corrosion resistant materials for boilers (primarily for chlorides);

16. Perform a demonstration study of flue gas recirculation for controlling $NO_X$ emissions;

17. Study methods of controlling the reformation of dioxins.[1]

Adjustments of air flow to reduce grate temperatures and grate-dumping frequencies to reduce clinker buildup are being tested (Scaramelli, 1979). Some solutions have been developed for deposits on boiler sidewalls and convective tube surfaces, but more research is needed (McGowin and Kohan, 1983). Some on-line cleaning options that have been investigated to control fouling are steam soot blowing, compressed air blowing, acoustic blowing, and chemical additives. Research should also continue to determine optimum grate speed and bed depth for chain grate combustion systems. (Tweedale, 1988) Research is needed to:

18. Investigate on-line grate cleaning techniques.

The issue of co-firing was addressed by the panel but these issues are discussed in more detail in the chapter on RDF production and co-fired combustion. Specifically, the dedicated RDF panel felt that more research was needed to:

19. Study co-firing operational considerations (coal/RDF mix, type of coal, resulting slags).

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[1] One reviewer thought that this RD&D need should have received higher priority than it did.

### 13.3.6 Emissions

With concern growing about emissions from the combustion of all fuels, improved emission controls for RDF combustion are needed, including continuous emission monitors (Scaramelli, 1979). A primary issue is the technology to control emissions of toxic organic chemicals, particularly polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzo-furans (PCDFs) (U.S. Environmental Protection Agency, 1991). Argonne National Laboratory is conducting emission studies (i.e., inorganic acid gases, trace metals, organics) of full-scale co-firing of pelletized RDF/coal mixtures (Daugherty et al., 1989). Sweden and Canada have assigned high priority to RD&D for emissions (Dent and Krol, 1990). Likewise, the European Community has been researching the composition of densified RDF feedstock and emissions from their combustion (Van Santen, 1988).

One aspect of emissions control needing more research is air pollution control equipment. For example, more widespread industry adoption of spray-dryer absorber/baghouse equipment has been recommended (Ohlsson, 1989). Also needed are improvements in electrostatic precipitator performance (McGowin and Kohan, 1983).

Work is being conducted on co-firing RDF with fossil fuels, primarily coal, and the resulting emissions (Tinning, 1985). Research is also being conducted to more accurately assess the effects of the major variables of coal/RDF combustion, including boiler load, percent RDF fired, and coal composition, on particulate emissions (Norton and Levine, 1990).

The panel indicated that the major issue, regarding the control of toxic organic emissions, was one of public perception. Although the destruction rate of organic constituents appears to be high, much remains to be understood about such factors as combustion kinetics, degradation parameters, and compound precursors (Dent and Krol, 1990; Clarke and Virag, 1989; McGowin, 1989; Niessen, 1984; Graham et al., 1984; Ohlsson, 1989). State governments are sponsoring research aimed at controlling trace emissions of chlorinated organic compounds (Seeker et al., 1989; Ohlsson, 1989). Research is needed to:

20. Develop better and more reliable real-time surrogate indicators of specific emissions (e.g., air toxics and inorganics);

21. Reduce the cost of lowering emissions (e.g., cheaper sorbents, spray driers); and

22. Improve the reliability of continuous emission monitoring (CEM) systems.

Several researchers have identified the need to better understand nitrogen oxide ($NO_x$) formation and control (Donnelly, 1991; Russell and Roberts, 1984; Ohlsson, 1989). Some reductions in the formation of $NO_x$ are possible through existing technologies, but elimination of $NO_x$ from the flue gas stream is not well understood (Russell and Roberts, 1984). A major recommended step is to adopt continuous $NO_x$ monitoring (Russell and Roberts, 1984). Research is needed to:

23. Perform a demonstration study of the $NO_x$ control/selective non-catalytic reduction capabilities of RDF.

Carbon monoxide, a product of incomplete fuel combustion, is used by plant operators as an indicator for adjusting combustion unit air systems. Work is needed to better understand the role of carbon monoxide in RDF combustion (Donnelly, 1991; Zilkowski, 1990; Bacchi and Allen, 1991). The emission of both carbon monoxide and carbon dioxide need to be controlled. To accomplish this, research is needed to:

24. Reduce carbon monoxide emissions (Bacchi and Allen, 1991); and

25. Reduce carbon dioxide emissions.

The control of heavy metals in combustion gases from RDF firing requires more research (McGowin, 1989; Daugherty et al., 1989; Dent and Krol, 1990). Researchers note that emissions of fine particulates may permit excessive emissions of metals, demonstrating the need for better control of particulate emissions (Scaramelli, 1979). In general, researchers state that a better understanding of the formation and reaction kinetics of heavy metal compounds such as the oxides and chlorides of arsenic, cadmium, lead, and mercury is needed (Donnelly, 1991). Research is needed to:

26. Develop technologies for proactive control of regulated heavy metals (e.g., carbon injection).

Additionally, if information about the quality of refuse being burned or the capacity demand on the incinerator is lacking, estimates of emission factors are less certain. (Hasselriis, 1984) Additional research is needed to:

27. Evaluate the effect of preprocessing on emissions.

### 13.3.7 Residues (Bottom Ash, Fly Ash, Process Residues)

The issues relating to ash management are addressed in full in the chapter on ash disposal and utilization. The panel did feel that the following issues of ash in relation to dedicated RDF production and combustion were worthy of research attention:

28. Investigate methods to reduce residue streams;

29. Perform demonstration studies of composting of process residues;

30. Develop waste handling and recovery systems for nonprocessable residues and processable residues; and

31. Investigate and demonstrate uses of process waste.

### 13.3.8 Alternate Combustion Systems

A broad area worthy of more attention is the development of innovative RDF combustion systems. For example, the more uniform combustion conditions characteristic of

fluidized-bed combustion may permit a lower temperature for acceptable dioxin control (Scaramelli, 1979). Research is needed to:

32. Investigate issues of RDF combustion in fluidized beds.

### 13.3.9 Other Potential RD&D Topics

The following RD&D topics were identified in the literature review, but were not subsequently accepted by the panel of technical experts (listed in Appendix A).

Better control of acid gas emissions will involve developing a better understanding of acid gases and improving current control technologies (McGowin, 1989; Donnelly, 1991; Zylkowski, 1990). Past research has shown that baghouse (fabric filter) screening will improve acid gas control after spray lime neutralization in dry scrubbers, while other research has emphasized improvements in electrostatic precipitators (Flynn et al., 1984). Recent efforts towards developing in-furnace lime-neutralization injection, which would streamline emission control processes, suggest an interest in more cost-effective approaches to the current technology of spraying dry scrubbers followed by baghouses (Scaramelli, 1979). Research is also addressing inorganic acid gas emissions from co-firing RDF with coal (Daugherty et al., 1989).

## 13.4 Prioritized RD&D Needs

In this section the priorities assigned to the RD&D needs by the panel of technical experts on dedicated RDF production and combustion are presented and discussed. The priorities are based upon an assessment by each panel member of the potential contribution of each RD&D need towards making RDF combustion technically feasible and commercially viable. The prioritized list of RD&D needs was reviewed, discussed, and sometimes modified by the panel. After a final priority had been assigned to each RD&D need, the panel members categorized the needs as being high priority, medium-to-high priority, medium priority, low-medium priority, or low priority. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 13-2, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in Section 13.3 is in the right-hand column. The rationale discussed by the panel of technical experts is presented below. The rationale tend to focus on RD&D needs where panel members had very different opinions on the priority, and to ignore RD&D needs on which there was a group consensus. Also, discussion of rationale was constrained by the limited amount of time available to the panel.

In general, the prioritized list focused on four areas. The panel placed heaviest emphasis on research needs that enhance public acceptance of RDF as it relates to emissions. The panel agreed that there is a significant gap between public perception of the industry (which is largely negative) and reality. The panel felt that technology oriented needs that may reduce the quantity of residue and reduce emissions deserved second priority. The third most important need is for methods that improve the economic efficiency of the process. Finally, the panel felt that recovering materials for other uses is important, because it is the primary characteristic that distinguishes RDF from other technologies. The panel

## Exhibit 13-2. Prioritized RD&D Needs for Dedicated RDF Combustion

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| 100 | Develop technologies for proactive control of regulated heavy metals | 26 |
| 74 | Identify MSW components that contribute to combustion and environmental concerns | 2 |
| 68 | Evaluate methods/technologies to remove toxic contaminants from MSW | 9 |
| 58 | Develop higher temperature/pressure steam designs and corrosion resistant materials | 15 |
| | **Medium-to-High Priority** | |
| 58 | Study methods of controlling the reformation of dioxins | 17 |
| 53 | Develop improved processes to recover noncombustible materials | 8 |
| 47 | Develop improved processes to minimize the input of noncombustible materials | 7 |
| 47 | Investigate methods to reduce residue streams | 28 |
| 47 | Perform demonstration studies of composting of process residues | 29 |
| 47 | Investigate and demonstrate uses of process waste | 31 |
| 47 | Study the distribution and feed rate of material into boilers | 13 |
| 47 | Evaluate the effect of preprocessing on emissions | 27 |
| 47 | Develop waste handling and recovery systems for nonprocessables and residues | 30 |
| | **Medium Priority** | |
| 47 | Study economic effects of major changes in composition of MSW stream | 4 |
| 47 | Develop better and more reliable real-time surrogate indicators of specific emissions | 20 |
| 47 | Improve the reliability of continuous emission monitoring (CEM) systems | 22 |
| 41 | Develop a process to recover reusable combustible materials | 10 |
| 41 | Develop methods to identify occupationally hazardous substances in MSW | 3 |
| 41 | Investigate issues of RDF combustion in fluidized beds | 32 |
| | **Low-Medium Priority** | |
| 37 | Conduct operational consideration studies on co-firing | 19 |
| 37 | Study the control of $NO_X$ and selective non-catalytic reduction capabilities of RDF | 23 |
| 37 | Reduce the cost of lowering emissions (e.g., cheaper sorbants, spray driers) | 21 |
| 37 | Determine the optimum combustion conditions | 14 |
| 37 | Develop methods and technologies to identify items in MSW that damage equipment | 1 |
| 32 | Reduce carbon monoxide (CO) emissions | 24 |
| 32 | Develop technologies to accept objects in MSW that cannot be handled at present | 5 |
| 32 | Develop technologies for rendering potentially hazardous items nonhazardous | 6 |

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **Low Priority** | |
| 26 | Study the regulatory, health, and other effects of extended storage of RDF | 12 |
| 26 | Perform a demonstration study of flue gas recirculation to control $NO_x$ emissions | 16 |
| 21 | Investigate on-line grate cleaning techniques | 18 |
| 21 | Reduce carbon dioxide ($CO_2$) emissions | 25 |
| 21 | Study the effects of long-term RDF storage on the Btu value of RDF | 11 |

deemphasized the need for DOE sponsored demonstration projects since many have been done before or should be funded by industry.

### High Priority RD&D Needs

These top priorities deal with environmental concerns, particularly with regard to heavy metals, a subject in which less research has been performed than in other areas. The panel achieved a strong consensus that controlling heavy metals in emissions (No. 27) is very important. The panel stressed that it is easier to control what comes out of an MSW unit than what goes into one, and that public acceptance is closely tied to the emissions from a unit. The panel also emphasized the importance of identifying and removing from MSW most metals, glass, and other items such as chlorides (No. 9). Research on components that contribute to combustion and environmental concerns (No. 2) are not unique to dedicated RDF but are common to other technologies as well. The panel also strongly agreed on the need for improving boiler design (No. 15); several members stressed that the most common difficulties in the industry are achieving and maintaining adequate boiler temperatures and dealing with corrosion of the boilers.

### Medium-to-High Priority RD&D Needs

The panel felt that in general, RDF combustion raises concerns that are important in many cases because of public perception and acceptance. This is especially true for the issue of dioxin generation (No. 17). RD&D related to residues (Nos. 28, 29, and 30) is important, because if residues can be reduced, the industry's burden on landfill capacity will also be reduced. The panel emphasized the need to reduce or remove noncombustible materials from MSW (Nos. 7 and 8) both to avoid damaging equipment and to reduce residues. Preprocessing of MSW (No. 27) should also be evaluated as a means to reduce emissions problems. The panel also agreed that boiler feed systems (No. 13) should also be further investigated.

### Medium Priority RD&D Needs

The panel felt that an economic study of MSW stream changes (No. 4) is applicable to other technologies in addition to RDF production and dedicated combustion. Several panel members felt that real-time indicators and continuous monitoring (Nos. 20 and 22) were the key to public acceptability; one panel member stated that the problem RDF faces is "two percent technology, 98 percent public acceptability." Of less importance, the panel believed that more research should be invested into recovering reusable combustible materials from

the incoming MSW stream (No. 10), while also identifying occupationally hazardous items (No. 3). The panel also felt that fluidized bed combustion (No. 32) should be researched.

**Low-Medium Priority RD&D Needs**

The panel felt that determining optimal combustion conditions (No. 14) is an ongoing effort and of lower research priority, while operational studies on co-firing RDF alternatives (No. 19) can also be taken care of in the chapter on RDF production and co-fired combustion. The group felt that, in general, improving MSW handling capabilities (Nos. 1, 5, and 6) should be a relatively minor challenge. As a result, RD&D needs in this area were rated lower. Much of the research in lowering emissions (Nos. 21, 23, and 24) has already been done or is generic across combustion technology.

**Low Priority RD&D Needs**

The panel felt that there have been few problems with storage of RDF (Nos. 11 and 12). Other emissions problems with $NO_x$ (No. 16) and $CO_2$ (No. 25) were also considered minor. The panel felt that more important than improving grate-cleaning techniques (No. 18) was overall control of slagging and fouling.

## 13.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate dedicated RDF combustion with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

**Cost of RD&D Program**

The panel estimated that the cost of implementing an RD&D program that focuses on the more highly prioritized RD&D needs could range from $20 million to $30 million.

**Difficulty of Technology Development**

The panel felt that the difficulty of improving the technology in response to the identified RD&D needs would be very low since dedicated RDF technology is mature and already viable in the near term.

**Commercial Development Risk**

The panel felt that commercial development risk for dedicated RDF is probably low at present. As indicated earlier, there is a gap between public image and reality, but the panel felt that there is a large potential market for dedicated RDF. The panel estimated that a moderate investment beyond RD&D (more investment than for a landfill, less investment than for gasification) would be necessary to develop the industry. The panel estimated the cost to build a 1,000 tpd facility at $200 million.

### Flexibility

The panel felt that dedicated RDF can handle 75 to 80 percent of the MSW stream and is comparable to mass-burn technology in terms of flexibility. The technology is appropriate on a medium to large scale (i.e., 800 tons and up). Dedicated RDF is compatible with both existing and future technologies and is compatible with recycling programs.

### Cost Impacts

The panel could not agree upon the cost impact of RDF.

### Net Energy Benefit

As a benchmark, the panel estimated that a 1,000 tpd MSW mass-burn facility produces 50 megawatts and that a dedicated RDF combustion facility would have a comparable conversion efficiency. Dedicated RDF combustion can produce steam or electricity. It is more efficient at recovering resources than landfilling or mass-burn, but is not as efficient as source separation or MRFs. For nonrenewables, it is more efficient than MRFs for aluminum and steel, but less efficient for glass.

### Human Health and the Environment

The panel felt that dedicated RDF poses less risk to human health than do landfills and about the same risk as other resource recovery technologies. The panel felt that dedicated RDF poses less environmental impact than most technologies but emphasized that there is a problem with public perception of environmental impact. The panel noted that there are few site-specific environmental impacts.

### Occupational Health and Safety

The panel felt that dedicated RDF is more dangerous to workers than composting (due to pressure vessels and hot surfaces) and less dangerous than hand picking at a MRF.

### Appropriateness for Government Funding

The panel felt that dedicated RDF is appropriate for DOE funding, with the exception of equipment improvement and development. The panel also felt that dedicated RDF is compatible with existing regulations.

# 14. SOURCE SEPARATION AND COLLECTION

## 14.1 Technology Description

Source separation is a process through which members of a community separate recyclable material from ordinary municipal solid waste (MSW). Source separation reduces waste disposal volumes and increases the potential for resource conservation. A variety of methods may be used to separate and collect recyclables, but the specifics of an individual source separation and collection program will generally be unique to the community for which it is designed.

An important factor in the success of any source separation program is the level of participation by individual households or other generators. Participation may be entirely voluntary, encouraged by economic incentives, or mandated by ordinance. The complexity of the source separation program (i.e., the number of materials collected and the type of collection service offered) also influences participation. Programs may be designed to separate out any number of materials, including various types of paper, aluminum, metal, plastics, glass, yard waste, used oil, and batteries. Participation may be higher, however, if participants are asked to separate MSW into only a few categories (Denison and Ruston, 1990). Source separation may be combined with the use of a materials recovery facility (MRF) so that some separation occurs at the source and further separation and processing occurs at the MRF. Another option is for separation at the time of collection as materials are loaded into the collection vehicle.

The convenience of the collection system will also effect participation. Collection may be organized through the use of drop-off centers, which are central facilities to which individual recyclers bring separated materials. Drop-off centers may be located almost anywhere, including at a landfill or transfer station. They can be attended by personnel to assist recyclers or they may be unattended. Economic incentives may be combined with drop-off centers so that recyclers are paid for at least some of the materials they deliver. Such facilities are called "buy-back centers."

Active collection services, however, are likely to have higher participation levels than drop-off centers. Participation tends to be highest when recyclable material is picked up on the same day as regular trash (Denison and Ruston, 1990). This type of collection can be accomplished with a system in which normal collection vehicles are equipped with racks or trailers to hold recyclable material. This option, however, tends to limit the volume and variety of materials that can be collected, especially when racks are used because of their limited size. Systems that collect recyclable material separately from ordinary trash service offer more flexibility and may utilize specially designed vehicles (Robinson, 1986). Such systems, however, require a sizeable capital investment. They also result in some duplication of effort because collection crews will visit each collection point twice, once for regular service and once for recyclables collection. (Robinson, 1986; Denison and Ruston, 1990) Other factors that effect the efficiency and convenience of a recycling program are crew size, frequency of collection, point of collection (backyard versus curbside or alley), type of storage container (reusable containers or one-way containers such as bags), and availability of containers (Robinson, 1986).

## 14.2 Technology Status

Across the United States, the number of recycling initiatives to reduce the amount of MSW which is landfilled has increased dramatically over the past few years. One of the most popular approaches is source separation and curbside collection of MSW for the purpose of recycling. In 1989 the number of curbside recycling programs in the nation rose 45 percent; in 1990 it rose 79 percent (Glenn and Riggle, 1991). In 1990 approximately 2,711 curbside recycling programs were serving a population of about 37 million Americans (Glenn and Riggle, 1991). Of the curbside programs identified in 1990, only 44 collected a single material, while the remaining 2667 were multi-material programs. As of late 1990, every state except Alaska and Delaware had curbside recycling programs in place and at least 19 states had mandatory curbside recycling in some localities. Thirty-three states currently have comprehensive recycling laws that require separation of recyclables and/or detailed statewide plans that contain one or more provisions to stimulate recycling. (NSWMA, 1990)

With the increase in the number of recycling programs, a number of states have increased the amount of MSW they recycle each year. In 1989, only Washington and Oregon claimed recycling rates of over 20 percent; while in 1990, Colorado, Delaware, Minnesota, and New Jersey also claimed to reach that level. Another 11 states had 1990 recycling rates between 10 and 20 percent (Glenn and Riggle, 1991), though these recycling rates estimates are difficult to verify. Virtually all programs include source separation of several materials, including glass, paper, metal cans, and yard waste. Some curbside programs have achieved recovery rates of over 40 percent, although rates generally range from 20 to 30 percent of the waste generated. (NSWMA, 1990)

In addition to recent state legislation that mandates recycling programs, in the past two years enhanced environmental awareness in communities across the U.S. has contributed to a significant increase in the number of voluntary recycling programs. While the majority of programs were mandatory at the end of 1989, by the end of 1990 almost 60 percent of the programs were voluntary. The Northeast has the largest concentration of mandatory programs. Connecticut, New York, Rhode Island, and Massachusetts have 80, 76, 22, and 18, respectively, while Pennsylvania has 274 and New Jersey 492, all of which are mandated by state law. Outside of the Northeast, only California and Minnesota have a substantial number of mandatory programs. (Glenn and Riggle, 1991)

## 14.3 Description of RD&D Needs

RD&D needs in the area of collection and source separation focus on improving and expanding curbside collection programs and assessing the efficiency, costs, and energy and environmental impacts of various source separation strategies. RD&D needs are identified in four major areas: (1) improving collection recovery; (2) expanding the range of materials collected; (3) assessing alternative source separation strategies; and (4) assessing the energy and environmental impacts of recycling. These RD&D needs include consideration of the commercial, industrial, and institutional markets as well as the residential market. An overriding concern of the panel members was for the development of markets for recycled materials. (See the chapter on Material Recovery Facilities for specific RD&D needs in this area.) Sections 14.3.1 through 14.3.4 describe the RD&D needs for source separation and collection that were identified by the panel of technical experts (listed in Appendix A). Each RD&D need has been assigned a reference number for easy identification. Section 14.3.5

describes an RD&D topic that was identified in the literature review (see the introduction chapter), but was not subsequently accepted by the panel of technical experts. This topic is not prioritized or discussed further.

### 14.3.1 Improving Collection Recovery

Researchers studying recyclable material collection generally agree that curbside collection programs recover the greatest percentage of recyclable material from the municipal solid waste stream as compared to other collection methods such as drop-off centers and buy-back centers. To a large extent, the higher recovery rate for curbside collection is attributed to its convenience. A widely held "convenience assumption" states that participation in a recycling program and, thus, the recovery of recyclable material increases as the convenience of participation in a recycling program increases. Most researchers seem to agree that curbside collection is the most convenient method of collection and results in a greater participation and a higher recovery rate than less convenient collection methods such as buy-back centers or voluntary drop-off centers. However, other factors may affect the recyclables recovery rate in a collection program. While some work toward identifying these factors may have already been completed for residential recycling programs, a substantial amount of research remains to be done, particularly in the areas of commercial, institutional, and industrial solid waste recycling. Research is needed to:

1. Identify and study the factors that affect recovery of recyclables from residential recycling programs, including factors that impact participation and the quantity of material recovered per capita;

2. Identify and study the factors that affect recovery of recyclables from commercial and institutional recycling programs; and

3. Identify and study the factors that affect recovery of recyclables from the industrial sector (non-hazardous industrial solid waste).

One method suggested for increasing participation in a residential recycling program is to establish variable rates for municipal solid waste collection. These rates could be volume-based or weight-based fees and may be collected on a tax-basis or through direct charging. Research is needed to:

4. Investigate different mechanisms for establishing variable rates for residential solid waste collection.

Alternatively, mechanical solutions may improve collection recovery. These potential solutions include redesigning collection vehicles to meet specific needs such as compaction of recyclables. For example, the low density of plastic wastes makes them expensive to collect and transport. In some cases, this expense may cause some communities to forego plastics recycling as part of their overall recycling program. As a result, manufacturers and recyclers are looking for ways to fit more plastic material onto recycling trucks by densifying material at the curbside, such as densifying plastic material in the collection vehicle itself (Rankin, 1988). An additional research need is to:

5. Research and evaluate collection vehicle designs with particular emphasis on their capability for improving collection recovery.

Finally, improvements in collection recovery may be achieved by expanding the collection area beyond the traditional single family urban or suburban residential areas. Certain types of recyclable materials (e.g., newspapers, aluminum, glass) have been collected and recycled in the U.S. for more than 40 years through buy-back and drop-off centers. Curbside collection of multiple recyclable materials is a more recent concept which is still being researched and developed. As the popularity of recycling continues to grow, however, local and state officials are increasingly pressured to improve recycling rates. One method of producing this increase may be to enlarge recycling programs to include rural areas, multi-family dwellings, and multi-tenant commercial establishments. The problem with such expansions, however, is that the infrastructure needed to handle them usually does not exist. Thus, research is needed to:

6. Assess the feasibility of collection programs in rural areas;

7. Design and develop collection programs for multi-family dwellings, including a demonstration project to identify any special equipment necessary for efficient recyclables collection and socioeconomic issues that may affect participation and recovery rates; and

8. Design and develop collection programs for multi-tenant commercial buildings.

### 14.3.2 Expanding the Range of Materials Collected

Attaining a higher recovery rate for recyclable materials involves more than simply raising participation rates in recycling programs and improving the efficiency of the collection process. A key factor in increasing recovery rates is developing and marketing additional uses for certain recyclable materials and creating additional material processing technologies that are capable of handling a greater degree of contamination of the material being recycled. Developing these new uses and processing technologies would allow municipalities to collect additional types of materials and some contaminated materials that currently are not acceptable. The specific research needs in this area are to:

9. Evaluate current and potential alternative glass recycling practices giving special attention to issues such as potential energy conservation or use and safety hazards posed by broken glass in the recyclable materials stream;

10. Develop additional uses for recovered glass (especially mixed glass);

11. Develop additional uses for other recovered materials such as plastics (including new uses for resins other than PET and HDPE) and mixed paper; and

12. Develop new processing technologies for recyclable materials that are capable of handling greater degrees of contamination (particularly glass contamination of other recyclable materials such as paper).

### 14.3.3 Assessing Source Separation Strategies

Separating recyclable material from the municipal solid waste stream is a necessary step in the recycling process. Recyclable materials must be separated from waste material in order to be suitably prepared for material recovery markets. Once recyclable material has been separated from the solid waste stream, the various fractions must still be separated from one another before they can be marketed. Currently, there is some debate concerning the level of materials separation that should be required prior to or during municipal solid waste and recyclables collection. Thus, there is a need to:

13. Compare the efficiency of co-collecting recyclable materials and solid waste in the same truck to having a dedicated truck and crew for recyclables;

14. Evaluate the costs and benefits of wet/dry collection systems; and

15. Compare the costs and benefits of commingled collection of recyclables to those of driver sorting.

A number of studies have been conducted to estimate the total cost of a curbside collection program for various communities. Different studies, however, have used different measures to determine the cost of these programs. The results are confusing and make cost comparisons extremely difficult. There is a need to:

16. Estimate the economic benefits and costs of various curbside collection programs.

Finally, separating recyclable material from the solid waste stream may not only allow for material recovery, but may also enhance the performance or reduce the environmental problems associated with subsequent municipal solid waste-to-energy processes or disposal practices. Research is needed to:

17. Assess the impact of source separation on the suitability of waste for downstream energy recovery, composting, material recovery, mixed waste processing, landfilling, and combustion.

This research should consider the impact of source separation on the performance and emissions of downstream energy, materials recovery, or disposal technologies. In addition, studies may consider the potential economic benefits of source separation prior to downstream technologies. (Dent and Krol, 1990)

### 14.3.4 Assessing the Energy and Environmental Impacts of Recycling

The overall environmental impact of recovering and recycling various materials is currently receiving much attention. Little work has been done, however, to assess the overall impact of recycling various materials on energy use and conservation, or to compare the

energy and environmental impacts of alternative collection, processing, and manufacturing systems for recyclable materials. Research is needed in this area to:

18. Study the energy impacts of alternative collection programs (e.g., curbside versus drop-off collection and multiple collection vehicles versus co-collection vehicles);

19. Study the energy consumption impacts of recycling by material commodity and energy type;

20. Determine the impacts of recycling on renewable and non-renewable resources (e.g., trees and bauxite); and

21. Study the environmental impacts of recycling (e.g., alternative collection, processing, and manufacturing systems) including analyses of all types of pollution such as vehicle emissions, residuals form processing, sludges, and runoff.

### 14.3.5 Other Potential RD&D Topics

The following source separation research need was identified in the literature, but was not subsequently accepted by the panel of technical experts.

Investigate potential for using bar coding to evaluate curbside collection programs. Test programs in a number of communities have indicated that labelling recyclable material collection bins used by households and businesses in curbside collection programs with bar codes and scanning the bar codes during collection may be an effective method for monitoring participation in curbside collection programs. The collection crew uses a portable computer to scan the bar code and register the time the recyclables were collected at a certain address. Studies of curbside collection programs of varying sizes, including programs in a major urban area, may investigate the potential for using bar coding of consumer recycling bins to obtain consistent consumer participation and collection efficiency data. Such studies should assess the value of these data in comparing the effectiveness of various curbside recycling programs, targeting areas within a community for consumer education and promotion efforts, monitoring the personal productivity of workers, and assessing the efficiency of existing collection routes. (Watson, October 1990)

## 14.4 Prioritized RD&D Needs

This section presents and discusses the priorities assigned to the RD&D needs by the panel of technical experts on source separation and collection (listed in Appendix A). The priorities are based upon an assessment, by each panel member, of the potential contribution of each RD&D need toward making source separation and collection technologies technically and economically feasible and commercially viable. The panel reviewed, discussed, and sometimes modified the prioritized list of RD&D needs. (See the introduction chapter for a more detailed description of the prioritization process.) The RD&D needs are listed by order of priority in Exhibit 14-1, from highest to lowest priority. The normalized scores for each RD&D need are in the left-hand column; a brief description of the need is in the center column; and a reference number for locating a more detailed discussion of the need in

**Exhibit 14-1. Prioritized RD&D Needs for Source Separation and Collection**

| Score | RD&D Need Description | RD&D No. |
|---|---|---|
| | **High Priority** | |
| 100 | Assess the impact of source separation on suitability of downstream technologies | 17 |
| 90 | Study the energy consumption impacts of recycling by material and energy type | 19 |
| 85 | Compare the efficiency of co-collection to having a dedicated truck and crew | 13 |
| 80 | Evaluate current and potential alternative glass recycling practices | 9 |
| 80 | Study the energy impacts of alternative collection programs | 18 |
| 80 | Study the environmental impacts of recycling | 21 |
| 75 | Identify and study factors affecting recovery from residential recycling programs | 1 |
| | **Medium Priority** | |
| 70 | Develop additional uses for recovered materials such as plastics and mixed paper | 11 |
| 70 | Investigate the use of variable rates for residential solid waste collection | 4 |
| 70 | Design and develop collection programs for multi-family dwellings | 7 |
| 70 | Develop additional uses for recovered glass (especially mixed glass) | 10 |
| 70 | Estimate the benefits and costs of various curbside collection programs | 16 |
| 60 | Determine the impacts of recycling on renewable and non-renewable resources | 20 |
| 50 | Design and develop collection programs for multi-tenant commercial buildings | 8 |
| 50 | Study factors affecting recovery from commercial and institutional recycling | 2 |
| 50 | Evaluate the costs and benefits of wet/dry collection systems | 14 |
| 35 | Assess the feasibility of collection programs in rural areas | 6 |
| | **Low Priority** | |
| 30 | Research and evaluate various collection vehicle designs | 5 |
| 30 | Develop new processing technologies for recyclable materials | 12 |
| 20 | Study factors affecting recovery of recyclables from the industrial sector | 3 |
| 20 | Compare the costs and benefits of commingled collection and driver sorting | 15 |

Section 14.3 is in the right-hand column. The panel's discussion of the rationale for the ranking of the RD&D needs is summarized below. Discussion of rationale was constrained by the limited amount of time available to the panel.

### High Priority Needs

The panel members ranked research to assess the impact of source separation on downstream energy recovery, composting, material recovery, mixed waste processing, landfilling, and combustion (No. 17) as the top RD&D need. Because source separation can change the composition of the waste input to downstream management operations, it can

influence the technical and economic feasibility and environmental impacts of these operations. The panel selected this study as the highest priority RD&D need primarily because it would address national solid waste management issues, would be especially appropriate for Department of Energy funding, and would yield results that influence the future direction of recycling programs nationwide.

The panelists also indicated that a study on the energy consumption impacts of recycling by material commodity and energy type (No. 19) could also have a significant impact on the future direction of recycling programs. Therefore, the panel ranked this study as the second highest priority RD&D need. In addition, the panelists indicated that the only existing studies in this area are outdated.

The panel members believed that comparing the efficiency of co-collecting recyclable materials and solid waste in the same truck to having a dedicated truck and crew for recyclables (No. 13) could have a significant impact on improving the cost, efficiency, and participation rates of collection programs. They ranked this comparative study as the third highest priority.

The panel assigned the next three RD&D needs (Nos. 9, 18, 21) equal priority rankings. The panel members believed that evaluating current and potential alternative glass recycling practices (No.9) is a high priority RD&D need because of the problems associated with glass recycling, such as safety hazards posed by broken glass in the recyclable materials stream, without significant energy and environmental benefits in return. Some panelists believed that the primary reason that glass is currently included in many recycling programs is to increase the percentage of material recovered, by weight, from the municipal solid waste stream.

According to the panel, as various state and local governments attempt to implement collection programs, government officials will become increasingly concerned with the energy use and conservation impacts of various programs. Thus, the panel rated a study of the energy impacts of alternative collection programs (No. 18) as a high priority need. Some panelists pointed out, however, that though not much work has been done in this area, the results of such a study are not essential for developing and implementing a successful collection program.

With rationale similar to that for No. 19, the panelists ranked a study of the environmental impacts of recycling (No. 21) as a high priority RD&D need. While this study may not be as appropriate for a Department of Energy research program as a study of the energy impacts of recycling (No. 19), the panel believed that it is an important study given its potentially significant impact on the future direction of recycling programs and because little previous work in this area has been done.

Finally, the panel selected a study of factors affecting recovery from residential recycling programs (No. 1) as the final high priority need. The panel considered understanding the factors influencing participation and recovery rates as critical for designing effective materials recovery programs.

### Medium Priority Needs

Panelists placed eight RD&D needs in the medium priority category and assigned five needs (Nos. 11, 4, 7, 10, and 16) identical scores of 70. Panelists disagreed significantly upon the importance of developing additional uses for recovered materials such as plastics and mixed paper (No. 11). Some panelists stated that it is extremely important to develop new markets for these materials, but other panel members reported that the benefits of developing new uses would not be substantial, as in the case of plastic, and that, for some materials, there are waste management techniques other than recycling (e.g., combustion or composting of mixed paper) that are environmentally and economically sound.

The panelists felt that needs Nos. 4, 7, 10, and 16 are important issues, but they believed that a substantial amount of existing research addresses them. In most cases, the primary need may be to compile the existing research results. The panel members strongly disagreed, however, about the need for new studies to estimate the benefits and costs of various curbside collection programs (No. 16). The major differences of opinion among panelists concerned the relative difficulty of understanding and using the results of the existing collection cost information.

### Low Priority Needs

The panel rated four RD&D needs (Nos. 5, 12, 3, and 15) as low priority needs. The panel members believed that these areas are more suited for private sector research than for government research and that the private sector has its own incentives for addressing these needs.

## 14.5 Discussion of the Evaluation Criteria

This section summarizes the efforts of the panel of technical experts to evaluate source separation and collection with respect to the evaluation criteria developed by the Peer Review Group. These evaluations were given to the members of the Peer Review Group prior to the Group's October 1-2 meeting to discuss and evaluate the relative importance of the RD&D needs for the twelve technologies, trade-offs, and their relationship to underlying policy goals and values.

### Cost of the RD&D Program

The panel estimated that its top priority need, No. 17, would require some immediate research followed by a long-term program. The first two years of research would require approximately $0.5 million and years 3 through 5 would require an additional $2 million. The panel estimated the cost of a research program addressing the next four highest priority needs, Nos. 19, 13, 9, and 18, at a minimum of $2 million over a two-year period. Addressing need No. 21 would consist of a series of environmental impact studies of various collection and material processing systems; the panel estimated that the costs of such a program at $1 million for one year of research. The final high priority need, No. 1, would require funding of approximately $300,000 to $500,000 over a period of one year. Turning to some of the medium priority needs, the panel estimated that approximately $300,000 each would be required for adequately addressing RD&D Nos. 11, 4, and 7, while RD&D No. 10 would require approximately $1 to $2 million.

### Difficulty of Technology Development

The panel members agreed that an RD&D program in the area of source separation and collection consists of low risk research, dealing mostly with program design rather than technology design, and that it is timely in light of the current popularity of recycling and recycling programs. The panelists believed that this research program would enhance the commercialization of recycling programs and improve public knowledge regarding the solid waste management process.

### Flexibility

With regard to program flexibility, the panelists stated that a source separation and collection RD&D program would cut across all materials and all aspects of the waste management process, facilitating improved waste management policy making decisions. The research would also allow communities to direct recycling efforts toward specific commodities, promoting increased compatibility between recycling and other waste management technologies.

### Net Energy Benefit

The panel members noted that a source separation and collection RD&D program would have the benefit of determining the most effective ways of saving energy through the recycling process (e.g., choosing the most energy efficient collection system and targeting materials for recovery based on energy savings over virgin material production).

### Human Health and the Environment

Panelists cited a number of human health and environmental benefits from the RD&D program, including reduction of toxic emissions, raw materials and natural resource savings, and reduced environmental degradation.

### Appropriateness for Government Funding

The panel members agreed that the source separation and collection RD&D program (particularly those research needs in the high priority category and at the top of the medium priority category) are well suited to the Department of Energy's research and funding objectives.

# 15. RELATIVE COST AND IMPACT OF RD&D

This chapter documents results from the October 1-2, 1991 meetings of the Peer Review Group which was charged to take a broad perspective in comparing certain MSW technology areas in terms of their potential RD&D costs and impacts according to specific criteria identified by the Group. This chapter presents the development of these results through discussions of:

- The composition of the Peer Review Group (Section 15.1);
- The methodology used by the Peer Review Group to rank the technology areas (Section 15.2);
- Definitions of the evaluation criteria (Section 15.3);
- Technology areas considered for further RD&D (Section 15.4);
- Cost and impact criteria scoring (Section 15.5);
- Evaluation criteria weights (Section 15.6); and
- The aggregate cost and impact scores (Section 15.7).

The Peer Review Group, unlike the panels of technical experts whose efforts are documented in chapters 3 through 14, did not attempt to define the specific RD&D needs associated with each technology area. While each member of the Peer Review Group received an interim report describing the RD&D needs and priorities developed by the panels of technical experts before the Peer Review Group's final meeting, the Peer Review Group did not accept these needs and priorities during their assessments of the technology areas. Some members of the Peer Review Group strongly disagreed with certain recommendations of the technical panels. The Peer Review Group's scoring of the areas must not be understood as a validation or endorsement of the specific RD&D needs presented in chapters 3 through 14.

The primary objectives of the Peer Review Group were to evaluate the technology areas by (1) the expected impacts (i.e., aggregate impact scores) of further RD&D with respect to a specified set of evaluation criteria; and (2) the expected costs (i.e., aggregate cost scores) of the RD&D needed to take each technology area from its current state to commercial viability within 5 to 10 years, or to overcome barriers to the wider use of already commercialized technologies.

## 15.1 The Peer Review Group

The Peer Review Group met twice during the course of this project. During the Peer Review Group's first meeting on July 24, 1991, the participants developed an initial list of evaluation criteria that could be used to assess the cost and impact of further RD&D in each technology area. (The initial list of evaluation criteria is presented in Appendix B.) At the Peer Review Group's second meeting on October 1-2, 1991, the participants refined the

evaluation criteria and ranked each technology area with respect to the other technology areas.

The Peer Review Group was comprised of people from the waste management industry, federal government, state government, research organizations, and one public interest group.[1] While a number of public interest groups were asked to participate in the Peer Review Group, only one group elected to join the Peer Review Group. We tried to maintain a linkage between the panels of technical experts and the Peer Review Group by having one or more members from each technical panel participate in the Peer Review Group. Unfortunately, not all of the "common" members were able to attend both efforts. The members of the Peer Review Group are listed in Exhibit 15-1, along with their affiliation and the meetings in which they participated (additional information is given in Appendix A).

## 15.2 Methodology

The general procedure used by the Peer Review Group to prioritize MSW areas for further RD&D during the two-day conference was to:

1. Review the prioritized RD&D needs listed by the eleven panels of technical experts in the September 23, 1991 interim report;

2. Expand the initial list of technical areas;

3. Revise the evaluation criteria;

4. Prioritize the technical areas for each criterion;

5. Assign relative weights to the evaluation criteria; and

6. Weight the normalized average scores for each criterion and combine to produce aggregate cost and impact scores for the technical areas.

Mathematically, the aggregate impact (Equation 1) and aggregate cost (Equation 2) scores for each technology area are calculated by summing the weighted scores for a set of cost and impact evaluation criteria:

$$\textbf{Aggregate Impact Score} = \sum_{i=1}^{m} \textbf{Weight}_i \times \textbf{Impact Score}_i \qquad [1]$$

where: m = the number of impact evaluation criteria
$weight_i$ = the relative importance of the $i^{th}$ impact evaluation criterion
$impact\ score_i$ = the relative impact of further RD&D on the $i^{th}$ impact evaluation criterion for the technology area

[1] One reviewer believes that the composition of the Peer Review Group is heavily oriented towards mass-burn combustion and that this raises questions about the impartiality of the evaluation of other technology areas.

## Exhibit 15-1. Peer Review Group Roster

| Names | Affiliation | July 24 | October 1-2 |
|---|---|---|---|
| Mr. James Aiello | ABB Resource Recovery Systems | X | X |
| Dr. Harvey Alter | U.S. Chamber of Commerce | X | |
| Dr. Richard Anderson | Wheelabrator Technologies, Inc. | X | X |
| Mr. David Beachler | Resource Energy Systems Division, Westinghouse Electric Corporation | X | X |
| Ms. Jean Bogner | Argonne National Laboratory | X | X |
| Ms. Marina Bouley | Browning Ferris Industries, Inc. | X | |
| Mr. Ed Chapman | Goldman, Sachs & Company | | X |
| Mr. Alan Cohen | CSI Resource Recovery Systems | X | |
| Dr. T.R. Curlee | Oak Ridge National Laboratory | X | X |
| Mr. Paul des Rosiers | U.S. Environmental Protection Agency | X | |
| Dr. Daryl Ditz | Cornell Waste Management Institute | X | |
| Mr. Edward Fox | Procter & Gamble | X | |
| Ms. Charlotte Frola | Solid Waste Association of North America | X | |
| Dr. Isaiah Gelman | National Council of Air and Stream Improvement | | |
| Mr. Andrew Grant | Babcock & Wilcox | | |
| Mr. Terry Grogan | U.S. Environmental Protection Agency | X | |
| Mr. William Heenan, Jr. | Steel Can Recycling Institute | X | |
| Mr. Rob Kaufman | American Paper Institute | | |
| Mr. Jonathon Kiser | National Solid Waste Management Association | X | X |
| Mr. Frank Kreith | National Conference of State Legislators | X | X |
| Mr. S.W. Kulick | New York State Solid Waste Combustion Institute | | |
| Mr. Steve Levy | U.S. Environmental Protection Agency | | X |
| Mr. Bill Liu | Chemical Waste Management | X | X |
| Mr. Parker Mathusa | New York State Energy Research | | X |
| Mr. Greg Maxwell | Waste Management of North America | X | X |
| Dr. Thomas Nosker | Center for Plastics Recycling | | |
| Ms. Abbie Page | American Society of Mechanical Engineers | X | X |
| Mr. Bob Peters | Solid Waste Association of North America | X | X |
| Mr. George Savage | CAL Recovery, Inc. | X | |
| Mr. Richard Seelinger | Ogden Martin Systems, Inc. | | X |
| Mr. George Simons | California Energy Commission | X | X |
| Mr. David Sussman | Ogden Martin Systems, Inc. | X | X |
| Dr. Aaron Teller | Research Cottrell, Inc. | X | X |
| Mr. Charles Velzy | Roy F. Weston, Inc. | | X |
| Dr. Aarne Vesilind | Department of Civil & Environmental Engineering, Duke University | X | X |
| Mr. John Young | Worldwatch Institute | X | |

$$\text{Aggregate Cost Score} = \sum_{j=1}^{n} \text{Weight}_j \times \text{Cost Score}_j \qquad [2]$$

where: n = the number of cost evaluation criteria
$\text{weight}_j$ = the relative importance of the $j^{th}$ cost evaluation criterion
$\text{cost score}_j$ = the relative cost of further RD&D on the $j^{th}$ cost evaluation criterion for the technology area

The terms in Equations 1 and 2 are defined and discussed in Sections 15.2.4 through 15.2.6.

### 15.2.1 Prioritized RD&D Needs

Several members of the Peer Review Group stated that their views on the RD&D needs and priorities associated with certain technology areas differed substantially from the RD&D needs identified and prioritized by the panels of technical experts (see Chapters 3-14). Although a general understanding of the RD&D needs associated with each technology area was required by Peer Review Group members to make their evaluations, they were not asked to explicitly define the RD&D needs and priorities they envisioned, because repeating the work done by the panels of technical experts was not necessary for this exercise.

### 15.2.2 Expanded List of Technical Areas

The Peer Review Group strongly recommended adding "source reduction" and "systems studies" as two additional areas even though RD&D needs for these areas had not been explicitly defined or prioritized. Since source reduction falls somewhat outside the scope of the project as originally envisioned by DOE, it was not originally included as a MSW management technology area addressed by a technical panel. The Peer Review Group, however, generally felt strongly that source reduction should be included due to its importance to MSW management and its impact on the implementation of other MSW technologies. The source reduction area is described more fully in section 15.3.1. The systems studies area includes common comparative studies, identified by many of the technical area panels, which are not specific to any one technical area. Systems studies include studies for identification and filling of key data gaps as well as economic analyses, comparative studies, and policy studies. The systems studies area is described more fully in section 15.3.2. The technology areas considered by the Peer Review Group are as follows:

1. Systems Studies (added during the October meeting of the Peer Review Group);

2. Landfill Gas;

3. Ash Utilization and Disposal;

4. Mass-Burn Combustion;

5. Material Recovery Facilities;

6. RDF Production and Co-Fired Combustion;

7. Source Reduction (added during the October meeting of the Peer Review Group);

8. Source Separation and Collection;

9. Modular Mass-Burn Combustion;

10. Composting;

11. RDF Production and Dedicated Combustion;

12. Anaerobic Digestion;

13. Gasification; and

14. Pyrolysis.

### 15.2.3 Revised List of Evaluation Criteria

The Peer Review Group developed a list of criteria to be used in evaluating the potential cost and impact of RD&D on each technology area. The original set of evaluation criteria developed by the Peer Review Group in their July 24, 1991 meeting can be found in Appendix B. During the final two-day meeting on October 12, 1991, the Peer Review Group held extensive discussions regarding the evaluation criteria which resulted in a revised list. The list of evaluation criteria, as revised by the Peer Review Group, is:

**Impact Criteria:**

- Net Energy Impact;
- Human Health and the Environment;
- Social and Institutional Acceptability;
- Cost of Energy Produced or Conserved;
- Commercialization Risk;
- Occupational Health and Safety; and
- Flexibility.

**Cost Criteria:**

- Research and Development Program Cost; and
- Demonstration Program Cost

These criteria are discussed in Sections 15.3 and 15.5 of this chapter.

### 15.2.4 Technology Area Scores

An approach known as "Consensus Group Process" was used to assess (i.e., score) the relative cost and impact of RD&D on each technology area with respect to the evaluation criteria. In general, for each evaluation criterion, the scores assigned to the technology areas by the Peer Review Group should be in the same rank order as, and proportional to, the expected cost or impact of RD&D on each technology area. The Peer Review Group was encouraged to focus on the relative cost and impact of further RD&D when scoring the technology areas and to avoid basing scores on the current state of the technology (though emphasis was placed on the 5-10 year time frame) or "gaming" the exercise. Most participants appeared to assess honestly the empirical questions posed and the use of average scores tends to reduce the effects of possible bias on the final ratings.

Each evaluation criterion was considered independently and in sequence by the Peer Review Group during the two-day meeting. For each evaluation criterion the individual members of the Peer Review Group assigned numerical scores to all of the technology areas ranging from 0 to 100. Because the scores represent a relative scale it cannot be assumed that a technology area assigned a score of 100 will realize a larger impact from further RD&D than would technology areas not considered in this report, or that a technology area assigned a score of 0 will not realize a larger impact from further RD&D than would technology areas not considered in this report. A disadvantage of this approach is that there is no measure against which to judge absolute values. Some additional assumptions and constraints associated with these scores are as follows:

- Members of the Peer Review Group must assign at least one technology area a score of 0 and at least one technology area a score of 100; the remaining technology areas were assigned intermediate scores;

- Scores should not be used to infer anything about the relative cost and impact of further RD&D on technology areas not considered in this study;

- The Peer Review Group members have some knowledge and understanding of each technology area;

- Average scores represent the general view of the Peer Review Group;

- Impact scores represent potential gains from further RD&D, independent of cost; and

- Cost scores are independent of the desirability of performing further RD&D.

Prior to assessing the technology areas with respect to each evaluation criterion the Peer Review Group held an open discussion until a consensus was reached on the definition of the criterion and the basis for high and low scores. Members of the Peer Review Group individually scored each technology area with respect to the evaluation criterion. The individual scores were then shown to the entire Peer Review Group and members whose

scores were substantially different were asked to explain the reasons underlying their score. Following this discussion members of the Peer Review Group were given the opportunity to change their scores, after which the average score for each technology area was calculated and normalized. The normalization consisted of rescaling all the average scores so that the highest average score would be equal to 100. A discussion of the technology areas with respect to their scores for each evaluation criterion is presented in Section 15.5.

### 15.2.5 Evaluation Criterion Weights

The members of the Peer Review Group assigned weights to each evaluation criterion in order to determine the relative contribution of each technology area's cost and impact score to the aggregate cost and impact scores (see Equations 1 and 2), respectively.
This process was similar to the scoring of the technology areas within a criterion, but participants were limited to 100 percentage points to be distributed among the impact criteria and 100 percentage points between the two cost criteria. The individual weights were reviewed and discussed by the Peer Review Group after which the members were given the opportunity to change their weights. More detailed discussion of the assessed weights is found in Section 15.6.

### 15.2.6 Aggregate Cost and Impact Scores

The aggregate cost and impact scores, as calculated by Equations 1 and 2, represent (1) the expected impact of further RD&D on each technology area with respect to criteria relevant to DOE's development of an RD&D implementation plan (aggregate impact); and (2) the expected cost of the RD&D needed to take each technology area from its current state to commercial viability or increased market penetration within 5 to 10 years (aggregate). The aggregate scores are based on the assumptions that there are no overlaps or interdependencies among the evaluation criteria. The aggregate cost and impact scores for the technology areas are presented and discussed in Section 15.6.

## 15.3 Definition of the Evaluation Criteria

The evaluation criteria fall into two groups, those that measure the relative impact of additional RD&D and those that assess the relative costs of the RD&D programs. The Peer Review Group did not explicitly define these RD&D programs, nor should they be assumed to be the RD&D programs recommended by the panels of technical experts in Chapters 3-14. The definitions of the cost and impact evaluation criteria developed by the Peer Review Group are as follows:

**Impact Criteria:**

- **Net Energy Impact.** The increase in a technology area's net energy production or conservation that could be realized through further RD&D, relative to the other technology areas. High scores are assigned to technology areas that could realize the largest increase in net energy production or conservation through further RD&D.

- **Human Health and the Environment.** The potential for reducing a technology area's adverse impacts on human health and the

environment through further RD&D, relative to the other technology areas. High scores are assigned to technology areas that could experience the largest reductions in adverse impacts on human health and the environment through further RD&D.

- **Social and Institutional Acceptability.** The potential for increasing a technology area's public and political acceptability through further RD&D relative to the other technology areas. This evaluation criteria can also be thought of as the potential for further RD&D to reduce or eliminate social and institutional barriers to the use of a technology. High scores are assigned to those technology areas for which social and institutional acceptability could be increased the most through further RD&D.

- **Unit Cost of Energy Produced or Conserved.** The potential for reducing the unit cost of energy produced or conserved within a technology area through further RD&D, relative to the other technology areas. High scores are assigned to technology areas that could realize the largest reductions in the unit cost of energy through further RD&D.

- **Commercialization Risk.** The potential for further RD&D to reduce the commercialization financial risks associated with a technology area relative to the other technology areas. High scores are assigned to technology areas where additional RD&D could yield the greatest reductions in the financial risks of commercialization.

- **Occupational Health and Safety.** The potential for RD&D to improve occupational health and safety within a technology area relative to the other technology areas. Since health and safety problems need to be identified and assessed before they can be dealt with effectively, RD&D to identify and assess problems is included in this definition, along with RD&D on ways to actually improve health and safety. High scores are assigned to technology areas where (1) further RD&D can greatly increase what is known about their occupational health and safety problems, and/or (2) where further RD&D has a significant potential for problems ameliorating health and safety problems associated with the processes or materials involved.

- **Flexibility.** The potential for further RD&D to increase the amount and/or types of waste handled by a technology (e.g., tons per year) relative to the other technology areas. The reason for the increase does not matter. For example, the amount of waste handled by a technology could be increased by developing larger or smaller systems that can penetrate new markets, by making it easier to integrate with other waste management technologies, or by increasing the variety of waste types that can be managed by the technology. High scores were assigned to technology areas that were considered to have the greatest potential for increase in the amount and types of waste that could be handled as a result of further RD&D.

**Cost Criteria:**

- **Research and Development Program Cost.** The total cost of the research and development program that would be needed to advance the technology area to the point where a full-scale demonstration could be conducted, relative to the other technology areas. This evaluation criteria is independent of any judgement regarding the commercial viability of any MSW technology. High scores are assigned to technology areas with the lowest cost.

- **Demonstration Program Cost.** The total cost of a full-scale demonstration of the technology -- or improvements to the technology -- produced by the research and development program, relative to the other technology areas. This evaluation criteria is independent of any judgement regarding the need to demonstrate a technology. High scores are assigned to technology areas with the lowest cost.

## 15.4 Technology Areas Considered for Further RD&D

The Peer Review Group evaluated 14 technology areas, two more than were included in the literature review or considered by the panels of technical experts. The two additional technology areas are "systems studies" and "source reduction."

### 15.4.1 Source Reduction

Source reduction was included as an area worthy of further RD&D because the Peer Review Group members believed that many potential users of other MSW management technologies are seriously considering source reduction as a partial solution to their MSW problems. Some members of the Peer Review Group pointed out that many municipalities are rejecting or delaying the installation of new waste-to-energy facilities until the role of source reduction is better determined. The Peer Review Group characterized source reduction as an important issue that is not well understood but cannot be ignored. Specifically, implementation of a source reduction RD&D program may have a significant effect on the waste stream managed by other MSW technologies and may be an important part of an integrated MSW management system.

While source reduction does not produce energy it can conserve energy. The Peer Review Group, therefore, evaluated this area with respect to the impact of further RD&D on the conservation of energy. Source reduction of MSW is of greatest relevance for homeowners, but also extends to manufacturers and the service industry. Some of the Peer Review Group panel members surmised that source reduction would not be widely implemented in the short term while others consider that implementation of this technology could take place very rapidly. Most panel members agreed that source reduction will necessarily be a part of any MSW management system.

Source reduction includes both the reduction of toxics found in MSW as well as the reduction of MSW volume and weight. Toxic materials found in MSW can be categorized as (1) those causing human and environmental health problems, and (2) those disrupting or affecting the performance of a particular MSW technology process.

The largest problem in evaluating the potential effects of source reduction is the lack of information on its effectiveness. Members of the Peer Review Group believed that source reduction technologies and their efficacy are misunderstood by the public. For example, one member stated that a commonly held belief among the general public is that source reduction is more effective at reducing MSW volume and toxicity than other practices, and that this belief may be impeding the development and implementation of other MSW management technologies. Studies of source reduction may show that substantial costs are inherent with this technology area and many tradeoffs will need to be considered when source reduction is included in the design of a MSW management system. Such studies might also show that source reduction can make a contribution to solving the MSW problem but will not obviate the need to implement other MSW management technologies. Further studies of source reduction are required to evaluate this preferred option in EPA's MSW management hierarchy.

### 15.4.2 Systems Studies

The Peer Review Group included "systems studies" as an area worthy of further RD&D for two reasons: (1) many studies defined by the technical area panels are duplicated across technology areas because they are common to many MSW management technologies (e.g., characterization of the MSW waste stream and a comparative study of the health risks associated with MSW technology areas); and (2) both the Peer Review Group and the technical area panels considered these studies to be of paramount importance. Systems studies were to include general research needs that are not specific to any MSW management technology area. Needs common to all MSW management technology areas may include:

- Comparing the full fuel-cycle cost and net energy of each technology area;
- Comparing the impact of each technology area on human health and the environment;
- Linking data gathered by DOE with data gathered by other governmental agencies, industry, and research organizations (e.g., universities);
- An improved characterization of the MSW stream;
- Better analytical techniques for metals and toxic organics;
- Identification of standard analytical techniques;
- Establishment of a clearinghouse of information relating to MSW and MSW technologies; and
- Public and industry education.

Systems studies were also to include comparative studies across MSW technology areas looking at such factors as cost, energy production and conservation, human health and the environment, transportation, and societal impacts. The completion of such studies will play an important role in the design of optimal MSW waste management systems and will require:

- Identification of gaps in available data;
- Research to fill the data gaps;
- Development of appropriate analytic methodologies; and
- Application of such methodologies to produce objective results.

## 15.5 Discussion of the Impact and Cost Criteria Scores

This section presents and discusses, for each evaluation criteria, the average scores assigned to each technology area by the Peer Review Group. (The evaluation criteria are defined in Section 15.3 along with the basis for high and low scores.) The rationale used by the Peer Review Group in assigning scores is presented when available. The scores received by each technology area are summarized in the exhibits located at the end of each subsection. The technology areas are listed in the left-hand column, the average scores (normalized to 100) are in the center column, and the weighted average scores (i.e., average score × weight) are in the right-hand column. The weight assigned to the evaluation criteria by the Peer Review Group is reported at the bottom of each exhibit.

### 15.5.1 Net Energy Impact

The Peer Review Group was asked to assign high scores to technology areas that could realize the largest increase in aggregate net energy production and conservation through further RD&D. The normalized average scores and weighted average scores are presented in Exhibit 15-2. The systems studies area received the highest relative net energy impact score because members of the Peer Review Group believed the largest factor limiting increased energy production from MSW is public resistance to the implementation of currently available waste-to-energy technologies. For example, some members of the Peer Review Group believed that systems studies comparing the technology areas may be useful in overcoming the negative public image of mass-burn combustion by showing that it compares well against other technology areas that would produce or conserve less energy but have a better public image.

Landfill gas recovery also received a high relative net energy impact score. This is due to the abundance of energy that can be recovered from many existing landfills that are not currently being used for gas collection. Peer Review Group members stated that while implementation of this technology would require little RD&D, it could result in a large net energy impact.

Many Peer Review Group members scored the mass-burn technology area as having great potential for generating the highest energy impact per unit of waste. This technology area is already well developed and RD&D to improve the technology is currently being conducted by large companies within the industry. The largest net energy impact to be realized by the mass-burn technology area lies in the increased implementation of the technology, rather than in improved performance. This could result from systems studies helping to lower some of the social and institutional barriers to building mass-burn combustion systems.

**Exhibit 15-2. Average and Weighted Average Impact Scores for Net Energy Impact**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 100 | 30 |
| Landfill Gas | 79 | 24 |
| Ash Utilization & Disposal | 40 | 12 |
| Mass-Burn Combustion | 69 | 21 |
| Material Recovery Facilities | 40 | 12 |
| RDF Production & Dedicated Combustion | 42 | 13 |
| Source Reduction | 53 | 16 |
| Source Separation & Collection | 38 | 11 |
| Modular Mass-Burn Combustion | 38 | 11 |
| Composting | 15 | 5 |
| RDF Production & Co-Fired Combustion | 41 | 12 |
| Anaerobic Digestion | 32 | 10 |
| Gasification | 19 | 6 |
| Pyrolysis | 7 | 2 |

Weight = 0.30

The Peer Review Group evaluated the technology areas of source reduction, source separation, materials recovery facilities, and composting on this criterion according to the additional net energy that could be conserved through the results of further RD&D. Source reduction received a moderate score because group members indicated that it could provide a large net energy impact without requiring very much research. Some Peer Review Group members scored MRFs high based on the technology's potential to conserve energy. Other members scored MRFs low because they did not believe that further RD&D would have much impact on its net energy impact, and that MRFs will require answers to very basic questions before they become acceptable as an MSW technology. Composting received a low average impact score because it does not produce energy and was perceived as having a limited ability to conserve energy. One member of the Peer Review Group, however, believes that composting MSW could conserve a large amount of energy by (1) providing a water-conserving mulch that would reduce the demand for energy intensive desalinated water and (2) reducing tillage and fertilizer requirements. Many members of the Peer Review Group believe that the net energy impact associated with composting is mainly due to an increase in the quality of MSW from the removal of the compostable fraction of the MSW stream.

Ash utilization and disposal RD&D programs offer some potential for energy conservation but cannot be expected to directly result in the production of additional energy as they are mainly directed toward finding solutions for ash disposal problems. The solution of these problems, however, will make combustion of MSW more acceptable to the public. Therefore, some Peer Review Group members scored this technology area high, based on the additional energy that could be produced through increased implementation of MSW

combustion technologies, while others gave this technology area a score of 0 because advances in this technology have no potential for directly increasing energy production.

### 15.5.2 Human Health and the Environment

The Peer Review Group was asked to assign high scores to technology areas that could experience the largest relative reductions in adverse impacts on human health and the environment through further RD&D. The normalized average scores and weighted average scores are presented in Exhibit 15-3. The Peer Review Group assigned systems studies the highest impact score because most participants believed that RD&D comparing the technology areas on the basis of their impact on human health and the environment will aid the design of integrated MSW programs that minimize such impacts.

The Peer Review Group assigned landfill gas the next highest score. There are large numbers of landfills generating landfill gas that is currently being released to the atmosphere. It was estimated by one participant that 8 to 10 percent of atmospheric methane loading is from this source. The Peer Review Group concluded that further RD&D would help implement landfill gas capture and recovery systems, and could also result in a large reduction in the effects of landfill gas on human health and the environment.

Some members of the Peer Review Group scored source reduction and source separation low because they have relatively low impacts on human health and the

**Exhibit 15-3. Average and Weighted Average Impact Scores for Human Health and the Environment**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 100 | 19 |
| Landfill Gas | 92 | 17 |
| Ash Utilization & Disposal | 62 | 12 |
| Mass-Burn Combustion | 45 | 9 |
| Material Recovery Facilities | 60 | 11 |
| RDF Production & Dedicated Combustion | 29 | 6 |
| Source Reduction | 55 | 10 |
| Source Separation & Collection | 57 | 11 |
| Modular Mass-Burn Combustion | 37 | 7 |
| Composting | 62 | 12 |
| RDF Production & Co-Fired Combustion | 26 | 5 |
| Anaerobic Digestion | 35 | 7 |
| Gasification | 19 | 4 |
| Pyrolysis | 11 | 2 |

Weight = 0.19

environment (and therefore low potential for improvement due to further RD&D) while others gave high scores to these technology areas because they believed that it is important to inform the public that these technology areas may also have adverse effects and therefore high potential impact due to further RD&D. Similarly, many participants scored mass-burn combustion low because the effects of this technology are well characterized and controlled (and therefore have little potential for improvement due to further RD&D) while others rated this technology area high because they believed that it is important to conduct further RD&D to demonstrate to the public that impacts of this technology on human health and the environment are low.

### 15.5.3 Social and Institutional Acceptability

The Peer Review Group was asked to assign high scores to those technology areas for which social and institutional acceptability could be increased the most through further RD&D. The normalized average scores and weighted average scores are presented in Exhibit 15-4. Mass-burn combustion received the highest score because many participants believed that the greatest impact can be achieved by increasing the social and institutional acceptability of mass-burn combustion through RD&D programs that can develop public information about the technology for dissemination to the public. Participants averred that this will bring the public's perception of mass-burn more in line with reality. Ash utilization and disposal scored

**Exhibit 15-4. Average and Weighted Average Impact Scores for Social and Institutional Acceptability**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 74 | 13 |
| Landfill Gas | 54 | 10 |
| Ash Utilization & Disposal | 88 | 16 |
| Mass-Burn Combustion | 100 | 18 |
| Material Recovery Facilities | 17 | 3 |
| RDF Production & Dedicated Combustion | 72 | 13 |
| Source Reduction | 25 | 5 |
| Source Separation & Collection | 19 | 3 |
| Modular Mass-Burn Combustion | 59 | 11 |
| Composting | 38 | 7 |
| RDF Production & Co-Fired Combustion | 51 | 9 |
| Anaerobic Digestion | 18 | 3 |
| Gasification | 11 | 2 |
| Pyrolysis | 5 | 1 |

Weight = 0.18

high because the Peer Review Group believed that the social and institutional acceptability of ash disposal and utilization can also be improved through RD&D programs that develop information about ash utilization and disposal for dissemination to the public.

The importance of informing the public about MSW management technologies to gain improved social and institutional acceptability was also confirmed by the high score assigned to systems studies. Many participants scored source reduction low due to the current high acceptance (and therefore low potential for improvement) of this MSW management option. Others rated source reduction higher because they believed that further RD&D would show the limits of this technology which has been portrayed as a panacea to the MSW problem. The Peer Review Group scored pyrolysis and gasification low because they see a limited potential for improving the public's perception of these technologies through further RD&D.

### 15.5.4 Unit Cost of Energy Produced

The Peer Review Group was asked to assign high scores to technology areas that could realize the largest reductions in the unit cost of energy through further RD&D. The normalized average scores and weighted average scores are presented in Exhibit 15-5. While ash utilization and disposal itself does not produce energy, the Peer Review Group assigned it the highest impact score because of the large impact that a cost reduction would have on the cost of energy produced by MSW combustion technologies. For example, some members of the Peer Review Group estimate that 25 percent of the cost of energy from mass-burn combustion systems goes to tipping fees for ash disposal.

Systems studies received the next highest score for reasons that include:

1. The need for information on the unit cost of energy produced or conserved by the various MSW management technologies; and

2. The need for information to help design integrated MSW management systems that will reduce the unit cost of energy production and conservation.

The Peer Review Group assigned landfill gas a high score because of the potential for further RD&D to reduce the unit cost of energy from landfill gas by increasing (1) the recovery of the large volume of landfill gases that are currently being wasted; (2) the amount of gas being produced in landfills; and (3) the quality (i.e., value) of the collected gas.

### 15.5.5 Commercialization Risk

The Peer Review Group was asked to assign high scores to technology areas where additional RD&D could yield the greatest reductions in the risks of commercialization. The normalized average scores and weighted average scores are presented in Exhibit 15-6. Five technology areas, MRFs, source separation and collection, systems studies, ash utilization and disposal, and composting received high average scores for this evaluation criteria; source reduction received a moderate score, and the remaining technology areas all received moderately low scores.

**Exhibit 15-5. Average and Weighted Average Impact Scores for Unit Cost of Energy Produced or Conserved**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 98 | 14 |
| Landfill Gas | 91 | 13 |
| Ash Utilization & Disposal | 100 | 14 |
| Mass-Burn Combustion | 66 | 9 |
| Material Recovery Facilities | 33 | 5 |
| RDF Production & Dedicated Combustion | 50 | 7 |
| Source Reduction | 36 | 5 |
| Source Separation & Collection | 33 | 5 |
| Modular Mass-Burn Combustion | 40 | 6 |
| Composting | 30 | 4 |
| RDF Production & Co-Fired Combustion | 37 | 5 |
| Anaerobic Digestion | 40 | 6 |
| Gasification | 21 | 3 |
| Pyrolysis | 9 | 1 |

Weight = 0.14

**Exhibit 15-6. Average and Weighted Average Impact Scores for Commercialization Risk Factors**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 73 | 6 |
| Landfill Gas | 45 | 4 |
| Ash Utilization & Disposal | 73 | 6 |
| Mass-Burn Combustion | 42 | 3 |
| Material Recovery Facilities | 100 | 8 |
| RDF Production & Dedicated Combustion | 39 | 3 |
| Source Reduction | 56 | 4 |
| Source Separation & Collection | 83 | 7 |
| Modular Mass-Burn Combustion | 31 | 2 |
| Composting | 71 | 6 |
| RDF Production & Co-Fired Combustion | 24 | 2 |
| Anaerobic Digestion | 45 | 4 |
| Gasification | 43 | 3 |
| Pyrolysis | 41 | 3 |

Weight = 0.08

The primary reason given for assigning MRFs the highest score is that material recovery facilities tend to operate with a small profit margin. RD&D could be performed to generate and compile information on the composition and volume of waste generated in a given area and on the available markets for recovered materials. Such information can be used to site and tailor MRFs to the available wastes and markets, and could make the difference between success and failure. The high average score received by systems studies has a similar basis, except that it could involve the generation and compilation of information useful to decision makers on all of the technology areas.

### 15.5.6 Occupational Health and Safety

The Peer Review Group was asked to assign high scores to technology areas where (1) further RD&D can greatly increase what is known about their occupational health and safety problems, and/or (2) where further RD&D has a significant potential for ameliorating health and safety problems associated with the processes or materials involved. The normalized average scores and weighted average scores are presented in Exhibit 15-7. Three technology areas, MRFs, composting, and systems studies received high scores for this evaluation criterion, while the other eleven technology areas received substantially lower scores. A number of reasons were given by members of the Peer Review Group for the high scores received by MRFs and composting:

- Relatively little is known about the potential occupational hazards of MRFs and composting, primarily because they are emerging technologies and there has been little formal study of these activities. As a result, it is likely that further RD&D could generate a significant amount of new knowledge about these potential hazards.

- The occupational hazards associated with MRFs and composting are perceived to be high in comparison with the other technology areas under consideration because they are more likely to involve direct contact with the waste (e.g., hand sorting), exposure to airborne contaminants (e.g., dust, gases, or pathogens), working near potentially dangerous mechanical processes or heavy equipment (e.g., shredders and tractors). Given these potentially high but poorly studied hazards, it is likely that further RD&D could do much to reduce the risks.

Some participants also expressed the view that occupational hazards of MRFs and composting may not be adequately regulated, perhaps because they have been given little attention by regulatory agencies such as the Occupational Safety and Health Administration (OSHA), or because of streamlined permitting procedures designed to encourage the use of MSW recycling technologies like MRFs.

The high score received by systems studies reflected the belief of many participants that (1) some of the technology areas have occupational health and safety problems not yet identified or assessed, and (2) that much of the information needed to identify and assess the hazards exists but needs to be compiled and studied. The fact that systems studies are applicable to all of the other technology areas may have contributed to its high score.

**Exhibit 15-7. Average and Weighted Average Impact Scores for Occupational Health and Safety**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 82 | 5 |
| Landfill Gas | 45 | 3 |
| Ash Utilization & Disposal | 49 | 3 |
| Mass-Burn Combustion | 25 | 2 |
| Material Recovery Facilities | 100 | 6 |
| RDF Production & Dedicated Combustion | 53 | 3 |
| Source Reduction | 46 | 3 |
| Source Separation & Collection | 63 | 4 |
| Modular Mass-Burn Combustion | 31 | 2 |
| Composting | 83 | 5 |
| RDF Production & Co-Fired Combustion | 40 | 2 |
| Anaerobic Digestion | 57 | 3 |
| Gasification | 6 | 0 |
| Pyrolysis | 8 | 0 |

Weight = 0.06

The other eleven technology areas received low to moderate average scores from the Peer Review Group. Reasons for assigning a low score to a technology area included (1) a low expectation that the technology would be implemented during the next 5 to 10 years (e.g., pyrolysis and gasification), and (2) information on occupational hazards already being readily available. For the most part, however, the specific reasons for the low to moderate scores were not articulated.

### 15.5.7 Flexibility

The Peer Review Group was asked to assign high scores to technology areas that were considered to have the greatest potential for increase in the amount and/or types of waste that could be handled as a result of further RD&D. The normalized average scores and weighted average scores are presented in Exhibit 15-8. The scores for this evaluation criterion are difficult to interpret because some participants based their scores on the amount and/or variety of waste that the technologies can currently handle, rather than the increase that could be realized through further RD&D. Despite the confusion over the definition and method of scoring flexibility, the results of the analysis were affected very little by this evaluation criterion because it was given a very low weight by the Peer Review Group.

All of the technology areas except for pyrolysis and gasification received moderate average scores. Pyrolysis and gasification received low average scores because the consensus was that further RD&D would not have much impact on the amount of waste they

could handle -- relative to the other technology areas -- and that pyrolysis and gasification currently have very little flexibility with respect to the wastes that can be handled.[2]

Systems studies received the highest average score of all the technology areas because many members of the Peer Review Group believed that taking a "systems approach" to the management of MSW (e.g., develop an optimal integrated waste management system) would result in the greatest increase in overall flexibility.

Based on the comments of some participants, it appears some members of the Peer Review Group incorrectly assigned high scores to technology areas because they are currently able to handle a wide variety and/or volume of wastes, rather than because of the increase that could result from further RD&D.

The low average scores received by mass-burn and modular mass-burn combustion reflect the belief that these technologies already handle a large volume and/or variety of wastes, and that further RD&D is unlikely to have much impact.

### 15.5.8 Research and Development Program Cost

This evaluation criterion considers the total cost of the research and development(R&D) program needed to advance a technology area to the point where a full-

**Exhibit 15-8. Average and Weighted Average Impact Scores for Flexibility**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 100 | 5 |
| Landfill Gas | 95 | 5 |
| Ash Utilization & Disposal | 75 | 4 |
| Mass-Burn Combustion | 65 | 3 |
| Material Recovery Facilities | 71 | 4 |
| RDF Production & Dedicated Combustion | 60 | 3 |
| Source Reduction | 77 | 4 |
| Source Separation & Collection | 88 | 4 |
| Modular Mass-Burn Combustion | 50 | 3 |
| Composting | 81 | 4 |
| RDF Production & Co-Fired Combustion | 61 | 3 |
| Anaerobic Digestion | 66 | 3 |
| Gasification | 28 | 1 |
| Pyrolysis | 25 | 1 |

Weight = 0.05

[2] One reviewer believes that further RD&D would certainly increase flexibility.

scale demonstration could be conducted, independent of any judgements regarding the desirability or ultimate commercial viability of the technology area. The Peer Review Group was asked to assign high scores to technology areas with the lowest total expected cost. For example, a technology area that is currently ready for a full-scale demonstration should receive a score of 100. The normalized average scores and weighted average scores are presented in Exhibit 15-9.

**Exhibit 15-9. Average and Weighted Average Cost Scores for Research and Development Program Cost**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 75 | 49 |
| Landfill Gas | 78 | 51 |
| Ash Utilization & Disposal | 62 | 40 |
| Mass-Burn Combustion | 100 | 65 |
| Material Recovery Facilities | 54 | 35 |
| RDF Production & Dedicated Combustion | 54 | 35 |
| Source Reduction | 51 | 33 |
| Source Separation & Collection | 57 | 37 |
| Modular Mass-Burn Combustion | 63 | 41 |
| Composting | 51 | 33 |
| RDF Production & Co-Fired Combustion | 59 | 38 |
| Anaerobic Digestion | 36 | 23 |
| Gasification | 8 | 5 |
| Pyrolysis | 0 | 0 |

Weight = 0.65

Some members of the Peer Review Group expressed the concern that an accurate assessment of the relative R&D costs cannot be made without considering the individual R&D programs needed to bring each technology area to the demonstration phase. (The Peer Review Group did not consider individual R&D programs.) Another concern expressed by some participants was that cost scores might be linked to biases held by members of the Peer Review Group towards certain technology areas, since these scores could affect how DOE distributes future research funds.

Mass-burn combustion was assigned the highest score by the Peer Review Group due to the consensus that this technology is already developed beyond the demonstration phase and, therefore, does not require additional R&D to meet this criterion. Landfill gas, systems studies, and ash management also received high scores because they require relatively little additional knowledge or relatively little additional R&D money before these technology areas can be demonstrated. Pyrolysis and gasification were scored very low because most

participants regard these technologies as not currently being technically or commercially viable; bringing these technologies to the demonstration phase would be very difficult, costly, and time-consuming.

### 15.5.9 Demonstration Program Cost

This evaluation criterion considers the total cost of a full-scale demonstration of a technology or improvements to technology, independent of any judgement regarding the need for a demonstration. The Peer Review Group was asked to assign high scores to technology areas with the lowest total expected cost. Some participants were hesitant about scoring this evaluation criterion because they were unfamiliar with what might be required to demonstrate some of the technologies. The normalized average scores and weighted average scores are presented in Exhibit 15-10.

Mass-burn combustion received the highest average score because of the commonly held belief that the existence of numerous full-scale mass-burn facilities would make most demonstrations relatively inexpensive. Demonstrations of mass-burn technology will mostly be limited to minor variations of the current technology and could be done through retrofits of existing equipment. Landfill gas also received a high score because full-scale commercial facilities exist and the R&D demonstration costs are expected to be relatively small.

**Exhibit 15-10. Average and Weighted Average Cost Scores for Demonstration Program Cost**

| Technology Area | Average Scores (Normalized to 100) | Weighted Score (Average × Weight) |
|---|---|---|
| Systems Studies | 80 | 28 |
| Landfill Gas | 83 | 29 |
| Ash Utilization & Disposal | 70 | 25 |
| Mass-Burn Combustion | 100 | 35 |
| Material Recovery Facilities | 61 | 21 |
| RDF Production & Dedicated Combustion | 60 | 21 |
| Source Reduction | 67 | 23 |
| Source Separation & Collection | 67 | 23 |
| Modular Mass-Burn Combustion | 62 | 22 |
| Composting | 63 | 22 |
| RDF Production & Co-Fired Combustion | 57 | 20 |
| Anaerobic Digestion | 35 | 12 |
| Gasification | 12 | 4 |
| Pyrolysis | 1 | 0 |

Weight = 0.35

The systems studies score was based on the estimated costs of performing the data collection and analysis included in this technology area. The Peer Review Group assigned a high score to systems studies because of the belief that the cost of studies and data collection will be low compared to the other technology areas that will have extensive capital costs.

Pyrolysis and gasification received very low average scores because full-scale facilities do not currently exist and it is expected that numerous complications would be encountered during the construction of full-scale demonstration facilities.

## 15.6 Discussion of the Evaluation Criteria Weights

Four of the seven impact evaluation criteria (net energy impact, human health and the environment, social and institutional acceptability, and the cost of energy produced or conserved) were assigned more than 80 percent of total weight and thus dominated the rankings of the technology areas with respect to the impact of further RD&D. The small weight assigned to the flexibility criterion is at least partially due to differences in opinion among the participants on how flexibility should be defined and scored.

For the two cost evaluation criteria, the Peer Review Group assigned 65 percent of the weight to research and development program cost and assigned 35 percent of the weight to demonstration program cost. However, due to the similarity of the scores assigned to the two cost criteria the weights did not have much influence on the aggregate scores (i.e., the aggregate cost scores were similar to both the R&D and the demonstration scores).

## 15.7 Discussion of the Aggregate Cost and Impact Scores

This section presents and discusses the aggregate cost and impact scores for each technology area. Each aggregate impact score represents the overall expected impact of further RD&D on the technology area relative to the other 13 technology areas. Each aggregate cost score represents the expected total cost of the RD&D needed to take the technology area from its current state to commercial viability or wider use, relative to the other 13 technology areas in the next 5 to 10 years. The aggregate cost and impact scores for each technology area (calculated using Equations 1 and 2, the evaluation criteria weights, and the normalized average scores shown in Exhibits 15-2 through 15-10) are presented in Exhibits 15-11 and 15-12, followed by a brief discussion of key factors.

The aggregate cost and impact scores are displayed by Exhibit 15-11 in tabular form. The evaluation criteria are ordered by weight (largest to smallest) and the technology areas are ordered by aggregate relative impact score (largest to smallest). In order to illustrate how the 14 technology areas compare with respect to both the expected relative cost and impact of further RD&D, the aggregate relative impact scores are plotted against the aggregate relative cost scores in Exhibit 15-12. Further RD&D is expected to cost the least and have the greatest overall relative impact (i.e., relative to the other technology areas considered in this study) in the next 5 to 10 years on technology areas that appear in the upper left-hand corner of the plot. Similarly, further RD&D is expected to cost the most and have the least overall impact on technology areas that appear in the lower right-hand corner of the plot.

Based on the aggregate cost and impact scores the technology areas appear to fall into three general groups (see Exhibit 15-12):

- **RATED HIGH:** Low relative cost (high cost score) and high relative impact (high impact score). Mass-burn combustion, systems studies, landfill gas, and ash utilization and disposal all received high aggregate cost and impact scores relative to the other technology areas.

- **RATED MODERATE:** Moderate relative cost (moderate cost score) and moderate relative impact (moderate impact score). MRFs, dedicated RDF production and combustion, source reduction, source separation and collection, modular mass-burn combustion, composting, co-fired RDF combustion, and anaerobic digestion all received moderate aggregate cost and impact scores.

- **RATED LOW:** High relative cost (low cost score) and low relative impact (low impact score). Gasification and pyrolysis both received low aggregate cost and impact scores.

Of all the technology areas, the RD&D program for mass-burn combustion is expected to be the least expensive. Many participants believed that mass-burn combustion would be relatively inexpensive because most of the RD&D would focus on increasing the social and institutional acceptability of mass-burn combustion, rather than the development, construction, and operation of expensive physical facilities which already exist. There appeared to be some overlap between the RD&D envisioned by the Peer Review Group for mass-burn combustion and systems studies.

Systems studies received the highest aggregate impact score and the third best aggregate cost score. The high impact score may be partially due to the applicability of systems studies to the other thirteen technology areas. Some participants tended to include public education and performance evaluation studies in this technology area, although comparative studies are the primary focus of systems studies. The fact that systems studies received high scores for all of the evaluation criteria reflects the scarcity of objective studies that evaluate, link, and present information on performance in ways that aid RD&D efforts and decision makers (i.e., public officials and the general public). Members of the Peer Review Group reiterated that the lack of such studies is a major obstacle to the development and use of the technologies considered in this report. The high average score that systems studies received for the cost evaluation criteria indicates that such studies would be inexpensive relative to the other technology areas, primarily because systems studies do not require the construction and operation of expensive physical facilities. Members of the Peer Review Group stated that the performance of systems studies would serve to:

- Identify more clearly what is known and not known (e.g., data gaps to be filled) about the various technologies and their impact;

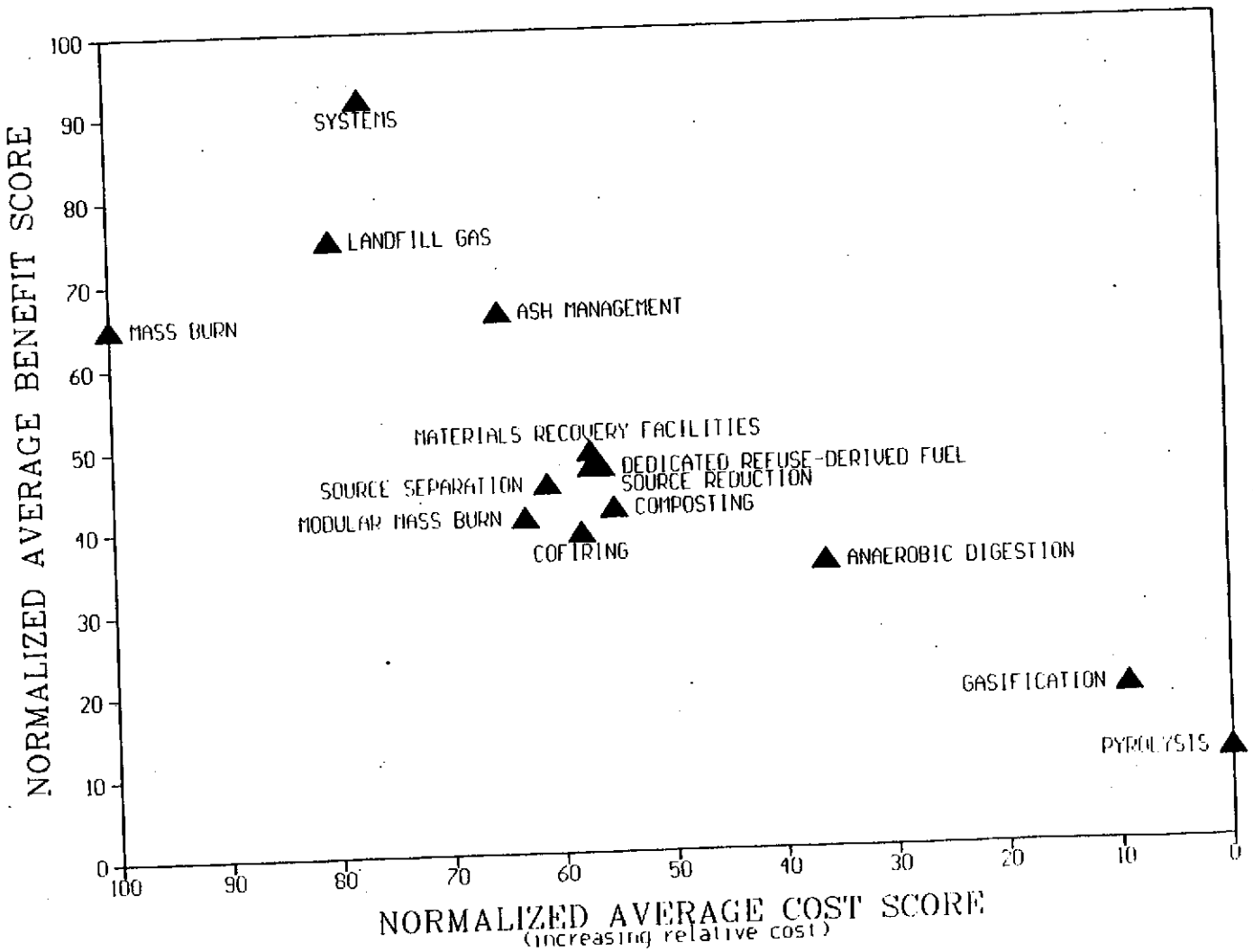
- Facilitate the development of optimized MSW management systems by identifying when, where, and how the technologies can be used in combination; and

- Decrease the reliance of both public officials and the general public on information published by the opponents and proponents of the

## Exhibit 15-11. Average Weighted Aggregate Technology Area Cost and Impact Scores

| Evaluation Criteria | Systems | Landfill Gas | Ash Utilization and Disposal | Mass-Burn Combustion | Material Recovery Facilities | RDF Production and Dedicated Combustion | Source Reduction | Source Separation and Collection | Modular Mass-Burn Combustion | Composting | RDF Production and Co-Fired Combustion | Anaerobic Digestion | Gasification | Pyrolysis | Weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Technology Areas | | | | | | | | | | | | | | |
| Net Energy Impact | 30 | 24 | 12 | 21 | 12 | 13 | 16 | 11 | 5 | 11 | 12 | 10 | 6 | 2 | 30 |
| Human Health & the Environment | 19 | 17 | 12 | 9 | 11 | 6 | 10 | 11 | 12 | 7 | 5 | 7 | 4 | 2 | 19 |
| Social & Institutional Acceptability | 13 | 10 | 16 | 18 | 3 | 13 | 5 | 3 | 7 | 11 | 9 | 3 | 2 | 1 | 18 |
| Cost of Energy Produced or Conserved | 14 | 13 | 14 | 9 | 5 | 7 | 5 | 5 | 4 | 6 | 5 | 6 | 3 | 1 | 14 |
| Commercialization Risk Factors | 6 | 4 | 6 | 3 | 8 | 3 | 4 | 7 | 6 | 2 | 2 | 4 | 3 | 3 | 8 |
| Occupational Health & Safety | 5 | 3 | 3 | 2 | 6 | 3 | 3 | 4 | 5 | 2 | 2 | 3 | 0 | 0 | 6 |
| Flexibility | 5 | 5 | 4 | 3 | 4 | 3 | 4 | 4 | 4 | 3 | 3 | 3 | 1 | 1 | 5 |
| Aggregate Impact Scores | 92 | 75 | 66 | 65 | 49 | 47 | 47 | 45 | 42 | 41 | 39 | 35 | 19 | 11 | |
| Research & Development Program Cost | 49 | 51 | 40 | 65 | 35 | 35 | 33 | 37 | 33 | 41 | 38 | 23 | 5 | 0 | 65 |
| Demonstration Program Cost | 28 | 29 | 25 | 35 | 21 | 21 | 23 | 23 | 22 | 22 | 20 | 12 | 4 | 0 | 35 |
| Aggregate Cost Scores | 77 | 80 | 65 | 100 | 56 | 56 | 57 | 61 | 55 | 63 | 58 | 36 | 9 | 0 | |

**Exhibit 15-12. Plot of the Aggregate Impact Scores vs. the Aggregate Cost Scores**



technologies, by providing information that is objective, comprehensive, and tailored to the needs and background of the audience.

Landfill gas received high aggregate scores for the cost and impact of further RD&D. Contributing to its high impact score are the potential for further RD&D to (1) facilitate tapping into the large number of existing landfills from which gas is not currently collected; (2) reduce the potential adverse effects on human health and the environment of the landfill gas that is now being released to the atmosphere; and (3) reduce the unit cost of landfill gas utilization.

The high aggregate cost and impact scores for further RD&D for ash utilization and disposal technology area are due, primarily, to the scores it received for the (1) social and institutional acceptability and (2) cost of energy produced or conserved. The social and institutional acceptability score was high because improved methods for ash disposal and utilization could do much to ameliorate the negative image of ash held by many people. The cost of energy produced or conserved received a high score because reducing the cost of ash disposal could significantly decrease the unit cost of energy produced by MSW combustion technologies. Social and institutional acceptability and the cost of energy produced are somewhat related for ash, in that increasing the acceptability of ash disposal might make it easier and less expensive to site and build MSW management and disposal facilities.

Gasification and pyrolysis both received low aggregate relative cost and impact scores. The primary reason for the low aggregate impact score is the Peer Review Group's belief that the technical advances required for the successful commercialization of each technology are not likely to occur in the 5 to 10 year time frame imposed by this study. The low aggregate cost score is due to the Peer Review Group's belief that both R&D and full-scale demonstration facilities would be very costly.

# APPENDIX A: WORKSHOP PARTICIPANTS

This appendix lists the names and addresses of the Peer Review Group and the technical experts that participated in the technical workshops. Facilitation team members for each workshop are also listed.

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## APPENDIX B: INITIAL LIST OF EVALUATION CRITERIA

The Peer Review Group developed an initial list of evaluation criteria during its first workshop on July 26, 1991. This initial list underwent substantial revisions during the second workshop on October 1-2, 1991. The initial list of evaluation criteria consisted of the following:

- Net energy benefit
  - Energy produced and conserved
  - Type of energy produced and conserved (renewable or non-renewable)
  - Materials produced (including chemicals)
- Cost of energy produced
- Full cost of the RD&D program
- Human Health
- Environment
  - Site impacts
  - Other impacts including pollution
- Occupational Health and Safety
- Funding and Regulatory Appropriateness
  - For funding by the U.S. Department of Energy
  - Compatibility of the technology with regulations
- Difficulty of technology development
  - Timeliness: short- or long-term
  - Risk of not succeeding
- Commercial Development Risk (given technical feasibility)
  - Public acceptability (image) of the technology
  - Political acceptability (image) of the technology
  - Availability of markets
  - Capital investment requirements beyond RD&D (short- and long-term)
- Flexibility
  - Portion of the waste stream affected
  - Scale of facilities (e.g., small-scale and large-scale)
  - Compatibility with other technologies (existing and future)

# APPENDIX C: OVERVIEW OF RD&D ASSESSMENTS, PROGRAMS, AND PLANS

## C.1 Introduction

As energy prices began to soar in the 1970s, government agencies at all levels, both in the United States and internationally, as well as private organizations and businesses began developing a growing interest in technologies for converting MSW to energy. Several agencies and organizations undertook studies to assess RD&D needs in the area of waste-to-energy technology. The extensive literature search conducted to prepare the working paper identified a number of sources that discuss small and large scale RD&D assessments, programs, and plans from the mid-1970s through the present time. This appendix presents an overview of these RD&D assessments, programs, and plans identified by the literature review.

Four major types of sources in the literature discuss, to varying degrees, RD&D assessments, programs, and plans developed by, or on behalf, of government agencies or private organizations. These sources are (1) comprehensive RD&D assessments, (2) papers presented at waste-to-energy conferences, (3) government or privately published reports, and (4) technical and professional journals. The comprehensive assessments, by definition, discuss RD&D needs for one or more waste-to-energy technologies. The result of these assessments is often an RD&D program or plan. Conference papers, government and private publications, and technical and professional journals generally describe RD&D programs and plans at the Federal, state, regional, or international level.

This appendix discusses MSW RD&D assessments, programs, and plans developed since the mid-1970s for four different types of organization: (1) federal government; (2) state and regional government; (3) international; and (4) private sector. This discussion is not necessarily exhaustive of all major assessments, programs, and plans initiated since the mid-1970s. It is possible that some waste-to-energy RD&D assessments, programs, and plans developed at the Federal, state and regional, or private level were not identified by the literature review. Also, though the literature review indicated that waste-to-energy RD&D projects have been conducted in a number of countries world-wide, the major international waste-to-energy RD&D work has been conducted through the International Energy Agreement. Thus, the discussion of international work in this appendix is limited to the work conducted under the International Energy Agreement. The RD&D programs of individual foreign countries are not considered in this appendix.

## C.2 Federal Activities

On the Federal government level, the U.S. Department of Energy (DOE) has had a major responsibility for directing waste-to-energy RD&D work in the United States. DOE has funded waste-to-energy RD&D assessments and sponsored RD&D since 1975. DOE's work has included both general and technology specific RD&D needs assessments for energy and resource recovery from municipal solid waste. Also on the Federal government level, the U.S. Environmental Protection Agency (EPA) has developed research agendas for integrated municipal solid waste management that consider source reduction, recycling and reuse, thermal destruction, and land disposal. This section discusses DOE and EPA work in the area of energy production and resource recovery from municipal solid waste, and presents

examples of major RD&D plans, programs, and assessments developed by or for these Federal agencies.

**U.S. Department of Energy Municipal Solid Waste RD&D**

DOE has funded waste-to-energy RD&D assessments and sponsored RD&D since 1975. In the seventies, the Urban Waste Technology Branch sponsored the Resource Recovery: Research Development and Demonstration Plan (see below).

In the early eighties, the then Energy from Municipal Waste Division of DOE's Office of Renewable Technology sponsored a series of Technology Status reports which included RD&D discussions in several cases. The series is as follows:

- Thermal Systems for Conversion of Municipal Solid Waste, Volume 1. An Overview, L. Hickman, Jr., ANL/CNSV-TM-120, Vol. 1 (1983).

- Thermal Systems for Conversion of Municipal Solid Waste, Volume 2. Mass Burning of Solid Waste in Large Scale Combustors: A Technology Status Report, W.D. Turner, Texas A&M University, ANL/CNSV-TM-120, Vol. 2 (1983).

- Thermal Systems for Conversion of Municipal Solid Waste, Volume 3. Small Scale Systems: A Technology Status Report, R. Hopper et al., Battelle Columbus Laboratories, ANL/CNSV-TM-120, Vol. 3 (1983).

- Thermal Systems for Conversion of Municipal Solid Waste, Volume 4. Burning Refuse-Derived Fuels in Boilers: A Technology Status Report, F. Hasselris, ANL/CNSV-TM-120, Vol. 4 (1983).

- Thermal Systems for Conversion of Municipal Solid Waste, Volume 5. Pyrolytic Conversion: A Technology Status Report, J. Kuester, Arizona State University, ANL/CNSV-TM-120, Vol. 5 (1983).

- Thermal Systems for Conversion of Municipal Solid Waste, Volume 6. Fluidized-Bed Combustion: A Technology Status Report, G. Trezek, University of California, Berkeley, ANL/CNSV-TM-120, Vol. 6 (1983).

- Landfill Gas Recovery: A Technology Status Report, R.E. Zimmerman and G.R. Lytwynyshyn, ESCOR, Inc., and M.L. Wilkey, Gas Research Institute, ANL/CNSV-TM-121 (1983).

- Biochemical Conversion of Municipal Solid Waste: A Technology Status Report, J. Pfeffer, University of Illinois, Urbana, and R. Isaacson, Gas Research Institute, ANL/CNSV-TM-122 (1983).

- Institutional Issues Concerning Issues from Municipal Waste: A Status Report, G.J. Ridzon and S.L. Blum, Northern Energy Corporation, and C.V. Pearson, Argonne National Laboratory, ANL/CNSV-TM-123 (1983).

- Energy from Municipal Waste: Mechanical Equipment and Systems Status Report, E. Hainsworth, J. Mayberry, and R. Piscitella, EG&G Idaho, Inc., EGG PSE 5974 (1983).

- Municipal Solid Waste Bioconversion Technologies, S. Leeper et al., EG&G Idaho, Inc., EGG-2193 (1982).

In the mid-1980s, the then Biofuels and Municipal Waste Technology Division convened a DOE Program Evaluation Workshop organized by Tinning (1985) of the American Society of Mechanical Engineers. This group produced RD&D recommendations for DOE.

Most recently, the DOE municipal waste related work is managed under the Waste Material Management Division of the Office of Industrial Technologies in Conservation and Renewables. This Division has sponsored the present study as well as a companion study entitled: Comparison of Municipal Solid Waste Management Alternatives. This study, conducted by Stanford Research Institute, will be completed early in 1992.

**U.S. Department of Energy, Resource Recovery: Research Development and Demonstration Plan, October 1979**

In the late 1970s, the Mitre Corporation undertook a comprehensive RD&D assessment for the U.S. Department of Energy. The goal of the assessment was to develop a near-term RD&D Plan for resource recovery. The plan identified actions to be taken within a three-year time frame to accelerate the commercialization of existing technologies and to develop additional waste-to-energy technologies for MSW. The final report discussed six main categories of technologies:

(1) Combustion systems (including mass-burn combustion, modular combustion, and RDF);

(2) Mechanical separation systems;

(3) Co-disposal;

(4) Pyrolysis systems;

(5) Bioconversion systems; and

(6) Source separation technologies.

The report presented technology descriptions, technology status, research status, and research needs for each technology. The report also identified potential individual research programs for each technology consisting of a combination of bench-, pilot-, demonstration-, and full-scale process and equipment evaluations as well as qualitative and quantitative studies. The study made no recommendations as to which technologies have the greatest potential for near- and long-term commercialization. Research needs for each technology were developed through site visits, personal contacts, and literature review.

As a peer review of the assessment, a two-day workshop was held in Wakefield, Massachusetts on June 12 and 13, 1979. At the 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. Input received during the workshop sessions was incorporated into the plan. As a further review, the research needs were presented to a special Urban Waste Panel of the National Research Council on August 13, 1979. This panel made recommendations to DOE for mid- and long-term R&D goals in resource recovery. Input from this panel was also incorporated into the RD&D plan.

**Modular Systems for Energy Recovery from Municipal Solid Waste, Prepared by Science Applications International Corporation (SAIC) for the Biofuels and Municipal Waste Technology Division, Office of Conservation and Renewable Energy, U.S. Department of Energy, June 1986**

SAIC conducted an assessment of the R&D activities and needs of the industry that manufactures modular combustion systems for recovering energy from MSW. The R&D assessment was based on discussions with representatives of 11 system and equipment vendors and other companies and organizations active in the field. Preparation of the assessment involved contacting the major companies in the industry to collect information on their R&D activities and to solicit their opinions on the R&D needed to gain wider commercial acceptance of modular systems and to increase waste-to-energy conversion. SAIC also solicited opinions on the role that the Department of Energy should play in supporting R&D for modular systems.

The interview responses were used to identify the technical problems of genuine concern to industry and to suggest areas where DOE-supported R&D would be useful. R&D topics identified by the industry were oriented toward overcoming impediments to project implementation rather than toward the technical problems of modular combustion systems. The R&D needs focused on two major areas: (1) fundamental combustion processes and (2) environmental effects and pollution control. The assessment did not establish any priority or time frame for implementing the suggested potential R&D projects.

**U.S. Environmental Protection Agency, Office of Solid Waste, The Solid Waste Dilemma: An Agenda for Action, February 1989**

The final report of the Solid Waste Task Force of the U.S. Environmental Protection Agency's (EPA's) Office of Solid Waste recommends using "integrated waste management" systems to solve municipal solid waste generation and management problems at the local, regional, and federal levels. Integrated waste management systems are designed so that some or all of four waste management options (source reduction, recycling, combustion, and landfilling) are used as complements to one another to safely and efficiently manage municipal solid waste.

The integrated waste management system is the framework for the national goals presented in the report. The report presents EPA's stated goal of managing 25 percent of the nation's municipal solid waste through source reduction and recycling by 1992, with yard waste composting to play a key role in attaining this goal. In addition, the report concludes that the U.S. must strive to reverse its ever-increasing per capita generation of garbage and

work to reduce the risks associated with landfills and combustors, inasmuch as these management alternatives will be necessary to handle most of the wastes. The report also calls for the risks of recycling to be examined to determine if risk reduction is also needed for recycling.

The report outlines EPA's program to address the stated goals. It also presents a number of recommendations for state and local governments, industry, and consumers. The report includes recommendations for promoting information exchange and technology transfer among all levels of government and the waste management industry, improving national and regional solid waste management planning, fostering source reduction and recycling (including composting), and reducing the risks associated with landfilling and combustion.

**U.S. Environmental Protection Agency, Office of Research and Development, Municipal Solid Waste Research Agenda, April 1991**

The U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) prepared a research agenda for municipal solid waste management. Input to the agenda was solicited at an ORD-sponsored workshop in Washington, DC in October 1988 and at a Municipal Waste Technology Conference in San Diego, CA, in January 1989.

ORD defined three fundamental goals for its proposed municipal solid waste research program. These goals incorporate the integrated waste management concept and the four technologies that comprise it -- source reduction, recycling and reuse, thermal destruction, and land disposal. The three goals will form the basis for an ORD Municipal Solid Waste Research Program:

**Maximize Reduction and Recycling:** ORD's research will identify opportunities for significantly reducing waste quantities and toxic constituents in the municipal waste stream, and will provide science and technology support to achieve at least a 25 percent recycling rate, EPA's current target.

**Ensure that Municipal Waste Management Practices are Safe:** ORD research will provide the foundation for environmentally safe municipal waste management practices by characterizing releases from waste management operations, evaluating their risks to health and ecological systems, and identifying improved, innovative control measures to mitigate these risks.

**Stimulate Innovative Technology:** ORD will stimulate the development and application of innovative technologies in recycling, combustion, and disposal of municipal solid waste to reduce waste quantities requiring disposal or improved emission and effluent controls.

Within these three goals lie six programmatic areas of research. These six areas of research build upon and broaden the scope of existing and past Agency municipal solid waste research efforts:

(1) Promote the development and implementation of strategic planning and evaluation for integrated waste management;

(2) Stimulate the development and implementation of source reduction approaches that minimize or prevent the generation of municipal solid waste or reduce its toxicity;

(3) Expand the utilization of recycling to reduce the amount of municipal solid waste that requires disposal;

(4) Stimulate the development and implementation of technologies and methodologies that effectively reduce the health and environmental risks associated with the thermal destruction (incineration) of municipal solid waste;

(5) Identify and promote the utilization of technologies and methodologies that effectively reduce the health and environmental risks associated with the land disposal of municipal solid waste; and

(6) Develop and promote the implementation of effective approaches to safely manage municipal combustion residuals, sewage sludge, and medical/infectious wastes.

Within each of the specific research areas, objectives were established and supporting tasks were reviewed by EPA's Offices of Research and Development, Solid Waste, Air Quality Planning and Standards, and Water Regulations and Standards, and presented to representatives of state and municipal governments. Since immediate funding of all tasks is not practical, the tasks were ranked from highest to lowest priority, under each objective, using the following criteria:

- Degree to which the task meets the current and expected needs of EPA program offices, regional offices, and state and local governments;
- Degree to which the task responds to policy, regulatory, and statutory needs;
- Degree to which the task will significantly impact the municipal solid waste management crisis in the near term;
- Degree to which the task will produce results (information, methodology and/or technology) that can be used widely in municipal solid waste management; and
- Degree to which the task will be cost effective in achieving the municipal solid waste research goals.

The report presents descriptions of each of the six research areas, the objectives for each area, and the proposed prioritized tasks.

## C.3 State and Regional Activities

Waste-to-energy RD&D on the regional and state levels is conducted through the U.S. Department of Energy's State Energy Management Program and through state energy programs. The literature review identified two states, California and New York, with broad-scale waste-to-energy RD&D programs.

### U.S. Department of Energy Regional Biomass Energy Program

The U.S. Department of Energy's State Energy Management Programs Division, Office of Technical and Financial Assistance, administers the Regional Biomass Energy Program in five geographical regions: Northwest, Western, Great Lakes, Northeast, and Southeast. The program encourages development and application of biomass and municipal waste-to-energy technologies and carries out activities related to technology transfer, industry support, resource assessment, and matching local resources to conversion technologies. The program is designed to advance biomass energy feedstock production and conversion by the private sector and the use of municipal waste for energy, through the support of regional projects. Projects are geared toward establishing the availability of biomass resources within the various regions through resource assessment studies, technology transfer to the private sector, and cooperation between the Department of Energy and industry through cost-shared projects that will build private sector confidence to adopt biofuel technologies. The program also encourages development of individual state bioenergy programs.

Further information on the five regional programs may be obtained through the following contacts:

**Northwest Region**
Mr. Pat Fox
Program Manager
Bonneville Power Administration
Box 3621
Portland, OR 97208
(503) 230-3449
FAX: (503) 230-4973

**Western Region**
Mr. Dave Swanson
Western Area Power Authority
1627 Cole Boulevard, P.O. Box 3402
Golden, CO 80401
(303) 231-1615
FAX: (303) 231-1632

**Great Lakes Region**
Mr. Fred J. Kuzel
Council of Great Lakes Governors
35 East Wacker Drive #1850
Chicago, IL 60601
(312) 407-0177
FAX: (312) 407-0038

**Northeast Region**
Mr. Russ O'Connell
CONEG Policy Research Center, Inc.
400 North Capitol Street, NW, Suite 382
Washington, DC 20001
(202) 624-8454
FAX: (202) 624-8463

**Southeast Region**
Mr. Phillip C. Badger
Tennessee Valley Authority
Southeast Regional Biomass Energy Program
435 Chemical Engineering Building
Muscle Shoals, AL 35660
(205) 386-3086
FAX: (205) 386-2963

**The California Energy Commission Programs in Energy from Biomass and Wastes**

A 1979 California State law established a Biomass Development Program (BDP) and insured that the California Energy Commission (CEC) would play a major role in promoting and assessing a wide range of biomass technologies and applications. The law allocated $10 million to promote various biomass technologies. The Biomass Demonstration Program is best characterized as an ongoing experiment between 1979 and 1986 that provided both technical assistance and funds to develop conventional technologies for direct combustion, methane fermentation, gasification, and fuel collection. The CEC concluded that the program was successful as a mechanism to evaluate the commercial feasibility of a wide range of biomass applications.

By June 1986, 92 proposals had been received and evaluated, 67 for conversion technologies, direct combustion, gasification and anaerobic digestion, and 25 for collection and processing equipment. Nineteen projects received BDP funds. Both the successes and failures in this program provided the public and private sector with valuable insights into the limitations of biomass applications. Based on its experience, the CEC concluded that direct combustion technology had been commercialized. However, methane fermentation, gasification, and fuel collection still confront major technical and economic barriers to commercial development.

Commercial development of biomass continues today as a private sector function without the need for assistance from the CEC. The CEC does, however, play a small but important role in the development of biomass technologies that have not yet reached the

commercialization stage. The CEC's Energy Technologies Advancement Program (ETAP) was established by the California Legislature to move the CEC from programs that provide assistance for proven technologies to program support for the types of energy projects that are still in the research and development stage. Since the private sector is reluctant to risk investment in biomass applications during the research and development stage, the CEC continues to provide support in this area.

The primary goal of the ETAP program is hardware development. To accomplish this goal, ETAP offers loans and research contracts using an innovative funding program. Between 1985 and 1988, 26 projects were selected for funding, including three biomass projects.

In the waste-to-energy area, the CEC has responsibility for siting all electrical power plants in California that generate over 50 megawatts. There has not been a waste-to-energy facility over 50 megawatts sited in California. While a number of waste-to-energy projects have been proposed throughout the state, they have generally failed to become operational because of local opposition focusing on environmental and health concerns.

**New York State Energy Research and Development Authority Programs Multi-Year RD&D Plan, Toward a Secure Energy Future, 1991-1996**

The New York State Energy Research and Development Authority (the Authority) is a public benefit corporation created by the State Legislature in 1975. The Authority manages a broad program of energy research designed to develop and apply efficient technologies to help ensure that New York has secure and economical future supplies of energy, while protecting environmental values and promoting economic growth.

The Authority's 1991-96 Multiyear RD&D Program is a vehicle to inform others, including those who might propose and/or cosponsor projects, about the breadth and scope of the Energy Authority's program and the specific objectives it is intended to achieve. Internally, the Plan provides a road map for staff, guiding their development of specific projects for implementing the planned program. The program consists of two major components: (1) Energy Efficiency and Economic Development and (2) Energy Resources and Environmental Research.

Increased efficiency in energy use in New York State is the primary focus of the Energy Efficiency and Economic Development program. Improving energy efficiency reduces negative environmental impacts, the cost of energy for State consumers, and the amount of energy the State must import. Thereby contributing to the economic well-being of New York residents and businesses.

The Energy Resources and Environmental Research program is designed to increase the contribution of New York's energy resources to its energy needs and to increase fuel diversification while mitigating adverse environmental impacts. This program has three strategies:

(1) Provide innovation assistance to make substituting alternative energy forms -- such as biomass, municipal wastes, wind, solar and coal fuels -- easier for businesses, public sector facilities and other institutions;

(2) Demonstrate innovative ways to recover energy from or reduce the amount of energy needed to treat municipal wastes; and

(3) Sponsor applied RD&D of innovative energy conversion processes.

The program, with these strategies as a base, is organized into two areas: (1) Energy Resources and (2) Environmental Research. The Energy Resources area focuses on using New York's renewable and indigenous resources, other than municipal wastes, to produce energy and energy-related products; on increasing New York State's use of coal, an inexpensive, domestically abundant energy source; and on increasing the use of transportation fuels not derived from petroleum. The Environmental Research area, on the other hand, focuses on developing technologies to recover the energy from or reduce the amount of energy needed to use, treat, or dispose of municipal solid wastes, wastewaters and sludges while minimizing the environmental impacts of each method.

The Authority's municipal solid waste (MSW) RD&D program is within the Environmental Research area. The MSW program relies on an integrated systems approach, recognizing that no single alternative will adequately deal with New York's wastes but that some combination of disposal options is needed. The resulting RD&D program emphasizes recycling and waste reduction, ash management, landfill management and combustion efficiency. Program strategies include the following:

- Assist municipalities in establishing waste reduction, recycling and composting programs; measure program participation rates, effectiveness and collection efficiencies; develop statistical methods to measure the environmental acceptability of recovered and processed materials; and develop markets for recycled materials and compost.

- Target for recycling specific high-energy-content materials such as used oil and plastics, problem wastes such as batteries, and mixed wastes such as construction and demolition wastes, and develop new technologies to recover and use these materials.

- Develop and demonstrate landfill management technologies and strategies that maximize energy production from biogas, recover reclaimed landfill wastes for recycling and energy production, minimize the energy needed to treat leachate, and store separated waste materials for future recycling of energy production.

- Develop and demonstrate sampling, testing and management methods to use or dispose of incinerator ash.

- Conduct tests,systems analyses and feasibility studies, and demonstrate energy production from burning special wastes, separately or mixed with other wastes or fuels. Target tires, reclaimed landfill waste, construction and demolition waste, medical wastes, and residues from waste paper recycling processes.

The proposed budget for municipal solid waste RD&D ranges from 2.25 million to 2.60 million dollars per year for five years.

## C.4 International Activities

The literature review indicated that waste-to-energy RD&D projects have been conducted in a number of countries world-wide. The major international waste-to-energy work, however, appears to be through the International Energy Agency (IEA). Eleven IEA countries participate in waste-to-energy work under the agreement. In addition to their individual waste-to-energy programs, these countries collaborate to identify areas for RD&D cooperation among themselves.

**Bioenergy Agreement of the International Energy Agency (IEA), 1986-Present**

Municipal solid waste conversion is one area of concern within the International Energy Agency (IEA) Bioenergy Agreement. Three countries initiated a cooperative project in 1986. Since that time the cooperation has expanded to eleven participants including Austria, Canada, Denmark, Finland, Italy, Japan, Netherlands, Norway, Sweden, the United Kingdom, and the United States. The activity is led by Dr. Pat Lawson at the Harwell Laboratory in the United Kingdom. The major aim of the work has been to establish a cooperative approach to the R&D undertaken in each country on MSW conversion. The emphasis has been on technical and environmental aspects of energy (rather than materials) recovery. This focus has encompassed a wide range of technology options and environmental issues including the following: production of RDF, combustion of RDF, mass combustion, thermal processing (pyrolysis, gasification, liquefaction), flue gas treatment, solid residues from MSW/RDF combustion, landfill gas, anaerobic digestion, PCDD/PCDF emissions, and mercury emissions.

The initial task of the participants was to identify the scope for collaboration. The recent and current research effort in each country was appraised and an investigation of national priorities was conducted. This work was undertaken in 1986, and the scope of the program has been refined periodically as new countries have joined in participation. A three-day workshop in Cambridge, United Kingdom, in June 1988 provided a forum for generating specific proposals on cooperative ventures. The result of this work is a series of reports summarizing both the commercialization of waste-to-energy technologies and the status of relevant research in most participating countries. The series of reports also highlights areas in which each country might benefit from a multi-national program of coordination or collaboration. Most reports have been published or are underway.

Beginning in 1992, a new phase of the cooperation will start. Because of the high level of interest by the participants in MSW utilization, a new three-year Programme of Work has been authorized. Six separate activities will be conducted in the following areas: MSW and RDF combustion, handling ash residues, landfill gas, MSW anaerobic digestion, separation/processing technologies, and sampling/analytical protocols. The new work will allow more in-depth study of technical and environmental issues in these areas. Typical interactions among participating countries for each of these activities include:

- Exchange of relevant information;
- Coordination of existing or planned nationally funded R&D programs;
- Production of handbooks and review studies using data and experience derived within each country;

- Compilation and statistical interpretation of data from national programs, development and harmonization of procedures for sampling, analysis, and reporting; and

- Periodic technical meetings and symposia to facilitate communication between experts.

## C.5 Private Activities

Privately funded waste-to-energy programs in the United States focus on a number of waste-to-energy technologies based upon the interests of the private organization. The literature identified two organizations with waste-to-energy programs: the Electric Power Research Institute and the Gas Research Institute.

**EPRI-Funded Programs on Electric Power Production from Biomass and Wastes**

The Electric Power Research Institute's (EPRI's) program on energy from biomass and wastes is conducted in the Storage and Renewables Department of the Generation and Storage Division. Elements of EPRI's program include the following:

- RDF Co-Firing Guidelines: EPRI published a report in 1988 (in three volumes) based on utility experience in co-firing refuse-derived fuel (RDF) together with coal. The utility experience was obtained during the years 1975-1983 and was documented in an EPRI/DOE project with the results published by Argonne National Laboratory. The report formulates the lessons learned as guidelines and cost estimates for co-firing RDF and coal in existing or new coal-fired utility boilers.

- Fluidized Bed Combustion of Waste Fuels: EPRI surveyed the experiences of commercial and pilot plant operations where wastes (e.g., RDF, wood, agricultural wastes, etc.) have been used as fuel in fluidized-bed combustors (both bubbling bed and circulating designs). The draft final report is to be completed in early 1992.

- Boiler Tube Failures in Waste-to-Energy Power Plants: Battelle Columbus Division is obtaining data on tube failures in plants burning municipal solid waste and will interpret the data in terms of EPRI's previous experience and guidelines related to tube failures in fossil power plants.

- Waste Tires as a Utility Fuel: EPRI has published proceedings from its conference in January 1991. Also, EPRI has prepared a paper on specifications for tire-derived fuel.

- Waste-to-Energy Screening and Permitting Guide: EPRI has made available three products for use by member utilities who are considering possible roles in helping their communities solve municipal solid waste disposal problems: (1) a screening guide book characterizing technologies and costs; (2) a PC software package providing calculation, design, and economic analysis capability; and (3) a separate environmental and permitting document dealing with the facts, issues, and regulations involved in getting a permit for a plant that uses MSW as fuel for power generation.

- Waste-to-Energy Technology Status Assessment: EPRI reported on site visits to nine plants that generate electric power from combustion or co-firing of MSW or RDF. The draft final report presents results of a literature review, technology descriptions, reports of problems, and possible research to address problems.

- Analysis of Biomass/Waste-to-Energy Opportunities for Electric Utilities: A new research effort underway at EPRI involves fundamental analysis of fuel properties and conversion technologies, as well as case studies and a comprehensive strategic analysis of biomass and wastes for electric power generation. Utility advisors are being sought to assist EPRI in evaluation of the work in progress and to transfer the results of the project into immediate use by electric utilities.

In addition, EPRI has also conducted substantial research in the biomass area which has included a survey of resources and conversion technologies for converting biomass (wood, wood waste, agricultural wastes, food processing wastes, etc.) to energy and research into producing electricity from short rotation woody crops. EPRI has produced a bibliography and database on biomass fuels and processes and has held biomass meetings consisting of an expert panel on combustion and gasification. In January 1992, EPRI was scheduled to hold a full conference on biomass.

**Gas Research Institute Programs in Methane from Biomass and Wastes**

The Gas Research Institute was founded in 1976 as a not-for-profit scientific research organization to serve the mutual interest of the gas industry and its ratepayers by developing technical options to assure continuing cost-competitive gas energy services. GRI's Methane from Biomass and Wastes subprogram is expected to make both near-term and long-term contributions to the gas resource base. In the early 1980s, the subprogram was investigating the recovery of methane from renewable resources including wastes.

The Methane from Wastes project area focused on developing additional gas supplies from unused or underutilized resources such as municipal solid wastes, industrial wastes, and sewage and agricultural residues, which require specialized handling and conversion processes for economical gas production. The project area was aimed at improving the operating conditions, yields, overall system efficiencies, and economics of various waste-to-methane processes. The objective of this project area was to research and develop waste gasification to reduce cost and/or improve efficiency. The program, which was discontinued in 1986, had the following goals:

- Identifying and assessing those research needs that will promote efficient utilization of wastes as a viable energy source;
- Identifying specific front-end processing requirements for anaerobic digestion of solid waste materials;
- Improving overall conversion efficiencies of waste gasification processes; and
- Developing small-scale, low-cost gas separation systems oriented toward the needs of landfill methane recovery and waste gasification processes.

## APPENDIX D: GLOSSARY

Most of the following definitions were taken from Hollander (1983) and Milne (1986).

**Air Classifier:** a mechanical device using air currents to separate solid components into "light-fraction" or "heavy-fraction." See Air Knife, Elutriation, Gravity Separation.

**Anaerobic digestion**: degradation of organic matter by microbes in the absence of air (oxygen) to produce methane and carbon dioxide (biogas).

**Bioassay**: an assay method that uses a change in biological activity as a means of analyzing a material's response to biological treatment; method of assessing toxic effects of industrial wastes by using viable organisms as test species.

**Biogas**: a gaseous mixture of carbon dioxide and methane produced by the anaerobic digestion of organic matter.

**Biomethanation**: the formation of methane by microorganisms from hydrogen, carbon monoxide, and carbon dioxide.

**Char**: a porous, solid carbonaceous residue resulting from the pyrolysis or incomplete combustion of organic material. If produced from coal, it is called coke; if produced from wood or bone, it is called charcoal. It is closer to pure carbon than the coal, wood, or bone from which it is produced.

**Composting:** a process of decomposing organic matter by microorganisms.

**Cracking**: a reduction of molecular weight by breaking bonds, which may be done by thermal, catalytic, or hydrocracking. Heavy hydrocarbons, such as fuel oils, are broken up into lighter hydrocarbons, such as gasoline.

**Electrostatic precipitator**: an apparatus for removing fine solid particles from stack gases by collection on electrically charged electrodes.

**Fast pyrolysis**: pyrolysis in which reaction times are short, resulting in higher yields of certain fuel products, which may range from primary oils to olefins and aromatics depending on the severity of conditions. Rapid heating suppresses the formation of charcoal.

**Feedstock**: any material used as a fuel directly or converted to another form of fuel or energy product.

**Flue Gas:** the exhaust gas from a combustion process.

**Fly Ash:** the finely-divided particles of ash entrained in flue gases arising from combustion of fuel. The particles of ash may contain incompletely burned fuel. The particles are frequently glassy spheres but they may also be of crystalline or even fibrous structure.

**Fusion Point, (Refractory):** the temperature at which a particular complex mixture of minerals can flow under the weight of its own mass. See pyrometric cone ash fusion temperatures.

**Fluidized bed**: a gasifier or combustor design in which feedstock particles are kept in suspension by a bed of solids kept in motion by a rising column of gas; produces approximately isothermal conditions with high heat transfer between particles and gases.

**Gasifier**: a device that converts solid fuel to gas. Generally refers to thermochemical processes. Major types are moving bed (fixed bed), entrained bed, and fluidized bed.

**Hammermill**: a device consisting of a rotating head with free-swinging hammers that reduce in suspension, chips, hogged fuels, pellets, etc. to a predetermined particle size through a perforated screen. Moisture content of hammermilled material should not exceed 20 percent.

**High-Btu gas**: a gas containing mostly methane with a heating value of 800-1,100 Btu per standard cubic foot (heating value of natural gas ≈ 1000 Btu per standard cubic foot.

**Hydrogasification**: a form of gasification that involves adding hydrogen to optimize the formation of methane or pipeline gas.

**Hydrogenation**: treatment of substances with hydrogen and suitable catalysts at high temperature and pressure to saturate double bonds.

**Landfill gas**: biogas produced from the natural degradation of the organic material in landfills.

**Low-Btu gas**: a gas comprising $H_2O$, $CO_2$, CO, $H_2$, $CH_4$, and $N_2$ with a heating value of about 90 to 200 Btu per standard cubic foot.

**Materials recovery facility (MRF)**: a centralized facility where recyclable materials are recovered from municipal solid waste, or some portion of a municipal solid waste stream, and prepared for marketing.

**Medium-Btu gas**: a gas comprising $CO_2$, CO, $H_2$, $CH_4$ and higher hydrocarbons but little or no $N_2$, having a heating value of 250-500 Btu per standard cubic foot.

**Methanation**: a process for producing methane by passing carbon oxides and hydrogen mixtures over nickel catalysts. Medium-Btu gas can be upgraded to high-Btu gas by methanation. The reactions are $CO + 3H_2 \rightarrow CH_4 + H_2O$; $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$.

**Methane**: $CH_4$, the major component of natural gas. It can be formed by anaerobic digestion of biomass or gasification of coal or biomass.

**Methane fermentation**: a bacteria-mediated process whereby organic matter is metabolized in an oxygen-free environment with a net release of energy, resulting in end-products of carbon dioxide and methane gas.

**Methane oxidation**: reaction characterized by the equation $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ and initiated by indigenous methanotrophic bacteria in aerated cover materials of a landfill. Methane oxidation may have a limiting effect on methane available to a gas recovery system as well as a mitigating effect on methane emissions.

**Methanogenic bacteria**: microorganisms capable of producing methane.

**Particulate emissions**: solid particles discharged with exhaust gas. Usually expressed in terms of (1) grains per cubic foot, (2) pounds per million Btu input.

**Particulates**: minute solid or liquid particles in the air or in an emission. Particulates include dust, smoke, fumes, mist, spray, and fog.

**Pellet**: a densified fuel form, usually cylindrical, die-formed, usually by extrusion, with random lengths and open broken ends. Generally of high density.

**Pyrolysis:** the chemical decomposition of an organic material by heat in an oxygen deficient controlled environment. Results in destructive distillation and formation of combustible (hydrocarbon) gasses, oil, char, and mineral matter. See Destructive Distillation.

**Refuse-derived fuel (RDF)**: fuel processed from industrial waste, municipal waste, garbage, or sewage sludge.

**Scrubber**: an air pollution control device that uses a liquid or solid to remove pollutants from a gas stream by adsorption or chemical reaction. (Scrubbers also reduce the temperature of the emission.)

**Shredder:** a size reduction machine which tears or grinds materials to a smaller and more uniform particle size. Shredding process is also called size reduction, grinding, milling, pulverization, hogging, granulating, breaking, macerating, chipping, crushing, cutting, rasping. Also see Hammermill.

**Source separation**: a process through which members of a community separate recyclable material from ordinary municipal solid waste.

**Tipping Floor:** unloading area for vehicles that are delivering waste materials to transfer station, incinerator or other processing plant.

**tpd:** tons per day.

**tpy:** tons per year

**Vitrification:** a process whereby high temperatures effect permanent chemical and physical change in a ceramic (clay) body with the development of a substantial proportion of glassy bond.

**Wet scrubber**: an air pollution control device used to remove pollutants by bringing a gas stream into contact with a liquid.

# BIBLIOGRAPHY


Abbasi, H.A., Khinkis, M.J., Penterson, C.A., Zone, F., Dunnette, R., Nakazato, K., Duggan, P.A., and Linz, D.G., "Development of Natural Gas Injection Technology for $NO_x$ Reduction from Municipal Waste Combustors." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 165-181.

Alter, H., "The Future Course of Solid Waste Management in the U.S." Waste Management Research, 9:3-20, 1991.

Alvarez, R.J., "Current Status of Energy Generation from Thermal Processing of Municipal Solid Waste in the United States." In Energy Recovery Through Waste Combustion, eds., Brown, A., Evemy, P., and Ferrero, G.L., Proceedings of a seminar held at Cambridge (UK), June 21-24, 1988. Barking, Great Britain: Elsevier Applied Science, 1988, pp. 15-24.

Andrews, J.C. Jr., "Incinerator Ash Disposal in the Tampa Bay Region." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 284-298.

Antonopolos, A.A., and Wene, E.G., "Current U.S. Research in Methanogenesis Microbiology." In Energy from Landfill Gas, eds. J.R. Emberton and R.F. Emberton, Conf. Proc. October 28-31, 1986, Solihull, United Kingdom, pp. 164-175.

Antonopoulos, A.A., and Wene, E.G., "Bioconversion of MSW and Recovery of Organic Acids." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 159-168.

Apotheker, S., "Market Quality Issues Loom for MRFs." Resource Recycling, May 1990, 28-81.

Archer, D.B., and Robertson, J.A., "The Fundamentals of Landfill Microbiology." In Energy from Landfill Gas, eds. J.R. Emberton and R.F. Emberton, Conf. Proc. October 28-31, 1986, Solihull, United Kingdom, pp. 116-122.

ASME/US BOM, "ASME/US Bureau of Mines: Investigative Program on Vitrification of Ash/Residues from Waste Comubustors." The American Society of Mechanical Engineers and the U.S. Bureau of Mines Center for Research and Technology Development, undated.

Bacchi, J.J., and Allen, R.J., "Improving Combustion Conditions at RDF Facilities." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, pp. 182-189, 1991.

Barrett, R.E., Krause, H.H., Jr., Engdahl, R.B., Levy, A. and Oxley, J.H., "Municipal Waste-To-Energy Technology Assessment." EPRI TR-100058, by Battelle Memorial Institute for the Electric Power Research Institute, January 1992.

Beckman, A.H., "Design, Construction, and Operation of a 400-TPD Mass Burn MSW-to-Energy Plant - A Case History." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, pp. 545-556, 1990.

Berenyi, E., and Gould, R., 1988-89 Resource Recovery Yearbook. New York: Governmental Advisory Associates, Inc., 1988.

Berenyi, E., and Gould, R., 1990-91 Materials Recovery and Recycling Yearbook. New York: Governmental Advisory Associates, Inc., 1990.

Biofuels and Municipal Waste Technology Program, U.S. Department of Energy, Five Year Research Plan, 1988-1992, Biofuels: Renewable Fuels for the Future, Report No. DOE/CH/10093-25, July 1988.

Bogardus, E.R., "Landfill Gas Legislation and Control in the United States." In Energy from Landfill Gas, eds. J.R. Emberton and R.F. Emberton, Conf. Proc. October 28-31, 1986, Solihull, United Kingdom, pp. 75-80.

Bogner, J., and Antonopoulos, A.A., "Summary of Current and Landfill Gas Recovery Research Project Funded by U.S. Dept. of Energy." In Energy from Landfill Gas, eds. J.R. Emberton and R.F. Emberton, Conf. Proc. October 28-31, 1986, Solihull, United Kingdom, pp. 437-447.

Bogner, J., Rose, C., Vogt, M., and Gartman, D., "Landfill Gas Generation and Migration: Review of Current Research." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 183-200.

Bogner, J.E., The U.S. Landfill Gas Resource: Low-Cost Biogas from Municipal Solid Waste, Report No. ANL/CNSV-TM-206, Argonne, IL: Argonne National Laboratory, 1988.

Bogner, J.E., Rose, C., and Piorkowski, R., "Modified Biochemical Methane Potential (BMP) Assays to Assess Biodegradation Potential of Landfilled Refuse." In Proceedings 5th International Conference on "Solid Wastes, Sludges and Residual Materials: Characterization, Technology, Management, and Public Policy", April 26-29, 1989, Rome, Italy.

Bogner, J.E., "Anaerobic Burial of Refuse in Landfills: Increased Atmospheric Methane and Implications for Increased Carbon Storage." In SCOPE/IGBP Workshop on Trace Gas Exchange in a Global Perspective, February 19-23, 1990, Sigtuna, Sweden, 1990.

Bogner, J., personal communication, August 14, 1991.

Boyhan, G.E., "Waste Disposal and Resources Recovery (Dade County), Inc." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 241-247.

Brna, T.G., and Klincius, R.K., "Characterization of a Lime Spray Dryer Absorber/Baghouse on a Refuse-Derived Fuel Combustor." In Proc. International Conf. on Municipal Waste Combustion, Vol.2, April 11-14, 1989, Hollywood, FL, pp. 11C-41 - 11C-58.

Brooks, C., ed., Energy from Municipal Waste: State-of-the-Art and Emerging Technologies -- Workshop Proceedings, November 28-30, 1983, Chicago, IL, prepared for the U.S. Department of Energy, Report No. ANL/CNSV-TM-137. Argonne, IL: Argonne National Laboratory, 1984.

Buekens, A.G., "Refuse Incineration in Europe." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 1-15.

Buekens, A.G., and Schoeters, J.G., " European Experience in the Pyrolysis and Gasification of Solid Wastes." Conservation & Recycling. Vol. 9, No. 3, 1986, pp. 253-269.

Bullock, D., and Burk, D., "Commingled vs. Curbside Sort." BioCycle, June 1989, 35-36.

Bulpitt, W.S., and Rittenhouse, O.C., "The SEI Fluid Bed Gasification Facility." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 753-761.

Butner, R.S., Sealock, L.J., Elliott, D.C., and Neuenschwander, G.G., "Thermochemical Conversion of High-Moisture Biomass Feedstocks." In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 67-76.

"Catalysis," Kirk-Othmer Encyclopedia of Chemical Technology, 3rd ed., Vol. 5, New York: John Wiley & Sons, 1979.

Chandler, A.J., Eighmy, T.T., Hartlen, J., Hjelmar, O., Kosson, D., Sawell, S.E., van der Sloot, H.A., and Vehlow, J., "An International Perspective on Ash from Municipal Waste Incinerators." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 87-94.

Chynoweth, D.P., and Legrand, R., "Anaerobic Digestion of Municipal Solid Waste and Sludge." In Proc. of the 23rd Intersociety Energy Conversion Engineering Conf., Vol. 4, ed. D.Y. Goswami, July 31-August 5, 1988, Denver, CO. New York: The American Society of Mechanical Engineers, pp. 407-413, 1988.

Chynoweth, D.P., Earle, J.F.K and Jerger, D.E., "Future Operation of Experimental Test Unit on MSW." In FY1987 Anaerobic Digestion: Annual Report prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, pp. 91-99, 1988.

Clarke, P.A., and Virag, P.E., "Planning for Air Toxics Monitoring for MSW & RDF Combustion Facilities." In Proc. International Conf. on Municipal Waste Combustion, Vol.1, April 11-14, 1989, Hollywood, FL, pp. 5C-71 - 5C-84.

Clausen, E.C., and Gaddy, J.L., "Processing High Solids Concentration of MSW by Anaerobic Digestion for Methane Production." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, pp. 117-127, 1988.

Compton, L.J., "Challenge of Compliance with EPA's New Municipal Waste Combustor Regulation." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 775-776.

Daugherty, K., Venables, B., and Ohlsson, O., "Emission Studies of Full-Scale Cofiring of Pelletized REF/Coal." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 471-502.

Daugherty, K., Ohlsson, O.O., and Venables, B., "Emission Studies of Full-Scale Cofiring of Pelletized RDF/Coal at Argonne National Laboratory." In Proc. of the 23rd Intersociety Energy Conversion Engineering Conf., Vol. 4, ed. D.Y. Goswami, July 31-August 5, 1988, Denver, CO. New York: The American Society of Mechanical Engineers, pp. 415-419.

de Macario, E.C., Macario, A., Rivard, C.J., and Grohmann, K., "Use of Monoclonal Antibody Probes to Track External Additions of Improved Hydroclytic Microorganisms in a Municipal Solid Waste Anaerobic Digester." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 70-74.

de Bertoldi, M., Rutili, A., Citterio, B., and Civilini, M., "Composting Management: A New Process Control Through $O_2$ Feedback." Waste Management & Research, (1988) **6**, 239-259.

Denison, R.A., and Ruston, J., eds., Recycling and Incineration: Evaluating the Choices. Washington, D.C.: Environmental Defense Fund, Inc., 1990.

Dent, C.G., Scott, P., and Baldwin, G., "A Study of Landfill Gas Composition at Three UK Domestic Waste Disposal Sites." In Energy from Landfill Gas, eds. J.R. Emberton and R.F. Emberton, Conf. Proc. October 28-31, 1986, Solihull, United Kingdom, pp. 130-149.

Dent, C.G., and Krol, A.A., "Municipal Solid Waste Conversion to Energy." Biomass, (1990) **22**, 307-327.

Diaz, L.F., and Golueke, C.G., "Integrated Solid Waste Management." In Proc. of the 23rd Intersociety Energy Conversion Engineering Conf., Vol. 4, ed. D.Y. Goswami, July 31-August 5, 1988, Denver, CO. New York: The American Society of Mechanical Engineers, pp. 421-426.

Diaz, L.F., and Golueke, C.G., "Status of Composting in the United States." Resource Recycling, February 1990, 40-74.

Diaz, L.F., Savage, G.M., and Golueke, C.G., "Critical Review of Energy Recovery from Solid Wastes." CRC Critical Reviews in Environmental Control, 14(3), 1985, pp. 251-295.

Diebold, J., and Stevens, D., "Progress in Pyrolysis and Gasification of Biomass: An Overview of Research in the United States." Pyrolysis and Gasification: Proc. of an International Conf. held in Luxembourg, May 23-25, 1989, eds., G.L. Ferrero, K. Maniatis, A. Buekens, and A.V. Bridgwater, Elsevier Applied Science, 1990, pp. 14-27.

Diebold, J., Evans, R., and Scahill, J., "Fast Pyrolysis of RDF to Produce Fuel Oils, Char, and a Metal-Rich By-Product." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 851-878.

DiPietro, J.V., Collins, M.R., Guay, M., and Eighmy, T.T., "Evaluation of pH and Oxidation-Reduction Potential on Leachability of Municipal Solid Waste Incinerator Residues." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 2B-21 - 2B-43.

"Directory of Materials Recovery Facilities." Waste Age, Vol. 21, No. 5, May 1990, pp. 59-65.

Donnelly, J.R., "Overview of Air Pollution Controls for Municipal Waste Combustors." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 125-144.

Durai-Swamy, K., Warren, D.W., Aghamohammadi, B., and Mansour, M.N., "Pulse-Assisted Gasification of Black Liquor and Organic Wastes for Medium-Btu Gas." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 689-713.

Durai-Swamy, K., Colaninno, J., and Mansour, M.N., "Design and Operation of a Novel Pulse-Enhanced Biomass Gasifier for Production of Medium-Btu Gas." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 833-852.

Durai-Swamy, K., Warren, D.W., and Che, S.C., "Pulse-Enhanced Biomass Gasifier for Production of Medium-Btu Gas." In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 77-86.

Eley, M.H., and Holloway, C.C., "Municipal Solid Waste Processing by Steam Classification Holloway Process." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 185-202.

Elliott, D.C., Beckman, D., Östman, A., Solantausta, Y., Gevert, S.B., Hörnell, C., and Kjellström, B., "A Technical and Economic Analysis of Direct Biomass Liquefaction." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 743-767.

Energy and Environmental Research Corporation, Municipal Waste Combustion Study: Combustion Control of Organic Emissions, prepared for the U.S. Environmental Protection Agency, Report No. PB87-206090. Springfield, VA: U.S. Department of Commerce, National Technical Information Service, May 1987.

Energy Technology Support Unit, The Department of Energy's Renewable Energy R&D Programmes, Progress Report 1988/89, Report No. ESTU-R--51, DE90 519536, United Kingdom, 1990.

Evans, R.J., and Milne, T.A., "Liquid Fuels from the Pyrolysis of Municipal Solid Waste and Its Components: Rapid Product Characterization and Process Parameter Screening by Molecular Beam, Mass Spectrometry." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 807-838.

Evans, B., Milne, T.A., and Filley, J., "Mass Spectrometric Studies of Municipal Solid Waste Pyrolysis." In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 209-220.

Feindler, K.S., "Continuous Belt Dryer for the Production of Sludge-Derived Fuel." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 327-346.

Feldmann, H., and Paisley, M., "Conversion of RDF to Medium-Btu Gas." 2In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 101-110.

Eighmy, T.T. and Gress, D.L., Bottom Ash Reuse Presentation to Wheelabrator Environmental Systems, Environmental Research Group, University of New Hampshire, April 8, 1991.

Fernandes, J.H., "Uncertainties and Probable Errors Involved in Various Methods of Testing Incinerator/Boilers." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 230-240.

Fernandes, J.R., and Alex, A., Plant Design for Sortation of Post Consumer Plastic Containers, Piscataway, NJ: Center for Plastics Recycling Research, 1990.

Finkelstein, A., "An Overview of Environment Canada's National Incinerator Testing and Evaluation Program (NITEP)." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 1-15.

Fletcher, P., "Landfill Gas Enhancement Techniques - Laboratory Studies and Field Research." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 1001-1027.

Flynn, B.L., Hsieh, J.Y., and Curtis, D.A., "Effect of Product Recycle an Dry Acid Gas Emission Control." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 385-396.

Frank, J.R., and Hayes, T.D., "Research Programs Sponsored by the Gas Research Institute on Methane from Biomass and Wastes." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 177-195.

Frank, J.R., Benson, P.H., Hayes, T.D., and Isaacson, H.R., "Gas Research Institute Programs in Methane from Biomass and Wastes." In Symposium Papers Energy from Biomass and Wastes VII, January 24-28, 1983, Lake Buena Vista, FL. Chicago: Institute of Gas Technology, 1983, pp. 1315-1329.

Franklin Associates, Ltd., Characterization of Municipal Solid Waste in the United States: 1990 Update, prepared for the U.S. EPA, June 1990.

Franklin, W.E., Paper Recycling: The View to 1995, American Paper Institute, February 1990.

Garg, M., Piskorz, J., Scott, D.S., and Radlein, D., "A Novel Catalytic Gasification Process for Production of High Methane Gases." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 489-509.

Glenn, J., and Riggle, D., "The State of Garbage." BioCycle, April 1991, pp. 34-38.

Goldstein, N., and Spencer, B., "Solid Waste Composting Facilities." BioCycle, 31(1), January 1990, pp. 36-39.

Goldstein, N., "Solid Waste Composting in the U.S." BioCycle, 30(11), November 1989, pp. 32-37.

Golueke, C.G., and Diaz, L.F., "Status of MSW Composting." BioCycle, 30(1), January 1989, pp. 32-35.

Goodman, B.J., "Overview of the Anaerobic Digestion Research Program." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 3-10.

Goodwin, R.W., "Utilization Applications of Resource Recovery Residue." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 897-916.

Gould, R., "The MRF Industry: Data, Issues and Trends." Resource Recycling, March 1990, pp. 52-83.

Gould, R., "MRFs, Past and Future." Waste Age, July 1990, pp. 84-86.

Graham, S.J., Pedersen, D.C., Pompelia, D.M., and Kunce, E.P., "Production of Polychlorinated Dibenzo-p-Dioxins (PCDD) and Dibenzofurans (PCDF) from Resource Recovery Facilities Part I. Sources, Emissions and Air Quality Standards." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 345-357.

Grogan, P., "A 'Multiplexed' Future for MRFs." Waste Age, Vol. 20, No. 12, December 1989, pp. 54-56.

Gustin, F.H., and Shannonhouse, H.P., "Conversion of MSW Incineration Ash into Construction Aggregate Meeting Federal Drinking Water Standards." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, Washington, D.C., pp. 917A-23, 1990.

Hainsworth, E., Mayberry, J. and Piscitella, R., "Energy from Municipal Waste: Mechanical Equipment and Systems Status Report." EG&G Idaho Inc., for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. EGG PSE 5974, 1983.

Hartman, R.M., "An Overview of the Fate of Metals During Combustion at the Mid-Connecticut Resource Recovery Facility." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, pp. 347-362, 1991.

Hasselriis, F., "Thermal Systems for Conversion of Municipal Solid Waste, Volume 4. Burning Refuse-Derived Fuels in Boilers: A Technology Status Report." For the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-120, Vol. 4, 1983.

Hasselriis, F., "Variability of Municipal Solid Waste and Emissions from Its Combustion." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, pp. 331-344., 1984.

Hasselriis, F., "Relationships Between Variability of Emissions and Residues from Combustion of Municipal Solid Waste and Waste Composition and Combustion Parameters." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 5A-44 - 5A-64.

Hattemer-Frey, H.A., and Travis, C.C., "A Perspective on Human Exposure to PCDDs and PCDFs Emitted from Municipal Waste Combustors." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 2C-19 - 2C-33.

Hayes, R.D., "Canadian Bioenergy R&D - 1989." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 99-128.

Helt, J.E., Henry, R.F., and Young, J.E., "Pyrolysis of MSW: The Current ANL/DOE Program." In Energy from Municipal Waste Research: A Technical Review of Thermochemical Systems - Workshop Proceedings, February 22-24, 1984, Kissimmee, FL, prepared for U.S. Department of Energy, Report No. ANL/CNSV-TM-144, September 1984.

Hickman, L., Jr., "Thermal Systems for Conversion of Municipal Solid Waste, Volume 1. An Overview." For the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-120, Vol. 1, 1983.

Himmel, M.E., Adney, W.S., Rivard, C.J., and Grohmann, K., "Detection of Extra-Cellular Hydrolytic Enzymes in Anaerobic Digestion of MSW." In FY 1988 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3520. Golden, CO: Solar Energy Research Institute, 1989, pp. 9-23.

Himmel, M.E., Adney, W.S., Rivard, C.J., and Grohmann, K., "Detection of Extra-Cellular Hydrolytic Enzymes in Anaerobic Digestion of MSW." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 13-28.

Ho, N.W.Y., "Enzymatic and Initial Genetic Studies on Methanogens." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 41-50.

Hoeks, J., "Changes in Composition of Soil Air Near Leaks in Natural Gas Mains," Soil Science, 113:46, 1972.

Hollander, H.I., ed., "Thesaurus on Resource Recovery Terminology." Sponsored by ASTM Committee on E-38, ASTM 04-832000-16, 1983.

Holmes, T., Kosson, D., and Wiles, C., "A Comparison of Five Solidification/Stabilization Processes for Treatment of Municipal Waste Combustion Residues, Part I - Physical Testing." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 228-247.

Hopper, R, et al., "Thermal Systems for Conversion of Municipal Solid Waste Volume 3. Small-Scale Systems: A Technology Status Report." Battelle Columbus Laboratories, for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-120, Vol. 3, 1983.

Institute for Local Self-Reliance, Beyond 40 Percent: Record-Setting Recycling and Composting Programs, August 1990.

Keller, J., "Advances in Collecting Plastics." In First United States Conference on Municipal Solid Waste Management: Solutions for the 90s, Proc. Vol. II, June 13-16, 1990, Washington, D.C., pp. 491-507.

Kellermeyer, D.A., and Ziemer, S.E., "Public Health Risks Associated with Disposal of MSW Incineration Ash." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 3C-1 - 3C-22.

Kenny, G., and Sommer, E.J., "A Simplified Process for Metal and Noncombustible Separation from MSW Prior to Waste-to-Energy Conversion." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 574-589.

Kim, N-W., Trautz, J.A., and Miller, D.J., "Flash Pyrolysis of Cellulose in the Presence of $K_2CO_3$." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 839-851.

Kiser, J.V.L., "A Comprehensive Report on the Status of Municipal Waste Combustion," Waste Age, November 1990, 100-159.

Klass, D.L., "The U.S. Biofuels Industry." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 1-46.

Koontz, R.P., Parker, S., and Glenn, B., "The Status of Biomass Fuels Technologies Research in the United States." Int. J. Solar Energy, Vol. 2, pp. 369-384, 1984.

Kosson, D.S., van der Sloot, H., Holmes, T.T., and Wiles, C.C., "A Comparison of Solidification/Stabilization Processes for Treatment of Municipal Waste Combustor Residues, Part II - Leaching Properties." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, pp. 248-262, 1991.

Krol, A., and Dent, C., "Energy from Municipal Solid Waste: The Potential Benefits of International Collaboration to the Research Programmes of the UK, Sweden, and Canada." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, pp. 33-66, 1989.

Kuester, J.L., "Thermal Systems for Conversion of Municipal Solid Waste, Volume 5. Pyrolytic Conversion: A Technology Status Report." Arizona State University, for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-120, Vol. 5, 1983.

Kuester, J.L., "Gasification of MSW in Fluidized- and Entrained-Bed Systems." In Energy from Municipal Waste Research: A Technical Review of Thermochemical Systems - Workshop Proceedings, February 22-24, 1984, Kissimmee, FL, prepared for U.S. Department of Energy, Report No. ANL/CNSV-TM-144, September 1984, pp. 143-165.

Lailas, N., "International Perspectives of Landfill Gas - A U.S. Overview." In Energy from Landfill Gas, eds. J.R. Emberton and R.F. Emberton, Conf. Proc. October 28-31, 1986, Solihull, United Kingdom, pp. 13-16.

Landrum, V.J., Barton, R.G., and Masser, C.C., "Medical Waste Incineration Practices in Municipal Waste Combustors." In Proc. International Conf. on Municipal Waste Combustion, Vol.2, April 11-14, 1989, Hollywood, FL, pp. 10B-30 - 10B-46.

Larson, L.E., and Rundstrom, D.A., "Development of a Downdraft Wood Gasification System for Electric Utility Boiler Applications." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 805-831.

Leeper, S. et al., "Municipal Solid Waste Bioconversion Technologies." EG&G Idaho Inc., for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. EGG-2193, 1982.

Macauley, B.J., Miller, F.C., and Harper, E.R., "Mushroom Compost Production Research." BioCycle, 31(6), June 1990, pp. 74-78.

Mancinelli, R.L., W.A. Shulls, and C.P. McKay, 1981, "Methanol-Oxidizing Bacteria Used as an Index of Soil Methane Content," Applied and Environmental Microbiology, 42:70-73, 1981.

Mancinelli, R.L., and C.P. McKay, "Methane-Oxidizing Bacteria in Sanitary Landfills." In Proceedings of the First Symposium on Biotechnological Advances in Processing Municipal Wastes for Fuels and Chemicals, ed. A. Antonopoulos. Minneapolis, MN, Argonne National Laboratory Report ANL/CNSV-TM-167, August 1984.

Marks, C.H., Sommerlad, R.E., and Visalli, J.R., "A New Concept: Separately-Fired Superheaters for Waste-to-Energy Plants." In Proc. International Conf. on Municipal Waste Combustion, Vol.2, April 11-14, 1989, Hollywood, FL, pp. 8A-1 - 8A-30.

Massoudi, M.S., "Feasibility of 100 Percent RDF Firing for Power Generation." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 111-118.

Mathusa, P.D., "The New York State Energy Research and Development Authority's RD&D Program in Biomass and Municipal Wastes." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 15-32.

McGowin, C.R., and Kohan, S.M., "EPRI-Funded Programs on Electric Power Production from Biomass and Wastes." In Symposium Papers Energy from Biomass and Wastes VII, January 24-28, 1983, Lake Buena Vista, FL. Chicago: Institute of Gas Technology, 1983, pp. 1331-1357.

McGowin, C.R., "Impact of RDF Cofiring on Power Plant Operation and Economics." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 567-590.

McKinney, R.E., "Effects of Trace Metals on Methanogenesis and Control of Sulfate Reducing Bacteria." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 52-63.

Merdes, R.S., "The Neutralysis System." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 642-651.

"Methane Recovery Projects Multiply." Engineering News Record (ENR), 227(23), December 9, 1991, p. 23.

Miles, T.R., and Miles Jr., T.R., "Overview of Biomass Gasification in the USA." Biomass, **18**, 1989, pp. 163-168.

Milne, T.A., "Biofuels Glossary." Solar Energy Research Institute. SERI/SP-271-2828, September 1986.

Molton, P.M., Fassbender, A.G., Robertus, R.J., Sullivan, R.G., and Brown, M.D., "Production of Fuel Oil from Sewage Sludge by the Stors Process." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 1153-1185.

Mudge, L.K., Gerber, M.A., and Wilcox, W.A., "Improved Gasification by Catalytic Destruction of Tars in Biomass-Derived Gases." In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 87-100.

National Solid Wastes Management Association, Recycling in the States - Mid-Year Update 1990, Washington, D.C., 1990.

National Wolid Wastes Management Association, Recycling in the States: 1990 Review, Washington, D.C., September 1990.

Nels, C.H., "Waste Management and Pyrolysis: Current Situation, Trends and Prospects." Pyrolysis and Gasification: Proc. of an International Conf. held in Luxembourg, May 23-25, 1989, eds., G.L. Ferrero, K. Maniatis, A. Buekens, and A.V. Bridgwater, Elsevier Applied Science, 1990, pp. 379-386.

Neulicht, R., and Visalli, J., "Combustion and Emissions Tests of the Vicon Incinerator at Pittsfield, Massachusetts." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 439-470.

"New Approach to Collecting Recyclables." BioCycle, November 1989, 54-55. Niessen, W.R., "Production of Polychlorinated Dibenzo-p-Dioxins (PCDD) and Dibenzofurans (PCDF) from Resource Recovery Facilities Part II." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 358-376.

Norton, G.A., and Levine, A.D., "Effect of Co-Combusting Refuse-Derived Fuel and Coal on Emissions of $SO_x$, $NO_x$, and Ash from Coal-Fired Boilers. In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 513-527.

Noteware, W.D., "Programs on Energy from Biomass and Wastes Funded by the California Energy Commission." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 129-176.

Nutter, J.B., "Recovery and Recycling of Post-Consumer Plastic Film." In First United States Conference on Municipal Solid Waste Management: Solutions for the 90s, Proc. Vol. II, June 13-16, 1990, Washington, D.C., pp. 683-695.

Ohlsson, O.O., A Review of Refuse-Derived Fuel (RDF) Facilities: Design Considerations and Opportunities, Argonne, IL: Argonne National Laboratory, 1989.

Ohlsson, O.O., Walter, D.K. and Goodman, B.J., "An Overview of RDF Processing Systems: Current Status, Design Features, and Future Trends." Presented at the International Joint Power Generation Conference, San Diego, CA, October 6-10, 1991.

Onischak, M., Knight, R.A., Evans, R.J., and Babu, S.P., "Gasification of RDF in a Pressurized Fluidized Bed." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 531-548.

Pease, R.R., "Control Options for Landfill Gas." In Proceedings from the GRCDA 12th Annual International Landfill Gas Symposium, March 20-23, 1989, Monterey, CA. Silver Spring, MD: GRCDA - The Association of Solid Waste Management Professionals, 1989, pp. 30-45.

"Petroleum (Refinery Processes, Survey)," Kirk-Othmer Encyclopedia of Chemical Technology, 3rd ed., Vol. 17, New York: John Wiley & Sons, 1982.

Pfeffer, J. and Isaacson, R., "Biochemical Conversion of Municipal Solid Waste: A Technology Status Report." Gas Research Institute and the University of Illinois, Urbana, for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-122, 1983.

Rankin, S., ed., Plastics Collection and Sorting: Including Plastics in a Multi-material Recycling Program for Non-rural Single Family Homes, Piscataway, NJ: Center for Plastics Recycling Research, 1988.

Rappe, M.S., Södeström, G., Ljung, K., Aittola, J-P., Vesterinen, R., Hoffren, H., Benestad, C., Jebens, A., and Oehme, M., "'Internordic' Method Calibration for Sampling and Analysis of Dioxins and Other Chlorinated Organic Compounds." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 4C-1 - 4C-14.

Rathje, W.L. and Thompson, B., The Milwaukee Garbage Project, Solid Waste Council of the Paper Industry, Washington, D.C., 1981.

Reed, T., "Principles and Operation of a Novel 'Pyrolysis Mill'." In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 247-258.

Reed, T.B., "Evaluation of Downdraft Gasification for MSW Conversion." In Energy from Municipal Waste Research: A Technical Review of Thermochemical Systems - Workshop Proceedings, February 22-24, 1984, Kissimmee, FL, prepared for U.S. Department of Energy, Report No. ANL/CNSV-TM-144, September 1984, pp. 125-142.

Rensfelt, E., and Ekström, C., "Fuel Gas from Municipal Waste in an Integrated Circulating Fluid-Bed Gasification/Gas-Cleaning Process." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 891-906.

Richards, R.S., and Bennett, G.F., "Vitrification of Municipal Solid Waste Combustor Ash." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 917-930.

Ridzon, G.J., Blum, S.L. and Pearson C.V., "Institutional Issues Concerning Energy from Municipal Waste: A Status Report." Argonne National Laboratory and Northern Energy Corporation, for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-123, 1983.

Rivard, C.J., Vinzant, T.B., Adney, W.S., and Grohmann, K., "The Microaerophilic Digestion of Processed Municipal Solid Waste for the Production of Organic Acids." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 169-179.

Robinson, W.D., ed., The Solid Waste Handbook. New York: John Wiley & Sons, 1986.

Roffman, H.K, "Characterization of Municipal Waste Combustion Ashes and Leachates: Results of Two Field Studies." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 777-786.

Rugg, M., and Kharod, S., "A Critical Examination of the Relationship Between Convenience and Recovery Rates in Residential Recycling Programs." In First United States Conference on Municipal Solid Waste Management: Solutions for the 90s, Proc. Vol. II, June 13-16, 1990, Washington, D.C., pp. 553-564.

Russell, S.H., and Roberts, J.E., "Oxides of Nitrogen: Formation and Control in Resource Recovery Facilities." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 417-423.

Scahill, J., and Diebold, J.P., "Adaption of the SERI Vortex Reactor for RDF Pyrolysis." In Thermochemical Conversion Program Annual Meeting, June 21-22, 1988, Golden, CO, prepared for the U.S. Department of Energy, Report No. SERI/CP-231-3355, Golden, CO: Solar Energy Research Institute, 1988, pp. 237-246.

Scaramelli, A.B., Resource Recovery Research Development and Demonstration Plan, prepared for U.S. Department of Energy, Report No. DOE/CS/20178-01, 1979.

Schindler, P.J., and Nelson, L.P., Municipal Waste Combustion Assessment: Technical Basis for Good Combustion Practice, prepared for the U.S. Environmental Protection Agency, Report No. EPA-600/8-89-063, 1989.

Science Applications International Corporation, Modular Systems of Energy Recovery from Municipal Waste, prepared for the U.S. Department of Energy, Report No. DOE/CE/30784-H3, June 1986.

Seeker, W.R., England, G.C., Maly, P., and Linz, D.G., "Retrofit of Natural Gas Firing Technology for Control of Chlorinated Dioxin/Furans in Existing RDF Combustors." In Proc. International Conf. on Municipal Waste Combustion, Vol. 2, April 11-14, 1989, Hollywood, FL, pp. 7A-19 - 7A-36.

Shieh, C-S., and Wei, Y-L., "Minimization of Trace Metal Leachings in Seawater from Stabilized MSW Incineration Ash." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 839-854.

Shortsleeves, J. and Roche, R., "Integrated Solutions that Work." Waste Age, pp 85-88, January 1991.

Siddens, S., "A Decade of Innovations in WTE Incineration." Solid Waste and Power, April 1990, pp. 16-23.

Smith, G.A., "Processing Household Recyclables." In Proc. International Conf. on Municipal Waste Combustion, Vol.2, April 11-14, 1989, Hollywood, FL, pp. 10A-19 - 10A-25.

Smith, D.J., "Can Recycling Save Waste-to-Energy?" Power Engineering, September 1988, 92(9), 21-27.

Solantausta, Y., and Kurkela, E., "The Production of Electricity from Peat by Integrated Gasification-Combined Cycle Conversion." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 853-864.

Speece, R.E., "Research into Factors Determining Anaerobic Digester Performance." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 213-222.

Stevenson, W.H., and Johnston, M.G., "Proposed Air Pollution Emission Rules for Municipal Waste Combustion Facilities." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 855-864.

Strauss, W., "Stabilization of Heavy Metals in Incinerator Ash and Potential Re-use of the Hardened Material." In Proc. International Conf. on Municipal Waste Combustion, Vol.2, April 11-14, 1989, Hollywood, FL, pp. 11B-1 - 11B-12.

Sussman, D.B., "Municipal Waste Combustion Ash: Testing Methods, Constituents, and Potential Uses." In Proc. International Conf. on Municipal Waste Combustion, Vol. 2, April 11-14, 1989, Hollywood, FL, pp. 11B-13 - 11B-25.

Taylor, H.F., "The Ten Myths of Municipal Waste Combustion and the Fundamentals and Politics of Garbage." In Proc. International Conf. on Municipal Waste Combustion, Vol.2, April 11-14, 1989, Hollywood, FL, pp. 7B-13 - 7B-42.

Taylor, A.C., and Kashmanian, R.M., Study and Assessment of Eight Yard Waste Composting Programs Across the United States, Report No. EPA/530-SW-89-038, Washington D.C.: Environmental Protection Agency, April 1989.

Temple-Pediani, R.W., "Design and Use of Commercial Producer Gasifiers for Waste." In Symposium Papers Energy from Biomass and Wastes VII, January 24-28, 1983, Lake Buena Vista, FL. Chicago: Institute of Gas Technology, 1983, pp. 495-513.

"Tests Used on Incinerator Ash May Overpredict Presence of Hazardous Elements, EPA Study Says." Environment Reporter, March 30, 1990, pp. 1909-1910.

Tinning, H.P., project manager, DOE Program Evaluation Workshop, June 19, 1985.

Trezek, G., "Thermal Systems for Conversion of Municipal Solid Waste, Volume 6. Fluidized-Bed Combustion: A Technology Status Report." University of California, Berkeley, for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-120, Vol. 5, 1983.

Tsai, G.J., and Tsao, G.T., "A Combined Chemical and Biological Process for Methane Production from Cellulosic Solids." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 595-611.

"Tunnel Approach to MSW Composting." BioCycle, 31(10), October 1990, p. 74.

Turner, W.D., "Thermal Systems for Conversion of Municipal Solid Waste, Volume 2. Mass Burning of Solid Waste in Large-Scale Combustors: A Technology Status Report." Texas A&M University, for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-120, Vol. 2, 1983.

Tweedale, A., "RDF Pellet Burning - R&D Trials Newcastle." In Energy Recovery Through Waste Combustion, eds., Brown, A., Evemy, P., and Ferrero, G.L., Proceedings of a seminar held at Cambridge (UK), June 21-24, 1988. Barking, Great Britain: Elsevier Applied Science, 1988, pp. 113-122.

U.S. Congress, Office of Technology Assessment, Facing America's Trash: What Next for Municipal Solid Waste?, OTA-0-424, Washington, D.C.: U.S. Government Printing Office, October 1989.

U.S. Department of Energy, Biofuels and Municipal Waste Technology Research Program Summary FY 1986, Report No. DOE/CH10093-6.

U.S. Environmental Protection Agency, Characterization of Municipal Waste Combustor Ashes and Leachates from Municipal Solid Waste Landfills, Monofills, and Co-Disposal Sites, prepared by NUS Corporation for the Office of Solid Waste and Emergency Response, EPA 530-SW-87-028A, October 1987.

U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Emissions form Municipal Solid Waste Landfills -- Background Information for Proposed Standards and Guidelines, EPA-450/3-90-011a, Research Triangle Park, NC, March 1991.

Van Der Sloot, H.A., De Groot, G.J., Wijkstra, J., and Leenders, P., "Leaching Characteristics of Incinerator Residues and Potential for Modification of Leaching." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 2B-1 - 2B-19.

U.S. Environmental Protection Agency, Municipal Solid Waste Research Agenda, ed. J.P.E. des Rosiers, prepared by U.S. EPA Office of Research and Development and the Office of Environmental Engineering and Technology Demonstration, April 1991.

Van Santen, A., "Status of R&D Activities in the European Economic Community." In Tenth Canadian Waste Management Conference, October, 25-27, 1988, Winnepeg, pp. 149-155.

Vence, T.D., "Potential of Recycling Ash from Resource Recovery Facilities in California." In Proc. of 1984 National Waste Processing Conference, June 3-6, 1984, Orlando, FL, New York: The American Society of Mechanical Engineers, 1984, pp. 640-654.

Vilppunen, P., "Energy Production by Anaerobic Digestion of Waste Sludge from Wood Processing Industries." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 937-952.

Walter, D.K, and Wallace, C.J., "Biofuels and Municipal Solid Waste: An Overview of the DOE Program." In Proc. of the 23rd Intersociety Energy Conversion Engineering Conf., Vol. 4, ed. D.Y. Goswami, July 31-August 5, 1988, Denver, CO. New York: The American Society of Mechanical Engineers, pp. 387-390.

Walter, D.K., "The U.S. Department of Energy Biofuels Research Program." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 47-62.

Walter, D.K., "Biofuels and Municipal Waste Research Program of the U.S. Department of Energy." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 1-14.

Walter, D.K., "Biofuels and Municipal Waste Technology: A National Perspective." In Energy from Biomass and Wastes XI, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1988, pp. 1-16.

Watson, T., "Curbside Goes High-tech." Resource Recycling, October 1990, 32-36.

Watson, T., "Solid Waste Composting Aims for the Mainstream." Resource Recovery, July 1990, 30-40.

Watts, R.R., DeMarini, D.M., Linak, W.P., Lemieux, P.M., McSorley, J.A., and Lewtas, J., "Use of Bioassay Methods to Evaluate Incinerator Emissions." In Proc. International Conf. on Municipal Waste Combustion, Vol. 1, April 11-14, 1989, Hollywood, FL, pp. 2C-35 - 2C-46.

Weaver, P. and Maness, P.C., "Photoenhanced Anaerobic Digestion of Organic Acids." In FY 1987 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3331. Golden, CO: Solar Energy Research Institute, 1988, pp. 29-33.

Weaver, P., and Maness, P.C., "Photoenhanced Anaerobic Digestion of Organic Acids." In FY 1988 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3520. Golden, CO: Solar Energy Research Institute, 1989, pp. 25-34.

Wene, E.G., and Antonopoulos, A.A., "Liquid-Liquid Extraction of Short-Chain Organic Acids from Anaerobic Digesters." In FY 1988 Anaerobic Digestion: Annual Report, prepared for the U.S. Department of Energy, Report No. SERI/SP-231-3520. Golden, CO: Solar Energy Research Institute, 1989, pp. 127-137.

Whalen, S.C., W.S. Reeburgh, and K.A. Sanbeck, "Rapid Methane Oxidation in a Landfill Cover Soil," Applied and Environmental Microbiology 56:3405-3411, 1990.

Wiles, C.C., "The U.S. EPA Program for Evaluation of Treatment and Utilization Technologies for Municipal Waste Combustion Residues." In Municipal Waste Combustion: Papers and Abstracts from the Second Annual International Conference, April 15-19, 1991, Tampa, FL. Pittsburgh, PA: Air & Waste Management Association, 1991, pp. 205-227.

Wiles, C.C., Kosson, D.S., and Holmes, T., "The United States Environmental Protection Agency Municipal Waste Combustion Residue Solidification/Stabilization Evaluation Program." In First United States Conference on Municipal Solid Waste Management Solutions for the 90s, Proceedings from the Combustion Sessions, June 13-16, 1990, Washington, D.C., pp. 883-896.

Yasui K. and T. Masuda. "Case Study 7: Solid Waste Disposal by PUROX System at Chichibu Clean Center." in First International Waste Recycling Symposium. November 16-18, 1981.

Zimmerman, R.E., Lytwynyshyn, G.R. and Wilkey, M.L., "Landfill Gas Recovery: A Technology Status Report." Gas Research Institute and ESCOR Inc., for the U.S. DOE Energy and Environmental Systems Division and Chemical Technology Division, Energy from Municipal Waste Program. ANL/CNSV-TM-121, 1983.

Zimmerman, R.E., and Isaacson, R., "Toxic and Non-toxic Components in MSW Landfill Gases." In Energy from Biomass and Wastes XII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1989, pp. 517-530.

Zylkowski, J.R., and Schmidt, R.J., "Waste Fuel Firing in Atmospheric Fluidized Bed Retrofit Boilers." In Energy from Biomass and Wastes XIII, ed. D.L. Klass. Chicago, IL: Institute of Gas Technology, 1990, pp. 483-512.

| Document Control Page | 1. NREL Report No. NREL/TP-431-4982 | 2. NTIS Accession No. DE920016406 | 3. Recipient's Accession No. |
|---|---|---|---|
| 4. Title and Subtitle<br>RD&D Priorities for Energy Production and Resource Conservation from Municipal Solid Waste | | | 5. Publication Date<br>August 1992<br>6. |
| 7. Author(s)<br>ICF Incorporated | | | 8. Performing Organization Rept. No. |
| 9. Performing Organization Name and Address<br>ICF Incorporated<br>9300 Lee Highway<br>Fairfax, Virginia 23031 | | | 10. Project/Task/Work Unit No.<br>WM21.1010<br>11. Contract (C) or Grant (G) No.<br>(C) RF-1-11005<br>(G) |
| 12. Sponsoring Organization Name and Address<br>National Renewable Energy Laboratory<br>1617 Cole Blvd.<br>Golden, CO 80401 | | | 13. Type of Report & Period Covered<br>Subcontract Report<br>14. |
| 15. Supplementary Notes<br>NREL Technical Monitor: Philip Shepherd (303) 231-7829 | | | |

16. Abstract (Limit: 200 words)

This report identifies research, development, and demonstration (RD&D) needs and priorities associated with municipal solid waste (MSW) management technologies that conserve or produce energy or resources. This assessment of RD&D needs and priorities was prepared for the National Renewable Energy Laboratory (NREL) of the United States Department of Energy (DOE) in recognition of the many changes that have occurred in the nature of MSW management over the past decade.

17. Document Analysis

a. Descriptors

municipal waste; waste to energy; combustion; resource recovery; recycling; composting; anaerobic digestion; landfill

b. Identifiers/Open-Ended Terms

c. UC Categories

249

| 18. Availability Statement | 19. No. of Pages |
|---|---|
| National Technical Information Service<br>U.S. Department of Commerce<br>5285 Port Royal Road<br>Springfield, VA 22161 | 289<br>20. Price<br>A13 |

Form No. 0069E (6-30-87)