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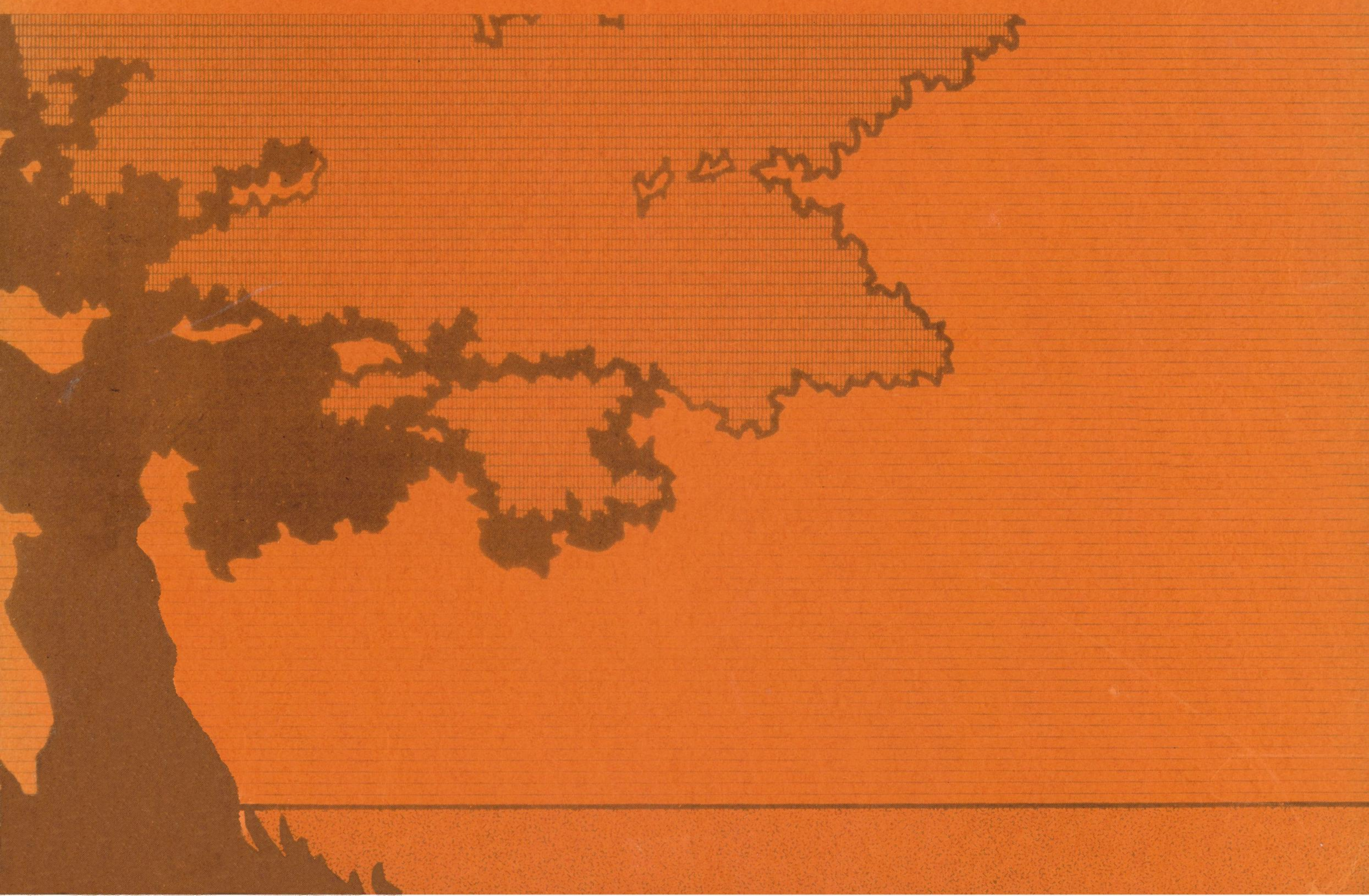
Land Disposal: Hazardous Waste

Proceedings of the Seventh Annual Research Symposium



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16. ABSTRACT

The Seventh Annual SHWRD Research Symposium on land disposal of municipal solid waste and industrial solid waste and resource recovery of municipal solid waste was held in Philadelphia, Pennsylvania, on March 16, 17, and 18, 1981. The purpose of the symposium were (1) to provide a forum for a state-of-the-art review and discussion of on-going and recently completed research projects dealing with the management of solid and industrial wastes; (2) to bring together people concerned with municipal solid waste management who can benefit from an exchange of ideas and information; and (3) to provide an arena for the peer review of SHWRD's overall research program. These proceedings are a compilation of papers presented by the symposium speakers. The technical areas covered in the Land Disposal: Municipal Solid Waste are gas and leachate production, treatment and control technologies and economics. The areas covered in Land Disposal: Hazardous Wastes are hazardous waste characterization, transport and fate of pollutants, hazardous waste containment, land treatment of hazardous wastes, hazardous waste treatment, uncontrolled sites/remedial action, and economics. Municipal Solid Waste: Resource Recovery include ~~the areas of~~ equipment and processing, recovery and use of materials, environmental aspects and economics/impediments and special studies.

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MUNICIPAL SOLID WASTE: RESOURCE RECOVERY

Proceedings of the Seventh Annual Research Symposium
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Sponsored by the U.S. EPA, Office of Research & Development
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FOREWORD

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

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

The Proceedings present the results of completed and ongoing research projects concerning resource recovery from municipal solid waste.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

PREFACE

These Proceedings are intended to disseminate up-to-date information on extramural research projects concerning municipal solid waste resource recovery. Theses projects are funded by the Solid and Hazardous Waste Research Divison (SHWRD) of the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory in Cincinnati, Ohio.

The papers in these Proceedings are arranged as they were presented at the symposium and have been printed basically as received from the authors. They do not necessarily reflect the policies and opinions of the U.S. Environmental Protection Agency. Hopefully, these Proceedings will prove useful and beneficial to the scientific community as a current reference on municipal solid waste resource recovery.

ABSTRACT

The Seventh Annual SHWRD Research Symposium on land disposal of municipal solid waste, hazardous waste, and resource recovery of municipal solid waste was held in Philadelphia, Pennsylvania, on March 16, 17, and 18, 1981. The purposes of the symposium were (1) to provide a forum for a state-of-the-art review and discussion of ongoing and recently completed research projects dealing with the management of solid and hazardous wastes; (2) to bring together people concerned with municipal solid waste management who can benefit from an exchange of ideas and information; and (3) to provide an arena for the peer review of SHWRD's overall research program. These proceedings are a compilation of papers presented by the symposium speakers.

The symposium proceedings are being published as three separate documents In this document, Municipal Solid Waste: Resource Recovery, four technical areas are covered. They are as follows:

(1) Equipment and processing
(2) Recovery and use of materials
(3) Environmental aspects
(4) Economics/impediments and special studies

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SESSION B - RESOURCE RECOVERY

OVERVIEW OF RESOURCE RECOVERY

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ABSTRACT

Resource recovery activities of the SHWRD are summarized broadly. Projects are described in four categories: MSW mechanical processing, chemical/bio-conversion techniques, waste-to-energy conversion systems, and impediments to resource recovery. Progress in our resource recovery research has been constrained because of low priority ranking in favor of hazardous waste research, constrained and unsteady funding and lack of well defined national resource recovery goals. Nonetheless, some good work has been produced, particularly in the areas of size reduction and refuse-derived fuels. Recovery of materials and energy from waste is a worthwhile national goal that can forestall shortages and greatly reduce the solid waste disposal problem at the same time. Good resource recovery practices are essential to good waste management.

INTRODUCTION

This report summarizes the activities of EPA's Solid and Hazardous Waste Research Division (SHWRD) in the field of resource recovery. These activities have been significantly decreased since SHWRD's Fifth Annual Symposium in 1978, when our resource recovery program was last discussed. Program de-emphasis occurred because all resources have been allocated to higher ranking programs on hazardous waste. Nevertheless, SHWRD considers resource recovery an important alternative for the proper management of municipal solid waste (MSW). Our current resource recovery activities, therefore, need to be documented and made available to further the cause of resource recovery insofar as possible.

Though capabilities for conducting meaningful research in resource recovery has been constrained over the years, SHWRD has made some significant contributions through support of selected activities. Some of these past contributions are summarized here along with our current activities.

LEGISLATIVE HISTORY

The Solid Waste Disposal Act of 1965 provided the legislative framework for Federal efforts to deal with environmental problems associated with solid waste. The 1965 Act authorized technical and financial assistance programs and called for promulgation of guidelines, training programs, and research and demonstration programs.

The Resource Recovery Act of 1970 amended the 1965 Act and mandated an increased effort promoting the recovery and use of materials from solid waste. Specifically, the 1970 Act authorized resource recovery demonstrations and the national disposal site study; it also extended authorization of research and development in the field of resource recovery. However, there have been only limited opportunities to pursue the research activities required to meet the resource recovery objectives identified by these two Acts. This is attributed largely to the low priority ranking of municipal solid waste research needs as compared to other environmental research needs.

This low ranking was caused partially by the lack of a well defined research strategy which recognized the need for support of technological developments in resource recovery. Because of this, funding for research in resource recovery has been constrained and unsteady. Also Legislative Acts did not establish a Federal regulatory authority for dealing with solid waste management and disposal problems. This circumstance existed until passage of the Resource Conservation and Recovery Act of 1976. Though this Act gave continued authority to EPA to engage in resource recovery research, little was done because program emphasis is directed toward hazardous waste management and control. Research support for the hazardous waste regulatory aspects of the Act has increased substantially in order to meet Congressionally-mandated and Federal court-imposed deadlines. Because of this program direction, current solid and hazardous waste research strategies do not include resource recovery research.

CURRENT STATUS OF RESOURCE RECOVERY PROGRAM

The objective of the MSW portion of the 7th Annual Research Symposium is unfortunately to wrap up our research activities in resource recovery. Some of the reports presented here are follow-ups to individual projects reported during previous research symposiums. Other papers summarize general areas of research in which SHWRD and its predecessors have been involved.

FY'79 Program

Only two research projects were initiated in FY'79: One involved a design for safely venting explosions in MSW shredders, and the other dealt with conveyors for moving various fractions of MSW.

Though budget constraints caused the project for venting shredder explosions to be considerably reduced in scope, it made the best use of limited research funds by developing design recommendations to minimize damage and danger from the explosions. The conveyor project originally was intended as a systematic study of materials handling during processing MSW for recovery, but budget reductions prevented all but the first phase from being conducted. Some data will nonetheless be produced for use in designing MSW conveyors.

Other FY'79 efforts were carry-overs funded in earlier years. These projects included, among others, completion of RCRA 8002 special studies of small-scale low-technology, MSW quantity and composition studies, source separation and mixed waste processing, glass and plastic recycling, impediments to economical resource recovery, and research priorities for energy and materials recovery. Updates will be provided for the last three projects listed.

During FY'79, support was continued for the American Society for Testing and Materials (ASTM) in developing consensus standards for secondary materials. Further reports will be made on this extremely important activity.

FY'80 Program

The SHWRD FY'80 activities in resource recovery were limited to nine projects carried over from previous years and one new project, these are listed by category as follows:

Facilities and equipment design:

1. Comparative study of selected full-scale air classifiers
2. Test and evaluation of New Orleans Recovery I facility and equipment
3. MSW full-scale shredder field testing
4. MSW shredder explosion protection (venting designs)
5. Engineering design for MSW conveyors
6. Engineering design manual for MSW size reduction (new project)

Refuse-derived fuels (RDF):

7. Fundamental considerations for the production of densified refuse-derived fuels (dRDF)
8. Selective enhancement of RDF

Secondary materials specifications:

9. Development and testing of consensus standard procedures for testing and analysis of secondary materials (in support of ASTM E38)

Other:

10. Priorities Study - RCRA Section 8002 (NAS)

During FY'79 plans were made to discontinue our research program as systematically and carefully as possible by providing resource recovery engineering design manuals in five areas (MSW size reduction, screening, air classification, front-end systems/processes, and combustion systems for RDF/dRDF).

Subsequent budget constraints limited us to a single manual, so we chose to produce one for MSW size reduction, because we had supported studies in this area from the experimental phase through field evalutions. Our research activities in MSW size reduction serve as the basis for one of the presentations. Other summary papers given on our past research support include the following:

- o Air classifiers
- o Production process for RDF/dRDF
- o Combustion of RDF/dRDF
- o Conversion of cellulosic wastes to useful products
- o Upgrading of pyrolytic oils
- o Gas from MSW/Sewage Sludge
- o Waste-to-energy systems
- o Health and safety aspects of resource recovery
- o User Charge Studies

Though it is impossible to give detailed results of all studies, we hope that the summaries will provide insight into the past resource recovery activities of SHWRD and its predecessors. Some activities have led to significant accomplishments, and others have only formed the basis for continuing efforts.

SUMMARIES OF RESOURCE RECOVERY ACTIVITIES

To provide a systematic approach to summarizing SHWRD activities in the field of resource recovery, we have grouped projects in the following four categories: MSW mechanical processing, chemical/bioconversion techniques, waste-to-energy conversion systems, and impediments to resource recovery. Only the highlights of these major areas are discussed.

MSW Mechanical Processing

Mechanical processing of MSW involves such unit operations as size reduction, conveyance, density classification (including air and water), and others. Research, development, and demonstration in this area have been somewhat fragmented and have not yielded sufficient information to enable design engineers, architects, city planners, etc. to select with confidence the equipment, unit operations, or systems they need. For example, few or no comparative data are available regarding the design and operational characteristics of density separators such as air classifiers.

Research on Separation Techniques--

SHWRD research related to the separation of various components of MSW from the total stream has involved:

1. Assessments of separation methods and equipment available;

2. Studies of the technical feasibility of using air classification to separate dry solid waste materials;

3. Refuse reclamation by means of automated procedures to code and separate the waste materials; and

4. Hydropulping and wet separation.

Some projects represented the first attempts at investigating the mechanisms involved in recovering MSW components. Although useful data were generated, early efforts suffered using simulated MSW, which very seldom reacts as does the actual MSW. This problem was especially evident in the coding/automatic separation projects. Attempts at selective coding and automatic separation of the coded MSW components failed with the dirty, contaminated MSW items but succeeded with the cleaner, simulated waste items. In many instances, attempts to adapt existing equipment to the processing of MSW were unsuccessful, resulting in facilities that were undersized, underdesigned, and unsuitable.

In 1968, the technical feasibility of an air classification process for separating dry solid waste materials was studied. The research was preliminary and confined to dry solid wastes, whose behavior was much different from the actual wet MSW. The project did provide some design considerations for zig-zag air classifiers. However, some alternative air classifier design configurations did emerge and were used.

Users later found that precise separations by air were probably not possible with current technology, and alternatives for removing fines were considered. Other research needs were:

- Full evaluation of the ability of air classification to produce selective separations;
- Establishment of design and operating conditions required to achieve the desired separation; and
- Comparative evaluations of design and engineering operating/maintenance performance characteristics of alternative air classifiers.

SHWRD was unable to support directly any research on the basic theory of MSW air separation techniques. But in 1977, the Office of Management and Budget (OMB) provided supplemental funds specifically designated for evaluation of operating large-scale resource recovery systems, equipment, and processes. A portion of the funds provided to SHWRD were used to conduct evaluations of full-scale air classifiers. The hope was that useful information could be provided for better equipment selection, design, and operation. The air classifier evaluations are summarized in this symposium.

Size Reduction Studies--

Size reduction is an important unit operation for processing MSW. At first the industry believed that existing stone crushers and grinders would prove to be more than adequate for reducing MSW. To the contrary, hammers wore excessively, grate bars broke, metal surfaces corroded, and the equipment used caused problems in general. MSW grinding costs were relatively high.

As it became apparent that size reduction of MSW was not an easy unit process to accomplish and required better understanding, some grinding projects were initiated in New York City and at Johnson City, Tennessee. These projects developed useful data but were not adequately designed to develop the basic understanding of size reduction that was needed.

Research was initiated at the University of California to study the theoretical relationships involved in size reduction of MSW. This study represents one of the very first attempts to conduct systematic solid waste research. The project has yielded excellent data and provided basic relationships useful in the design and operation of MSW size reduction equipment.

The OMB funding supplement for large-scale systems provided SHWRD an opportunity unique to our resource recovery research program. Although the research and pilot-scale studies had yielded basic shredder design and operational information, the data were not confirmed by field studies. In addition, good sources of comparative design and performance data on available operating equipment were not readily available. A portion of the OMB supplement was used to conduct performance evaluations of operating full-scale MSW shredders. Summaries of these investigations and evaluations are included in this symposium and as mentioned earlier, an engineering design and operating manual for MSW size reduction will be available late in 1981 documenting one of the very few areas of research we have been able to carry from the laboratory through field verification.

Other Processing Studies--

Other EPA-supported studies of MSW mechanical processing include evaluations of magnetic separations, ferrous metal recovery, aluminum separators, glass sorting, virbrating and rotary screening, dRDF production, and others. Results of many of these studies have been published, and others will be available soon.

Uses of Recovered Wastes--

Possible uses for recovered wastes are:

- Use of the materials as recovered (i.e., paper, glass cullet, cardboard, aluminum, etc.)
- Conversion of wastes to new products other than energy (i.e., cellulosic waste to protein, organic waste to compost, fermentation/conversion of waste to chemicals, waste glass to foam glass insulation, agricultural waste to building products, etc.)
- Use of waste as fuels/energy (i.e., direct firing of MSW as supplementary fuel with coal for energy production, conversion to oils and gases as in pyrolysis, generation of methane as in anaerobic digestion, recovery of methane from landfills).

Research to determine acceptable uses for as recovered waste materials has been sporadic, but some efforts have been expended to find uses for wastes such as wood bark, scrap tires, plastics, glass, aluminum, ferrous metals, and others. Though useful information was generated, lack of sufficient funds made it impossible to carry the projects through the development and demonstration phases.

SHWRD sponsored research for several years on the use of waste glass in structural clay brick manufacture. The composition of the waste glass recovered (typically 10% to 30% organics) has been evaluated both technically and economically with respect to the manufacture and furnace curing of the bricks. The use of waste glass slimes now appears technically feasible for this purpose, and energy requirements in the brick-curing stage have been reduced.

Mandated RCRA special studies resulted in reports on the status of glass and plastic recycling in the United States, as well as in assessment of the recovery and disposal of discarded tires. This symposium includes a presentation on glass and plastic recycling. Results of the tire study indicate that the tire market structure is important in determining collection and resource recovery practices in all the discarded tire technologies available. Authors of the report have thus recommended that a surcharge be issued for new tires, with the resulting proceeds to be distributed to qualified disposers.

Chemical/Bio-Conversion Techniques

Conversion of wastes to other useful materials is an intriguing resource recovery alternative. SHWRD has conducted limited research in this area, including composting, bio-conversion, chemical conversion, pyrolysis, and similar techniques to yield products more valuable than the original waste materials. These projects have varied from converting waste glass to foam glass insulation to converting cellulosic waste to protein as a food source. Many of these projects proved to be impractical, and others were not supported sufficiently to yield worthwhile benefits.

Hydrolysis--

The production of alcohols and other useful chemicals from the hydrolysis of cellulosic waste is a research area that has yielded some potentially worthwhile benefits. SHWRD's support of both enzymatic and acid hydrolysis research has resulted in the conclusion that acid hydrolysis has good potential for conversion of cellulosic waste to useful products. After study with a 1 liter and 5 liter reactor, and 1 ton per day pilot plant, it was determined that cellulosics pretreated with 1 percent sulfuric acid at temperatures around 450°F yielded up to 50 percent conversion to glucose in reaction times as short as 10 to 20 seconds. In addition, the sugars produced appear to be convertible to ethyl alcohol and single-cell proteins. Limited efforts in these areas are continuing, and the Department of Energy (DOE) may support additional work. Some of SHWRD's efforts will be presented in the symposium.

Pyrolysis--

One of the problems associated with the pyrolysis of waste is the low grades of oils, gases, and chars often produced. To improve the economics of selected pyrolysis processes, SHWRD supported research to upgrade the quality of pyrolysis products, especially oils. Some of these efforts are also summarized in this symposium.

Waste-to-Energy Systems

Potential Energy Yields from Waste--

The estimated quantities of MSW produced in the United States range from 130 to 150 million tons per year. At 150 million tons, MSW contains approximately 1.35×10^{15} BTU's, or about 1.5 percent of the energy used in the United States (about the amount used for residential and commercial lighting). The BTU content of each ton of municipal solid waste is roughly 1.3 barrels of oil equivalent (BOE), which is a popular way of expressing alternative energy amounts. If we recovered energy from about half of the available waste streams, the yield would equal approximately 250,000 to 278,000 BOE per day.

Possible Approaches--

Several technologies are available for converting waste to energy. Early approaches in the United States included the CPU-400 gas turbine, mass burning (at Norfolk, Virginia), processed RDF (at St. Louis, Missouri), and pyrolysis (Torrax, Purox, Landguard, and Bureau of Mines). More recent approaches include unprocessed waste combustion, processed RDF (fluff and densified), pyrolytic conversion, methane gas conversion, and small modular combustion. Most of these processes have been used in a variety of commercial applications.

SHWRD, its associates, and its predecessors have supported various projects relating to RDF and recovery of energy from waste. Examples of these projects are the use of fluff RDF with pulverized coal in St. Louis, Missouri, and Ames, Iowa, and the use of dRDF with lump coal in institutional and industrial stoker boilers. The production and use of RDF will be summarized in the symposium.

Economic Factors--

The availability of energy affects the economics of waste-to-energy conversion, and thus the currently constant rise in energy costs provides an increasing incentive for recovering the energy value of waste. The concept of barrels of oil equivalent (BOE) (i.e., the amount of oil that could be saved if the waste replaced the oil) may exaggerate the energy impact of waste-to-energy conversion. Most MSW, particularly the RDF approach, replaces coal and not imported oil. Though the energy problem may be long-term, the current crisis really involves a pricing problem in the liquid fuel market. MSW is converted to energy less efficiently than are fossil fuels, and energy from MSW does not come without cost. The waste must be processed into a usable form.

Costs affect waste-to-energy systems in several ways. Most waste-to-energy plants, particularly processed fuel types, are capital intensive. Construction funds often must come from bond issues requiring voter approval, which may partly account for the popularity of the contractor-owned/operated-for-fee plants. Earlier systems usually ran into difficult economic problems, and these poor economics still cause implementation problems today.

Many today argue that waste-to-energy conversion is an energy production process. But most waste-to-energy projects were originally conceived in response to the need to find an alternative waste disposal method. Some type of land disposal option is normally cheaper, assuming that land is available. Therefore, in many areas of the country, waste-to-energy systems are not politically supported because landfilling is still considerably cheaper. Even though long-term considerations may warrant it, decision makers face serious problems when they attempt to increase the costs for disposal of the community's solid waste.

In the past systems, the most logical customers have been the utilities. But in reality, the utility customer already has the lowest per-unit fuel costs and the least economic incentive for purchasing RDF. Waste-to-energy technologies may thus have to be more tailored to the smaller industrial and institutional customers.

Operational Problems--

Another factor affecting waste-to-energy conversion involves operational history. Very few of the plants listed as operational are really processing waste and producing energy on a daily basis. For a long time, the Ames, Iowa, plant was the only RDF plant operating in the United States on a daily basis. Long project implementation, start-up, and shake-down periods, cost overruns, and operational unrealiability are all factors that tend to make people lose interest rather quickly in waste-to-energy conversion plants. System suppliers have limited experience, since few have made second installations, and little or no concensus exists on a standard system design. The same design and operating mistakes appear again and again, as suppliers do things for the first time. Many plants are designed for nominal quantities of waste that have some average characteristic (i.e., moisture) that may be seen in operation. But operational problems occur at extremes. For example, if the quoted average of 8.25 percent of steel per month comes in the form of 1 ton of steel cable at one time, havoc strikes the shredder. Publicity has probably played a role in aggravating such problems. The plant should not be expected to run immediately: People and machines must be conditioned to run properly.

Environmental Concerns--

Environmental concerns will also affect waste-to-energy systems. This concern is broad, however, and not conclusive. The net environmental effect of waste-to-energy conversion appears to be positive with respect to air pollution, since regulated pollutants can be controlled. But concern exists about the increased discharge of some trace elements from waste-to-energy plants. A true environmentalist may be skeptical about constructing a large, capital-intensive plant that for many years will require large quantities of solid waste to recover the initial investment. Perhaps source separation would be a better environmental solution. Even so, one of the most promising resource recovery options today is the use of waste as a fuel. The option may provide a means for selected communities to offset part of their solid waste management costs.

Gas Recovery From Landfills--

One of the more successful resource recovery technologies has been the recovery and the use of landfill gas. Because of the economic and technical viability of this process, 11 landfill gas systems have come on line since 1975. SHWRD has participated in this research area by funding studies for enhancing gas production, controlling and measuring corrosion, and improving gas recovery and gas cleanup. Areas of future interest are measuring and controlling air and water emissions from the landfill gas treatment processes and improving techniques for prediction of landfill gas production. These efforts will be further described during the symposium.

Impediments to Resource Recovery

Economic and Socio-Instutional Impediments--

Perhaps the key factor to increasing the successful implementation of resource recovery is economics. If markets are available and offer a fair price, the profit motive will normally spur an increase in the amount of waste materials recovered (assuming that a reasonable techology is available). In cases where technology is lacking, a strong enough profit motive may spur the development of needed technology. On the other hand, technology development may provide an increased economic incentive by providing the recovered materials at a lower cost.

Interacting with the economics and the technology are institutional and social conditions that may either spur or deter implementation of resource recovery. Historically, the socio-institutional factors have been barriers to resource recovery. An example would be procurement specifications requiring the use of virgin materials rather than technically acceptable secondary material recovered from wastes. In some cases, fictitious institutional and social barriers may be the scapegoats for poor technology and/or poor planning. But, as the economics of resource recovery improve, social and institutional impediments may disappear or at least diminish in scope. The point to be noted is that the interactions among resource recovery technology, economics, and the socio-institutional factors are complex.

Although not as comprehensive as needed, SHWRD-supported research on the social-economic-institutional aspects of resource recovery has been conducted. These studies have included, among others, (1) projects to identify the socio-economic classes of society most or least likely to participate in source separation; (2) studies of the effects of user charges on MSW management (including resource recovery); (3) investigation of beneficial freight rates for secondary materials; (4) feasibility studies of future markers for scrap materials, and (5) studies of energy conservation through waste reduction.

The most recent study in this category was in response in Section 8002 of the RCRA. The study was designed to identify impediments to economical resource recovery facilities and it will be presented during this symposium. Findings should be of extreme interest to those concerned with implementing resource recovery projects.

Lack of Standards--

One of the impediments to the use of secondary materials is the lack of good standards for characterizing the value of the product. ASTM Committee E38 on Resource Recovery is developing consensus standards for materials and energy products recovered from waste. These standards will provide a common basis for determining the true market value of a recovered product. SHWRD is assisting with funding support to conduct testing of draft standard procedures, short-term special investigations, and associated activities. At the Orlando symposium in 1978, the project report emphasized RDF standards that were under development. Additional draft RDF standards have been developed, and activities associated with other secondary materials are being supported.

This very important ASTM project represents a noteworthy example of government cooperation with a consensus standard setting organization. In addition, because of the voluntary nature of ASTM, the return on funds invested is extremely high. This project will be updated during the symposium.

Inadequate Research and Assessment--

Adequate technical assessments and confirmation of technical feasibility are inherent to implementation of all technology, including resource recovery. Basic concepts must usually be researched at the laboratory scale, further researched and developed at the pilot scale, and finally confirmed and demonstrated on the production scale. Researchers should be an integral part of both pilot-scale and demonstration projects to ensure that the proper data, information, experimentation, and other aspects are considered. This would assist researchers to devise sound research projects for meeting development and production needs.

Opportunities for EPA research involvement in large scale resource recovery demonstrations and field studies have been limited. Nevertheless we have supported some large scale research evaluations of air classifiers, MSW shredders, selected processing equipment and processes at Recovery I in New Orleans; Ames, Iowa; St. Louis and other locations. Presentations will summarize selected portions of these evaluations.

SHWRD also supported research evaluations at the St. Louis and Ames, Iowa fluff RDF combustion processes. SHWRD sponsored the largest demonstration of dRDF combustion yet conducted at an industrial power plant at Erie, Pennsylvania. These studies will be summarized in this symposium with emphasis placed on the Erie, Pennsylvania, dRDF test burns.

Although inadequate, the research involvement in such large projects has helped to identify some technological impediments to economical resource recovery plants. It has also helped to confirm that omission of the required research or pilot-scale phase in the cycle may result in production plants that work inefficiently or not at all. At best this course of action results in long and expensive start-up and shake-down periods. Some researchers suggest that EPA's large scale demonstration projects would have had a better chance for success with proper research input.

Environmental Concerns--

Environmental concerns such as pollution control are major factors in resource recovery and can act as impediments. SHWRD and associated organizations have conducted several studies to assess the environmental aspects of resource recovery. A summary of waste-to-energy emissions and their control will be given at this symposium. Also to be presented is a discussion of the health and safety aspects of resource recovery.

Early SHWRD efforts in this area included investigations of pathogenic organism survival in composting processes and pathogens in solid waste landfills. More recent efforts include the St. Louis bacteria-virus study, which compared levels of bacteria from the St. Louis refuse processing plant with levels of bacteria at other solid waste handling facilities. This particular study was part of the basis for the formation of subcommittee E38.07 (Health and Safety), which is part of ASTM Committee E38 on Resource Recovery. The committee is concerned with providing a focal point for the rational considera- of health and safety aspects of the resource recovery industry. The sub-committee is in the process of developing several consensus standards for MSW microbiological measurements and MSW shredder explosions. Some of these studies will be summarized during the symposium.

CONCLUSIONS

A review of EPA-supported research in the field of resource recovery reveals limited opportunities for progress. This is attributed largely to low research priority ranking in favor of hazardous waste research, that resulted in constrained and unsteady funding. The low ranking was partially attributed to the lack of well defined national research goals which recognized the need for support of technological developments in municipal solid waste management, particularly resource recovery. In spite of these constraints, some sound and worthwhile technical progress has been made.

Though current emphasis on hazardous waste in essential to EPA's chief goal of protecting the environment and public health, resource recovery is also important to this mission. SHWRD, therefore, believes that a research program for resource recovery should be on-going.

HIGHLIGHTS OF SHREDDER RESEARCH IN RESOURCE RECOVERY PROCESSING

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ABSTRACT

Size reduction is widely utilized in the refuse processing industry. Much of the research on refuse size reduction thus far has been conducted under the auspices of the U.S. Environmental Protection Agency. This paper describes some of the key areas that have been under investigation, including analytical relationships, energy consumption, wear, and methods to compare and evaluate various shredders.

Introduction

Most of the size reduction equipment used in the refuse processing industry has been adapted from the mineral processing industry where it was used to comminute brittle homogeneous materials such as rocks and ores. Unfortunately, approximately 75 percent of the materials found in the solid waste generated in the United States are non-brittle. Consequently, the fact that a shredder, such as a hammermill, could effectively process brittle materials did not necessarily mean that it could be equally as effective in processing the heterogeneous mixture of brittle and non-brittle materials that constitutes solid waste.

A number of problems were encountered when hammermills were first used to size reduce solid waste. These problems included excessive jamming, extreme wear, explosions, and the inability to both control particle size and achieve rated throughput.

Heretofore, the refuse processing industry only had a superficial understanding of the basic comminution parameters and of the methods for their evaluation and control. Fundamental issues such as the relationship between power and throughput, factors that affect product size, the effect of changing the number of hammers or grate spacing, and methods to control and reduce maintenance costs remained essentially unknown.

The U.S. Environmental Protection Agency, realizing the increasing importance of size reduction in waste processing for material and energy recovery and recognizing the paucity of basic information on the subject, sponsored a series of studies for the purpose of rectifying the situation.

Test Programs

The performance of a size reduction device can be characterized by the parameters that affect the comminution process. The data base necessary to quantify these parameters was developed over the last decade through a systematic research program. The program involved an initial period of pilot-plant work followed by several phases of full-scale field tests.

The pilot studies were conducted, by the authors, at a research facility located in Richmond, California. Data collected during these studies were used to: 1) establish fundamental principles, 2) determine the dependent and independent variables involved in the comminution process, and 3) arrive at mathematical relationships between the vari-

TABLE 1. KEY VARIABLES IN THE COMMINUTION PROCESS

Independent Variables	Dependent Variables
Size Distribution of Feed	Specific Energy Consumption
Throughput	Product Size Distribution
Moisture Content of Feed	Machine Wear
Grate Spacing	
Relative Velocity of Size Reduction Devices	

ables. Both the dependent and independent variables in size reduction are presented in Table 1.

The next phase of the program involved a number of field tests of large-scale shredders located throughout the country. The tests were conducted under normal operating conditions at throughputs that were about an order of magnitude larger than in the initial studies. The main objective of the field tests was to serve the needs of the plant manager and the design engineer. This was accomplished by developing predictive relationships, design criteria, evaluation techniques, and levels of performance for large-scale shredding equipment. The location of the test sites and the values of important parameters are summarized in Table 2.

<u>Measurement and Predictive Capabilities</u>

The research program has allowed for the development of a number of measurement techniques and predictive relationships that can be used in the industry. Special equipment capable of measuring power consumption has been designed and built. It is adaptable to single phase, three phase-three wire and three phase-four wire systems. This equipment can provide a continuous record of power draw from shredders as well as other processing equipment. The central component of the instrumentation is a watt/watt-hour transducer which provides two output signals. The first, an analogue current signal which is directly proportional to power, is recorded, after conditioning, on a chart to provide both a time base and a permanent continuous record of power. A measurement of energy is obtained from the second signal which is digital and directly proportional to the integral of power over time. The flexibility, modularity, and portability of the power measuring equipment address the unique requirements found in testing and evaluating systems in large-scale facilities. Techniques and procedures have also been developed to obtain and evaluate size distribution, to select a minimum sample size required for analyses, to predict the influence of moisture content on size reduction, and to measure wear.

Mathematical expressions that describe some relationships between key comminution parameters have been established. For instance, it has been determined that the net power required for size reduction (P_N) is related to the throughput (Q_W-on a wet basis) and to the air dry moisture content of the waste (MC) by the following empirical relationship:

$$P_N = a\, Q_W^r\, (1 - MC)^s$$

For the shredders evaluated in the field tests, the constants a, r, and s have the following range of values: $0.14 \leq a < 47$, $0.27 < r < 1.9$, and $-12.6 < s \leq 4.8$. Care must be exercised in using the above relation for P_N due to the large range of the coefficient a, which we believe to be dependent upon the particular machine configuration, i.e. grate size, internal machine geometry, and number and geometry of hammers. The details and further refinement of this expression is under investigation.

The specific energy is consumed in shredding refuse can be expressed in terms of either the characteristic (X_0) or the nominal (X_{90}) size of the product as follows:

$$E_0 = bx^u$$

TABLE 2. SUMMARY OF AVERAGE VALUES OF IMPORTANT PARAMETERS

Shredder Installation	Throughput (tons(wet)/h)	Product Size Characteristic (cm)	Product Size Nominal (cm)	Specific Energy (kWh/ton)
Appleton East	24.8	3.7	9.8	3.4
Appelton West	18.1	5.6	11.2	3.9
Ames Primary	18.6	5.0	12.1	5.5
Ames Secondary	22.4	1.3	3.3	10.8
Cockeysville	49.5	2.1	6.2	10.0
Great Falls (20 ton/h)	14.8	2.4	5.6	6.4
Tinton Falls	60.8	3.8	9.6	2.3
Odessa	82.0	3.2	9.2	1.1

Analyses of laboratory and field test data indicate that when the energy is expressed in terms of kilowatt hours per ton (kWh/T) and the size in centimeters (cm), the coefficients b and u have the following values: for specific energy expressed on a dry basis (E_0), b = 23.3 and 49.9, u = -0.92 and -0.86 for X_0 and X_{90} respectively, for specific energy expressed on a wet basis (E_{0w}), b = 17.9 and 35.6, u = -0.90 and -0.81 for X_0 and X_{90} respectively.

Characterization of the comminution process can be further explained by additional parameters, two of which are residence time and mill holdup. The amount of time that material remains within the shredder has a pronounced influence on the product size distribution. Typically, this residence time is expressed as a distribution of the probable time a particle resides within the comminution device, R(t). In a hammermill with an integral set of grates, the spacing can be varied to change the particle size of the product. Because of the action of the hammers, the material within the shredder is well mixed precluding size stratification. Consequently, within the limits of this condition, the residence time distribution can be assumed to be independent of particle size. Thus, the grates act as a classifier or screen, allowing those particles smaller than the grate spacing to go through and returning the remainder to the comminution zone where the residence time distribution that is applied to the feed is again applied to the recycled material. The mean residence time may be determined from either the residence time distribution or the following equation

$$T = 3.6\ (H/Q)$$

where T is the mean residence time (sec), H is the mill holdup (kg) and Q is the flowrate (tons/h). Laboratory-scale testing has provided evidence to indicate that the form of a normalized residence time distribution R(θ) is not affected by flowrate. The residence time, R(t), and the normalized residence time, R(θ), distributions are related through the expression:

$$R(t) = R(\theta)/T$$

The mill holdup (H) is essentially the instantaneous mass of material within the shredder. Both the dynamics of shredding and the highly compressible nature of municipal solid waste provided the motivation for exploring the possible existence of a general relationships between flowrate and holdup. Test data have shown that an expression of the form

$$Q = kH^n$$

may be valid. In this expression, both k and n are constants. In general, k is affected by the grate spacing, the space between the grate bars, and the total cross-sectional area of the grate bars. Once mill holdup was recognized as an important parameter for characterizing refuse size reduction, its measurement was incorporated into the second phase of field tests. Even though limited data are available on mill holdup, the effects of grate geometry on the above relationship is currently under investigation.

Empirical relationships linking throughput to particle size are also being developed. Having established the relationships, it will then be possible to relate both power and energy to holdup and particle size. Expressions of this nature will provide a framework for addressing the second generation of problems now being encountered in the industry. Typically these problems are classified in the category relating to equipment not performing according to specifications. Either the rated throughput cannot be achieved (sometimes a factor of two too low) or the particle size is larger or smaller than required. Another set of problems involves optimization of multiple-stage shredding. Correcting these problems usually involves changing the grate spacing, hammer configuration, or both. The manner in which these changes are made can be costly. Having established reliable predictive techniques will eliminate the heretofore trial-and-error practices.

Several non-dimensional quantities were developed in order to compare various types and configurations of machines. One such parameter is defined as the degree of size reduction (Z_0) which is defined as:

$$Z_0 = (F_0 - X_0)/F_0$$

where F_0 and X_0 are characteristic feed size and product size respectively. The parameter (Z_0) has been found to be useful in generalizing the size reduction data obtained over a wide range of operating conditions. The nature of Z_0 is such that it approaches unity as X_0 goes to zero, and approaches zero as X_0 approaches F_0. To complete the generalization, an additional non-dimensional parameter is required and can be formed by the ratio of the grate opening size (D_0) to the characteristic feed size (F_0), that is, D_0/F_0. The parametric nature of the comminution process with grate opening size is shown in Figure 1. In the figure, the degree of size reduction (Z_0) is represented in terms of D_0/F_0. Essentially, for a particular value of D_0/F_0, the value of Z_0 increases as the size of the grate openings increase. In essence, a smaller characteristic particle size is produced as the grate openings increase in size. This trend holds true for raw MSW as well as for air classified and screened fractions. It is important to note that a complete explanation of this seemingly contradictory effect requires consideration of the interactive features of holdup, residence time, and throughput on particle size.

Using the laboratory data as an example, a further appreciation of the relationship between the energy and size variables (E_0, Z_0, and D_0/F_0) can be obtained from the non-dimensional diagrams shown in Figures 2, 3, and 4, for the size reduction of raw MSW, air classified light fraction (ACLF), and screened light fraction (SLF) respectively. The motivation for combining these three variables stems from the fact that the ratio of grate opening to characteristic feed size specifies both degree of size reduction (which characterizes the product size) and energy consumption. Consequently, one figure provides both the energy required for size reduction and the resulting size of the product when the type of material, feed size, and grate opening size are specified. A comparison of these figures shows that for a given value of D_0/F_0, the steepness of the curves for Z_0 and E_0 is generally the greatest for the SLF, followed by the ACLF, and more distantly by the SLF. The reason for the relatively high energy requirement and small degree of size reduction for SLF may be attributed to the fact that fiber makes up more than 75 percent of this fraction.

This situation may also be viewed in terms of the following two cases. In the first case, 2.5-cm (1.0-in.) grate openings and a D_0/F_0 ratio of 0.2 result in a decrease in the degree of size reduction from 0.93 for raw MSW to 0.86 for SLF (Table 3). In addition, the specific energy increases from 67 MJ/metric ton (17 kWh/ton) for raw MSW to 154 MJ/metric ton (39 kWh/ton) for

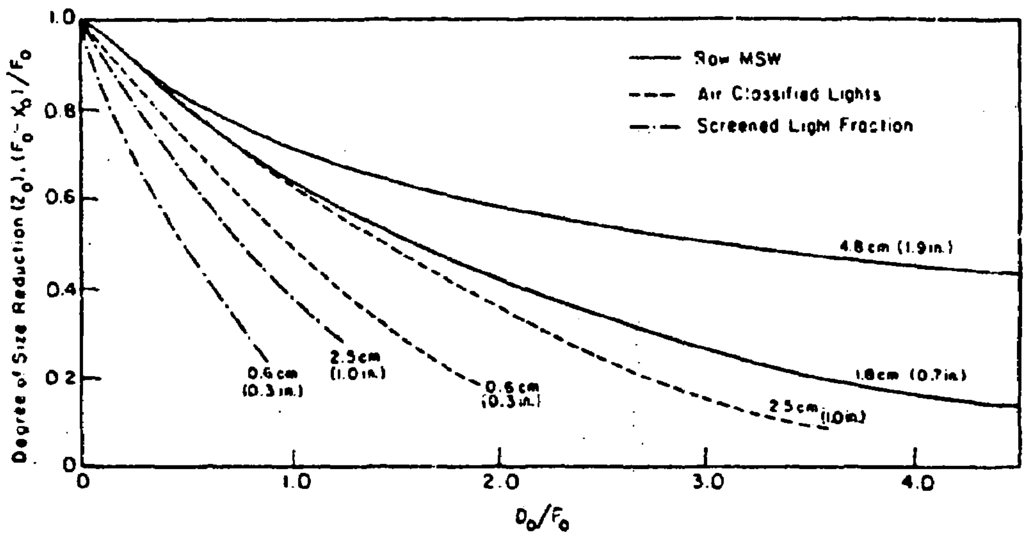

Figure 1. Degree of size reduction as a function of the ratio of grate spacing to characteristic feed size for raw MSW, ACLF, and SLF.

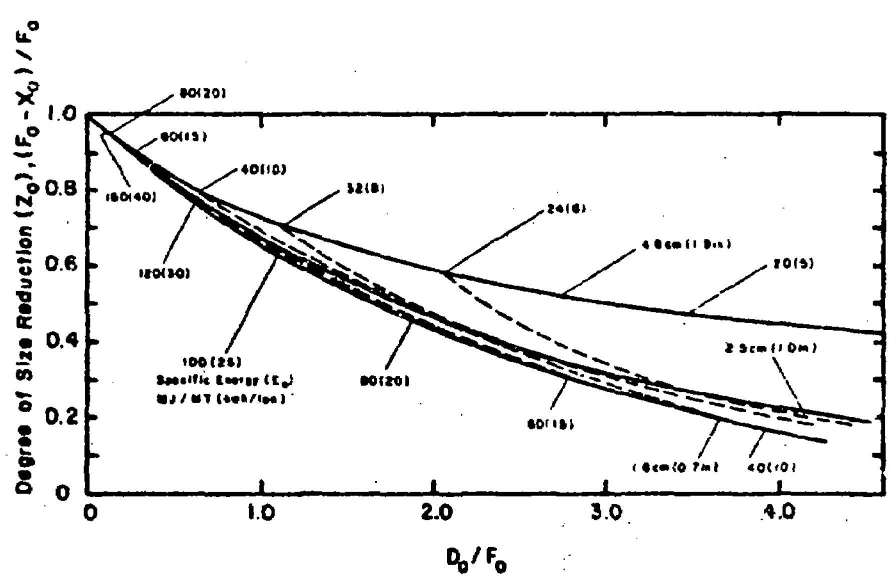

Figure 2. Degree of size reduction as a function of the ratio of grate opening to characteristic feed size for raw MSW.

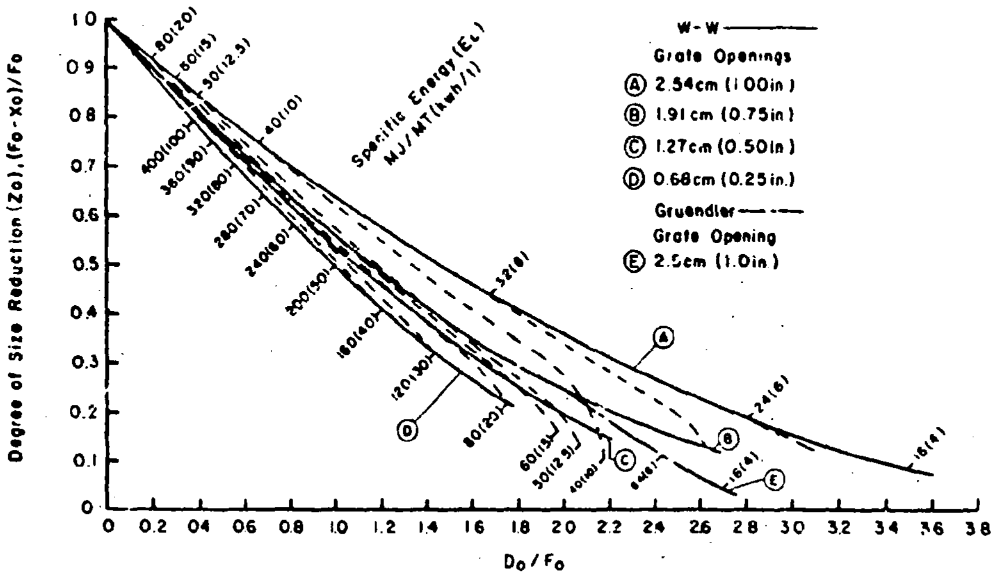

Figure 3. Degree of size reduction as a function of the ratio of grate opening to characteristic feed size for ACLF.

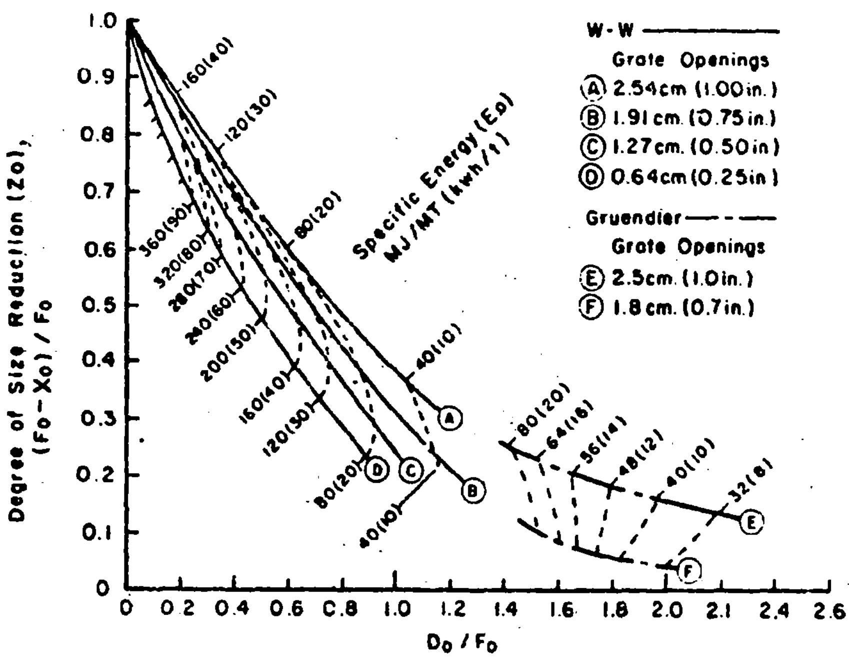

Figure 4. Degree of size reduction as a function of the ratio of grate opening to characteristic feed size for SLF.

TABLE 3. COMPARISON OF DEGREE OF SIZE REDUCTIONS AND SPECIFIC ENERGY FOR DIFFERENT SOLID WASTE FRACTIONS

D_o cm	D_o (in.)	D_o/F_o	Material	Z_o	E_o MJ/metric ton	E_o (kWh/ton)
2.5	(1.0)	0.2	Raw MSW	0.93	67	(17)
2.5	(1.0)	0.2	ACLF	0.92	79	(20)
2.5	(1.0)	0.2	SLF	0.86	154	(39)
2.5	(1.0)	0.8	Raw MSW	0.72	37	(9)
2.5	(1.0)	0.8	ACLF	0.71	40	(10)
2.5	(1.0)	0.8	SLF	0.48	59	(15)

TABLE 4. NORMALIZATION OF HAMMER WEAR MEASUREMENTS

Shredder	Alloy Hardness (R_c)	Average Characteristic Feed Size (F_o) (cm)	Average Characteristic Product Size (X_o) (cm)	Average Degree of Size Reduction (Z_o)	Hammer Wear (W_o) (kg/T_w)
Appleton West Mill Horizontal Hammermill	28	12.7	5.6	0.56	0.0034
	38	12.7	5.6	0.56	0.023
	48	12.7	5.6	0.56	0.016
	56	12.7	5.6	0.56	0.0013
Cockeysville Shredder #1 Horizontal Hammermill	28	20.3	2.0	0.90	0.057
	38	20.3	2.0	0.90	0.043
	34	20.3	2.0	0.90	0.031
	56	20.3	2.0	0.90	0.023
Great Falls Vertical 20 TPH Hammermill	28	12.7	2.4	0.81	0.056
	38	12.7	2.4	0.81	0.044
	48	12.7	2.4	0.81	0.033
	56	12.7	2.4	0.81	0.025

SLF. The second case assumes the same grate spacing, 2.5 cm (1.0 in.), and a D_0/F_0 of 0.8. For these conditions, raw MSW and ACLF yield similar degrees of size reduction and energy requirements (namely, Z_0 values of 0.72 and 0.71, and E_0 values of 37 and 40 MJ/metric ton (9 and 10 kWh/ton). However, the SLF yields considerably lower Z_0 values and a considerably higher value of E_0 than those for the other two materials.

Studies designed to evaluate machine wear were also conducted in both the laboratory and field tests. A comparative evaluation of hardfacing materials in terms of the degree of size reduction of raw and screened light fraction is shown in Figure 5 . Information on hammer wear obtained from the field tests is summarized in Table 4. A convenient method for representing test data gathered at different sites is shown in Figure 6. This method allows for a comparison of wear data collected from equipment shredding where different types of solid waste under various operating conditions. The general conclusion that can be drawn from the data in the figure is that hard alloys yield significant reduction in hammer wear. For example, if an alloy with a hardness of 56 R_C is used instead of an alloy with a hardness of 28 R_C, a reduction of 60 percent can be achieved. For an equivalent amount of material worn from the hammers, this 60 percent reduction in wear for hammers that are coated with the harder alloy corresponds to an operating time that is 250 percent of that for hammers coated with the softer alloy.

Conclusions

A systematic research program on refuse size reduction has been conducted during the past several years. The research was conducted on both pilot and full-scale plants.

The pilot-scale research was aimed at establishing fundamental principles and relationships between key variables in refuse size reduction. The full-scale test program involved the verification of the relationships developed in the pilot plant studies. Furthermore, the tests were designed such that the results would serve the needs of the refuse processing industry. Information acquired as a result of these studies included evaluation techniques and design criteria.

In the course of the research, equipment especially designed to measure power consumption was developed. Mathematical expressions linking major communication parameters were established. Non-dimensional parameters have also been developed to allow for the comparison of various types of shredders. Maintenance and operating costs, particularly those related to power consumption and wear, have been identified.

The next phase of this work will deal with the preparation of designs aimed at fulfilling the needs of the user community.

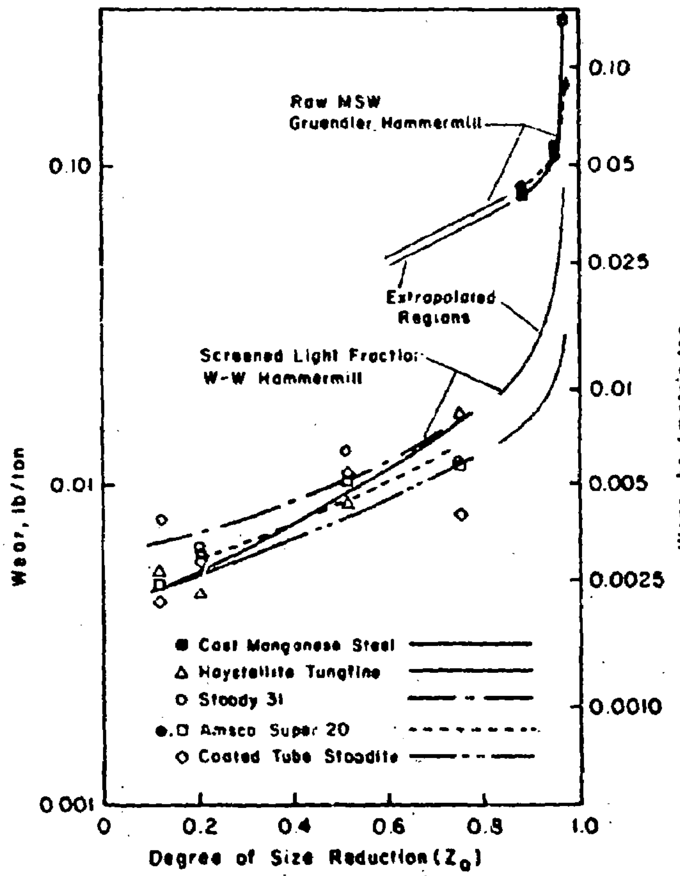

Figure 5. Hammer wear as a function of degree of size reduction for raw MSW and SLF.

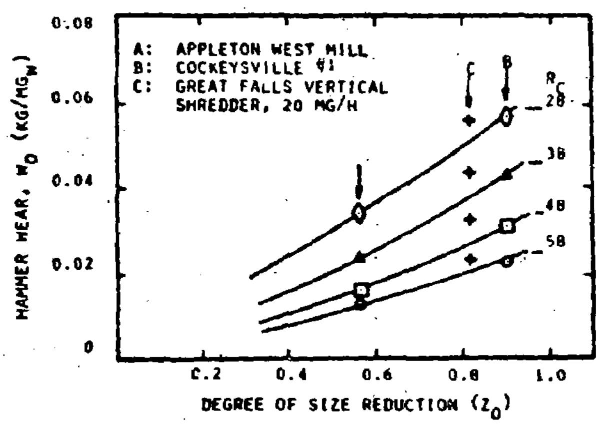

FIGURE 6. HAMMER WEAR AS A FUNCTION OF ALLOY HARDNESS AND DEGREE OF SIZE REDUCTION

EXPLOSION VENTING TEST PROGRAM FOR MUNICIPAL SOLID WASTE SHREDDERS

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ABSTRACT

A gas explosion test program is currently being conducted in a realistic full-scale mock-up of a municipal solid waste shredder. The 2200-ft^3 (61 m^3) mock-up simulates a horizontal shaft hammermill (including rotating shaft, discs, and hammers) with a large inclined feed hood. Varying amounts of propane have been injected into the shredder and the resulting gas concentrations generated by rotor-induced mixing have been measured. Results of gas mixing tests with unobstructed feed and discharge areas indicate that gas accumulations in the flammable range are most likely to occur at the ends of the shredder shaft. Seven explosion tests have also been conducted to date. In five of these tests, explosion vent panels have been deployed at the top of the shredder. Test results indicate that peak pressures of about 5 psig (34 kPa) can occur with this venting configuration if the entire shredder is filled with a propane-air mixture in the range 3.5-4.0 volume percent propane (which is not necessarily a worst-case mixture). Further tests will be conducted before generating recommended explosion venting guidelines.

INTRODUCTION

In recent years, shredding has become a common preliminary step for the landfill, resource recovery or incineration of municipal solid waste (MSW). The refuse throughput entering these MSW shredders is often too large to permit thorough screening of the input stream to remove all dangerous materials. Consequently, potentially explosive materials, such as gasoline, propane, paint thinner/cleaner, gunpowder, etc., occasionally enter the shredder. Impact sparks or hot spots generated during shredding (hammering) can ignite these materials and cause an explosion. So far, there have been well over 100 reported[7,8] shredder explosions resulting in property damage or injury.

As a result of these explosions, shredder manufacturers and operators have started implementing traditional protection measures for industrial explosion hazards. The most popular of these protection measures is explosion venting. Explosion venting is a technique for limiting structural damage caused by deflagrations, i.e., combustion explosions in which the flame propagates subsonically through the combustible fuel-oxidant mixture. The basic explosion venting concept is to allow an incipient pressure rise to actuate blowout panels so as to vent unburnt gas and combustion products before damaging pressures develop in the enclosure (shredder). To be effective, the vent deployment pressure, area, and location, must accommodate the volume generation rate of gaseous combustion products.

Existing explosion venting design criteria[4] are based on tests with simple structures such as rooms or spherical or cylindrical pressure vessels. MSW shredders represent a more severe explosion environment because of the effects of rotor windage/turbulence, internal obstructions (shaft, hammers, breaker plates, trash, etc.), and peripheral equipment such as inlet hoods and exhaust ducting. Since these effects escalate the rate of pressure rise and may also reduce vented gas flow rates, they should be accounted for in shredder explosion vent design guidelines.

The project described here is intended to develop and test explosion venting requirements for MSW shredders. The approach has been to perform explosion tests in a realistic full-scale mock shredder outfitted with different explosion vent configurations. Explosion test data are being compared to design-basis explosion pressures suggested in existing vent design guidelines. Based on this comparison, modified design guidelines will be recommended for MSW shredding facilities.

This paper represents a progress report on work performed through November 1980. The project is currently scheduled to be completed and a draft final report submitted in April 1981.

SHREDDER MOCK-UP

A full-scale mock-up of a large horizontal shaft hammermill has been constructed at the Factory Mutual Research Test Center in West Glocester, Rhode Island. Drawings of the mock-up are shown here in Figure 1. The mock-up is 27 ft (8.23 m) high with a total internal volume of 2200 ft^3 (62 m^3) including a 670 ft^3 (19 m^3) inlet hood.

The shredder structure consists of a structural steel frame with 1 1/2-in. (3.8 cm) thick plywood walls. The steel frame and sheet metal clad plywood wall panels are designed to withstand an internal explosion pressure of 5 psig together with thrust loads caused by vented gas. Some of the 4-ft x 4-ft (1.2 m x 1.2 m) plywood panels are fastened with collapsible washer type explosion vent fasteners so that the panels can blow off at a prescribed static overpressure during the explosion tests. The number of deployed panels and the deployment overpressure can be varied in accord with the desired test conditions. The deployed panels have been restrained with hinges in some cases and with various cable tether arrangements in other tests. The performance of these restraints is discussed under Explosion Test Procedure and Instrumentation.

As illustrated in Figure 1b, the hammermill shaft has been outfitted with 24 36-in. (91 cm) diameter plywood discs. Four simulated hammers in the form of 15-in. (38 cm) long aluminum bars can be fastened to each of the discs. However, only 16 hammers have been installed so far in order to limit the torque and horsepower requirements of the hammermill motor.

Tests reported here have been conducted with a 3-hp (2.2 kW) motor driving the shaft via a variable speed drive unit. The shaft speed has been varied from 260 to 690 rpm. As of this writing the 3-hp motor is being replaced by a 30-hp motor with a fixed speed transmission driving the shaft at 900 rpm.

Although there are no inlet or discharge conveyors, the discharge area of the shredder mock-up is designed to be representative of typical MSW shredder installations. There is a semi-cylindrical steel grating in the 46-in. x 105-in. (117 cm x 267 cm) discharge area at the bottom of the shredder, which is 3 ft (0.91 m) above the concrete test pad on which the shredder is constructed. The confinement associated with this configuration simulates the discharge conveyor section under an operating MSW shredder.

No attempt has been made to put any trash throughput into the shredder mock-up. By obstructing inlet and discharge areas, trash throughput in a real MSW shredder may affect the combustible gas accumulation process prior to an explosion and vented gas flow rates during the explosion. This has been simulated in the mock-up by obstructing the inlet and discharge areas with polyethylene sheets in some tests.

GAS MIXING TESTS

In both the gas mixing tests and the explosion tests, a known amount of propane was rapidly injected into the hammermill portion of the shredder. Rotor-induced air flow diluted the propane and governed the formation of the resulting propane-air mixture. The specific objective of the gas mixing tests was to determine the spatial and temporal extent of flammable propane-air mixtures generated by this injection and mixing process.

Three different injection locations, designated as locations I, I' and J in Figure 1, were utilized. A measured amount of propane (by weight) was fed into pipe sections and attached via solenoid valves to orifices I and/or J in the shredder end walls 41 in. (104 cm) above the shaft centerline, i.e., about 8 in. (20 cm) above the hammer circle. Injection at I' was achieved with a 36-in. (91 cm) horizontal extension from I so as to inject at the same height

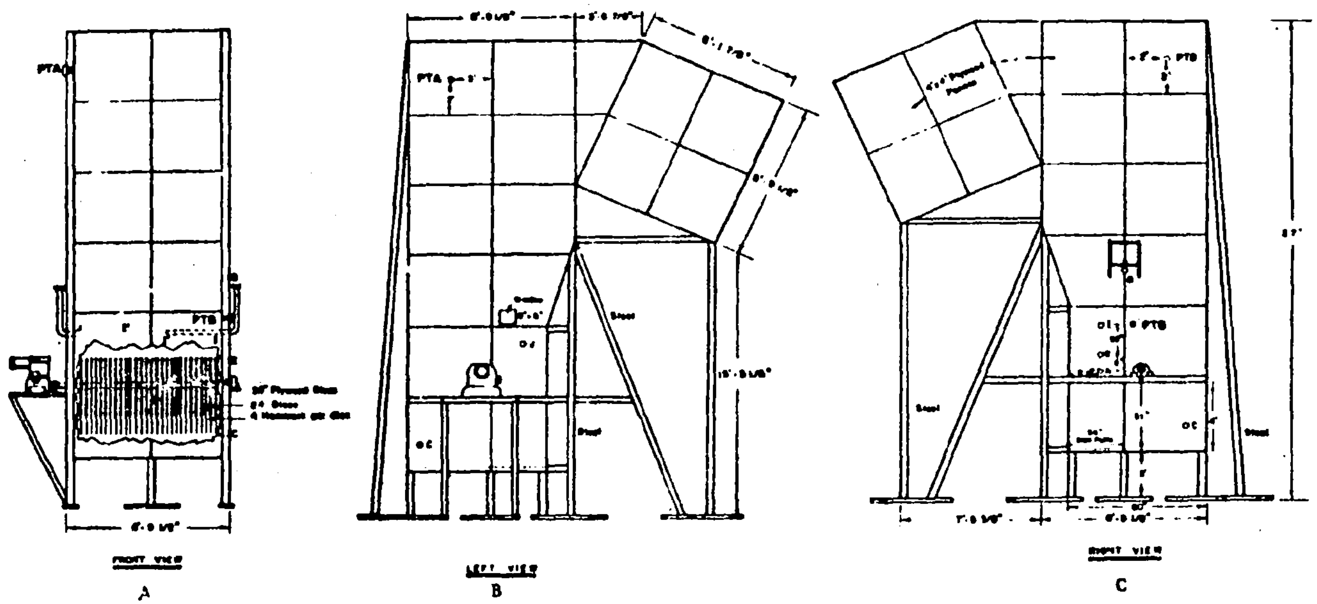

Figure 1. Shredder Mockup.

but closer to the mid-shaft center plane. The rationale for selecting these injection locations was to simulate release from a propane cylinder (or similar liquefied gas container) ruptured by a hammer during the shredding process.

Propane concentrations were measured with an Anarad AR-400 infrared gas analyzer calibrated for a range of 0-8% propane by volume. The analyzer was mounted directly on the shredder structural frame in order to keep instrument response time down to 5-10 s, depending on sample location. The output signal from the analyzer was recorded on an oscillograph in the instrumentation trailer about 200 ft (61 m) away from the shredder.

Only one sample point was used for each injection run, but the runs were repeated with different sample points to obtain an approximate concentration distribution. Sample locations are designated as locations A,B,C,D,D', and E in Figure 1. Locations A,D,D', and E are within the 36-in. (91 cm) diameter disc circle, while B is well above the hammer circle and C is at its lower edge.

Measured propane concentration histories at two different locations in Tests 2 and 7 are shown in Figures 2 and 3 respectively. The 2.2% propane lower flammable limit line is also drawn in these figures. Although most of the concentration histories were simple single-peaked curves as in Figure 3, there were some multiple-peaked curves as for location E in Figure 2. The multiple peaks are probably due to turbulent puffs of gas reaching the sample line.

Peak concentration measurements for all the gas mixing tests are shown in Table 1.

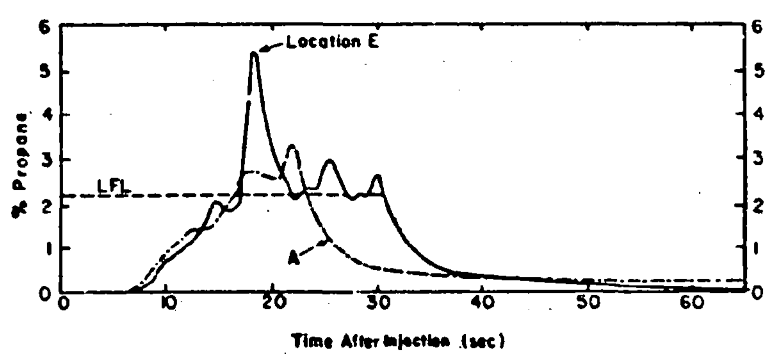

Figure 2. Propane concentration histories at two locations during gas mixing test 2.

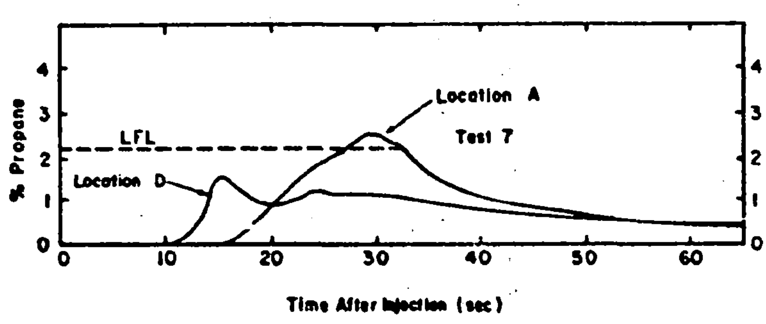

Figure 3. Propane concentration histories at two locations during gas mixing test 7.

TABLE 1. GAS MIXING DATA

Test #	Shaft speed (rpm)	Injector Location	Total wt of fuel (lb)	Sample Location — Maximum Concentration (C_{max}, vol %) - Duration of Flammable Concentration (T, s)												Open or closed bottom
				A		B		C		D		D'		E		
				C_{max}	T	C_{max}	T	C_{max}	T	C_{max}	T	C_{max}	T	C_{max}	T	
1	260	I	1	>8	25	0.5	-	2.0	-	1.6	-	-	-	-	-	Open
2	689	I	1	3.25	10	-		-		0.8	-	0.9	-	5.5	10	Open
3	690	I'	1	-	-	-	-	-	-	1.5	-	1.1	-	0.5	-	Open
4	480	I	1	2.75	-	-	-	-	-	1.0	-	1.0	-	-	-	Open
5	690	I,J	2	4.0	18	-	-	-	-	1.0	-	-	-	-	-	Open
6	660	I,J	3	8.0	31	-	-	-	-	-	-	-	-	-	-	Open
7	660	I,J	2	2.6	6	-	-	0.5	-	1.6	-	-	-	-	-	Open
8	660	I,J	2	3.6	20	-	-	-	-	-	-	-	-	-	-	Closed
9	660	I,J	2	7.5	15	-	-	-	-	-	-	-	-	-	-	Closed
10	660	I,J*	2	1.6	-	-	-	-	-	-	-	-	-	-	-	Closed

*Propane gas injected in the gas phase (top injection) in the last test, and in the liquid phase (bottom injection) in the first eight tests.

For concentrations exceeding the lower flammable limit, the durations of the flammable portion of the concentration histories are also listed in Table 1. For example, the peak concentration at location A in Test 7 (2 lb of propane, 660 rpm shaft speed) was 2.6% and the concentration exceeded the lower flammable limit for 6 s.

Peak concentrations at sample location A (at the end of the shaft) were consistently higher than at locations D and D' (midway along the shaft). This is probably because of the lower induced air velocity at the end of the shaft. Therefore, an air sweeping device installed at the end of the shaft, such as the weld beads used by Ahlberg and Boyko[1] for eliminating combustible debris accumulation near rotor end discs, may significantly reduce the chances of forming pockets of gas-air mixture in the explosive range. In the absence of such an air sweeping device, location A is a consistent potential ignition site, as was the case in the explosion tests in this project.

Concentration data for repeat tests (Tests 5 and 7, and Tests 8 and 9) differed by as much as a factor of 2.1. This lack of repeatability may be due to random turbulent fluctuations or (less likely) to the influence of ambient winds.

Perhaps the most striking feature of the data obtained for tests with the open discharge area is that the peak concentrations were under the lower flammable limit at all locations except A (and E in one test). This implies that flammable mixtures created from the release of 2 lb or less of flammable vapor are confined to a very small portion of the hammermill (near the end walls). Therefore, the chances of igniting a violent explosion are quite small unless much more than 2 lb of flammable vapor is released, or the shredder inlet and discharge areas are obstructed. This conclusion is consistent with reports[8,1] that shredder explosion damage usually results from either a large prolonged release of flammable vapor (for example, from a whole case of flammable solvent), or from gas accumulation in a jammed shredder.

EXPLOSION TEST PROCEDURE AND INSTRUMENTATION

Explosion tests in the shredder mockup have been conducted with propane-air mixtures of varying size and concentrations in the range 3.5-4.0% by volume*. Gas mixtures for the first two tests were formed by rotor-induced mixing with open inlet and discharge areas. However, this unrestrained mixing resulted in a very weak explosion in the first test and in no explosion at all (after three attempts) in the second test. Therefore, subsequent tests have been conducted by confining the gas mixture with polyethylene sheets.

An electric match was used for the ignition source in all but the last two tests which were fired by a condenser spark discharge. The electric match in the first test was placed near location A in Figure 1 because the highest concentrations were measured there in the gas mixing tests. In subsequent tests with a more uniform gas mixture, the ignition source was at location D, which is closer to the center of the hammermill.

Explosion pressures have been measured with two Dynisco Model PT321 strain gage transducers with a calibrated range of 0-10 psig. One transducer labeled Gage B, was mounted on one side wall of the shredder, 41 in. (104 cm) directly above the shaft (location PTB in Figure 1). The other transducer, called Gage A, was installed in the opposite side wall, 2 ft (0.61 m) below the top of the shredder (location PTA in Figure 1). Transducer output was wired to signal conditioning amplifiers and then in parallel to an oscillograph and a FM analog magnetic tape recorder. Data on the analog tape recorder has subsequently been digitized and stored on a Hewlett-Packard 2114 minicomputer.

Videotapes and high-speed movies have been obtained for most of the explosion tests. The video camera has been located sufficiently far from the shredder to obtain an overall view of deployed vent panels and vented flame, while the Hycam 16-mm camera has been mounted at a window in the shredder wall. Thus, flame evolution with-

*The stoichiometric propane air concentration is 4.0 volume percent. This is also approximately the concentration at which the maximum laminar burning velocity occurs[4], but is less than the concentration (5.2% propane) at which the highest pressures were measured in previous explosion venting tests[9,6].

in the shredder has been observed with the Hycam film.

Four deployable 16-ft^2 (1.5 m^2) vent panels at the top of the shredder have been employed in all of the tests to date. Vent deployment pressures were varied from test to test, as were the panel restraining techniques. Some panels were hinged only, some were tethered by aircraft cable, and others were both hinged and cabled. In the more violent explosions, such as the last test, none of these restraining methods were completely successful. A similar lack of success with blow-off panel tethers (for building panels) has been reported in the accounts of the Ontario shredder explosions[1]. One promising technique which has recently been tested successfully[8] is the use of jerry-rigged shock absorbing fasteners for the cables. A similar vent restraining technique may be tried in future tests in this project.

EXPLOSION TEST RESULTS

Test conditions and peak pressure data are summarized in Table 2. If we ignore the variations in propane concentration (There is only a minor change in laminar burning velocity in the range 3.5-4.0% propane[3].), the primary independent test variables are mixture volume, shaft speed, and vent deployment pressure. Although no formal analysis of variance has been conducted, it is clear from the data in Table 2 that all three independent variables significantly affect the maximum overpressure, P_{max}. For example, conditions in Tests 3 and 5 were identical except for the values of vent deployment pressure. The higher nominal vent deployment pressure in Test 3 (0.8 psig versus 0.2 psig) caused the values of P_{max} measured on both transducers to increase by 0.7-0.9 psig, i.e., by 35-53%. Similarly, increases in shaft speed and mixture volume also resulted in substantial increases in P_{max}.

The vent release pressure data in Table 2 indicate that the actual pressure at which the vent is fully deployed is several times higher than the static deployment pressure (based on the ratings of the explosion vent fasteners). This may be due either to the higher release pressure of the fasteners under dynamic loads, or to the inertia of the heavy vent panels after they have been released.

Pressure traces obtained in explosion Tests 3 and 6 are shown in Figures 4 and 5, respectively. The trace for Test 3 has one major peak corresponding to the time at which the vent panels are fully deployed. The trace for Test 6 has multiple peaks, which are often observed[9,6] in explosion venting tests with relatively small vent areas. The first peak in Figure 5 occurs when the vent panels are fully deployed, while the higher peak at 250 msec probably occurs when all of the combustible gas mixture has been burnt.

Peak pressures measured by Gage A at the top of the shredder were consistently higher (by 4-54%) than the values of P_{max} measured by Gage B in the hammer circle region of the shredder. The reason for this difference in peak pressures is not immediately apparent.

The test sequence indicated in Table 2 has been generally increasing in explosion severity. The last test conducted so far (Test 7) was considerably more violent than the preceding tests. There was minor damage to some plywood panels, vent panel restraints, and some welds on the structural frame. The damage has now been repaired and preparations are under way to go to more severe test conditions in the form of a higher shaft speed (900 rpm), more hammers (48), and propane concentrations of 4.0-5.5%. Of course, it will be necessary to use smaller gas mixture volumes and/or larger vent areas to test under these conditions without further damaging the mockup.

Existing explosion venting design guidelines are based upon a worst-case gas mixture (about 5.2% propane) filling the entire enclosure volume under the most turbulent conditions anticipated. As discussed previously, test conditions to date have been somewhat less severe than this hypothetical worst-case scenario. Nevertheless, it is interesting to make a preliminary comparison of our data with the existing explosion vent design guidelines.

In particular, we have compared our peak pressure data from the last two tests (with a gas mixture filling the entire hammermill), with pressures estimated from the Runes Equation and the Bartknecht nomographs in the 1978 NFPA Explosion Venting Guide[4]. The Runes Equation is generally regarded as

TABLE 2. SHREDDER EXPLOSION TEST DATA

Test #	Propane Weight (lb)	Propane Concentration (%)	Mixture Volume (ft^3)	Mixture Volume (% of Shredder)*	Shaft Speed (RPM)	Vent Area+ (ft^2)	Vent Release Pressure (psig) Static	Vent Release Pressure (psig) Actual	P_{max} (psig) Gage A	P_{max} (psig) Gage B
1	2	4.0	Uncontrolled Mixing		690	0	-	-	0.15	-
3‡	3	3.5-4.0	700	(44)	660	76	0.8	2.5	2.7	2.6
4	3	4.0	700	(44)	438	76	0.3	1.1	1.3	1.1
5	3	3.8	700	(44)	660	76	0.3	#	2.0	1.7
6	7	3.6	1600	(100)	250	76	0.2	1.3	4.8	3.1
7	7	3.7	1600	(100)	660	76	0.2	1.75	-	4.3

*Percentages of shredder volume are based on volume excluding inlet hood

+Vent area does not include shredder discharge area or inlet hood area

‡Test #2 did not produce an explosion because the uncontrolled mixing resulted in the ignitor firing a few seconds too late

#The actual vent release pressure is not known for Test 5 because the oscillograph was started too late

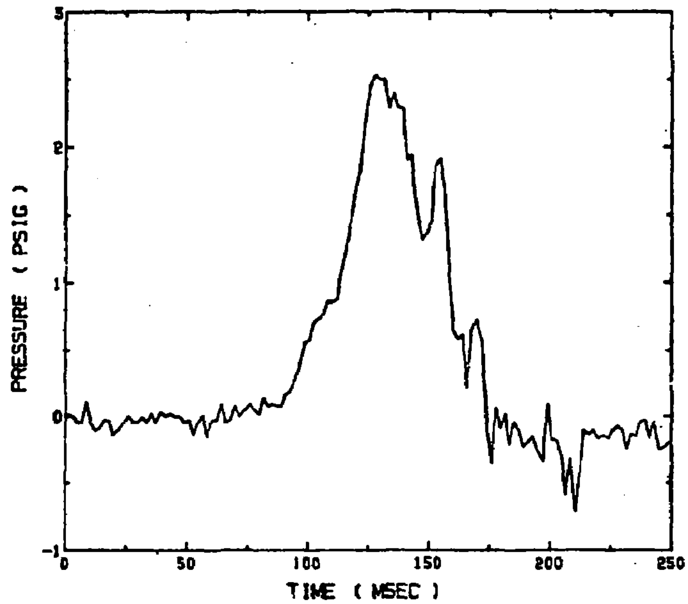

Figure 4. Pressure trace for gage A in Explosion Test 3

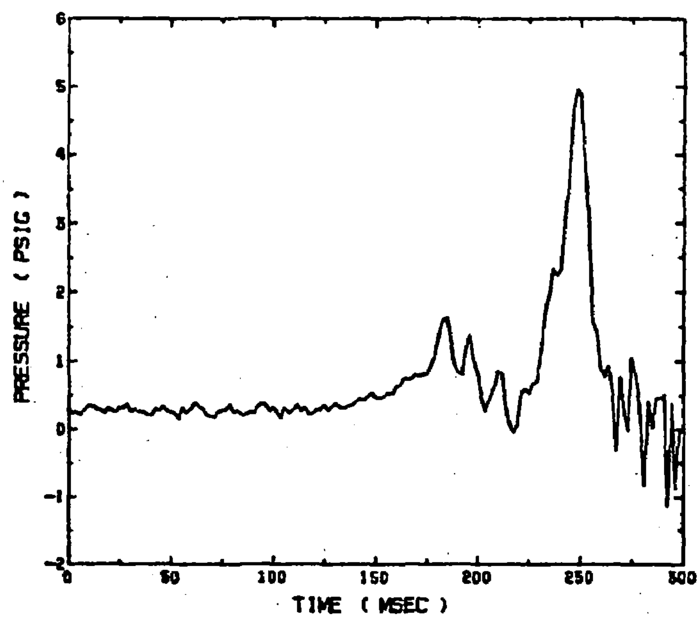

Figure 5. Pressure trace for gage A in Explosion Test 6

being quite conservative, since it implies that peak pressures can be somewhat higher than had been measured previously[5,6] in methane-air and propane-air explosion tests in room-size enclosures. However, the peak pressure data for shredder explosion Tests 6 and 7 (4-5 psig) are quite close to the pressure indicated by the Runes Equation for the corresponding vent ratio (ratio of minimum enclosure cross-sectional area to effective vent area) based only on the area of the vent panels at the top of the shredder.

Good agreement is also obtained when considering the Bartknecht nomographs in the NFPA Explosion Venting Guide[4]. The nomograph for hydrogen has been used because it represents a burning velocity hypothesized[4] to be comparable to a burning velocity for a turbulent propane-air mixture. These nomographs are presented in terms of enclosure volume, which, in the case of a shredder, can be calculated either with or without the volume of the inlet hood. If the inlet hood volume is neglected, the hydrogen nomograph estimates a peak pressure of about 3 psig (0.2 bar); while a peak pressure of 6 psig (0.4 bar) is suggested for a shredder volume that includes the inlet hood. In both cases, the only vent area credited has been the vent panel area at the top of the shredder. It is clear from these two comparisons, that explosion vent design on the basis of these existing guidelines should not include any credit for the discharge hood because it is apparently ineffective as a result of confinement of the discharge conveyor (or concrete test pad in the case of the mock-up).

Further explosion testing is planned, not only to explore the range of validity of these preliminary results, but also to investigate vent ducting effects. Plans have been formulated to install a 15-ft (4.6 m) high vent duct on top of the shredder. This type of vent duct configuration has recently been installed in several MSW shredding facilities[5].

PRELIMINARY CONCLUSIONS

The following preliminary conclusions are offered together with the caveat that they are subject to modification from test data and analysis to be forthcoming in the remainder of this project:

1. Flammable vapor releases of 2 lb (1 kg) or less in a large unobstructed MSW shredder are rapidly diluted and discharged everywhere except possibly at the ends of the hammermill shaft. An explosion resulting from this limited quantity of flammable vapor released in an unobstructed shredder is unlikely to do any significant damage, even in the absence of explosion venting or suppression.

2. If inlet and discharge areas are obstructed and a propane-air mixture in the range 3.5-4.0% propane forms throughout the shredder, peak explosion pressures of about 5 psig can be expected even when the entire top of the shredder is allowed to blow open. In the absence of any venting, considerably higher pressures would be expected.

3. If heavy explosion vent panels are attached to the shredder with collapsible washer-type fasteners, vent deployment pressures during a turbulent gas explosion in the shredder are several times as high as the hydrostatic release pressure.

4. If existing explosion venting design guidelines are used to estimate required vent areas, no credit should be taken for shredder inlet and discharge areas; these areas are too confined to be effective vents.

ACKNOWLEDGMENTS

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DESIGN CONSIDERATIONS FOR MUNICIPAL SOLID WASTE CONVEYORS

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ABSTRACT

An experimental and engineering evaluation of conveyors for municipal solid waste (MSW) was conducted by the National Center for Resource Recovery, Inc. This paper discusses the materials properties and characteristics affecting the conveyability of MSW and its processed fractions, and reports on experimentally determined values or observed characteristics. Tests on belt conveyors (horizontal or inclined) and vibrating conveyors were carried out for six waste fractions, using a specially assembled, closed-loop test rig. A procedure for the selection and operation of belt conveyors based on an admissible spillage rate is proposed, analyzed and corroborated by test results. Experiments performed on a vibrating pan conveyor are also described. Results discussed indicate trends and sensitivities over the range of frequency, amplitude and materials investigated.

INTRODUCTION

Considered in the abstract, a "generalized" resource recovery facility may be considered as a system in which one or more inputs (feedstocks and energy) are processed into a number of products (materials and/or energy) in a sequence of unit operations, such as shredding, air classification, screening, densification, etc. (Figure 1). As sketched, these operations are carried out either in series or in parallel. Such parallel or alternate streams might be provided for the sole purpose of improving reliability or availability, on a permanent or emergency basis.

What is also apparent from Figure 1 is that the function of <u>conveying</u> waste materials or processed fractions of wastes is crucial to the satisfactory operation of the system. Thus, it is imperative that conveyor systems for municipal solid waste (MSW) and its processed fractions be designed for reliability, low maintenance and low spillage, and yet not be specified so conservatively as to be grossly oversized and too costly.

A recent study of research needs in resource recovery was performed for the Department of Energy by A. Scaramelli *et al.* (1). Underlining the need for systematic research in materials handling and storage systems, the study cited a number of facilities which experienced conveying problems during startup or in full operation:

> "...Ames has experienced broken links in its drag conveyor due to jamming by oversize materials plugging of its pneumatic lines

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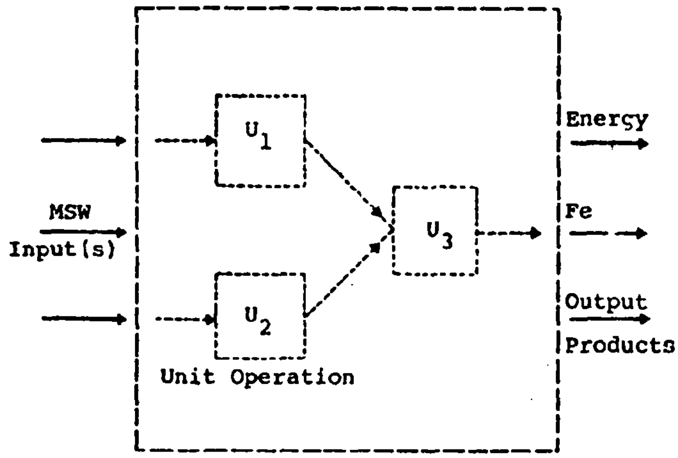


Figure 1. Resource recovery system schematic.

caused by bridging at rough internal surfaces; and jamming of airlocks by oversized objects... Chicago's problems with pneumatic line plugs are similar to those at Ames... Hamilton has experienced bridging at transition points... The screw conveyor at Lane County was too small, causing jamming and bridging..."

Obviously, there is available literature dealing with the choice, design, construction and operation of various types of conveyors for a large number of (in fact, most) bulk solids. As an example, the 1979 edition of a classic handbook on belt conveyors (2) lists a number of relevant physical or other descriptive properties for a total of 411 such materials, or forms of materials (chips, shavings, etc.), from alfalfa meal to zinc oxide, through crushed ice and ground oyster shells. Yet, with the possible exception of glass cullet, no such information is given or is available on the properties or conveyability of MSW and its processed fractions.

As a result, design choices and the selection of equipment in existing recovery plants were made on an ad hoc basis, possibly based on as little as a name, a compacted bulk density, a desired capacity and some idea of the largest size of particles conveyed. If problems developed in operation, the symptoms were more readily apparent than the causes. Many processing plants show examples of ingenuity in "fixing" a troublesome part of the conveying system, such as a special belt wiper or an unusual cleat arrangement. These field modifications are actually afterthoughts, attempting to remedy a problem not anticipated in the use of an unfamiliar and relatively heterogeneous material.

There is little argument that to the maximum extent possible, trouble in operation should be anticipated and prevented by sound design. However, the design engineer or equipment vendor might be lacking, even unknowingly, information or data vitally needed for this task. Some of these data, such as bulk density, are quantitative and should be measured following procedures which are meaningful for the particular application being considered. Others are assessed "characteristics," about which qualitative statements, for example, "very sticky," are made. Finally, the designer might not be aware, or avail himself, of all relevant conditions in use, such as the particular type of loading, discharge arrangement, frequency and intensity of surges, etc.

Upon starting the work reported in part in the present paper, it was recognized that there was a near total lack of data on properties and characteristics of MSW and its processed fractions, as they might affect conveyability. Second, it was unclear which of these descriptors of the materials were most significant in the design and trouble-free operation of systems. Finally, a need existed to provide an engineering basis for the evaluation and field testing of existing conveyor assemblies at existing resour recovery plants. These considerations provided the basis for the objectives of this investigation.

OBJECTIVES OF THE WORK

In mid-1979, the first phase of an investigation of conveyor systems was initiated by the National Center for Resource Recovery, Inc. (NCRR). Its objectives were to:

- determine, for commonly encountered waste materials, i.e., MSW and some of its processed fractions, which properties and characteristics had significance in assessing conveyability and conveyor design;

- measure these significant properties;

- establish criteria and methods for evaluating conveyors at resource recovery plants; and

- provide reliable engineering data for future use by conveyor design and plant operating engineers.

The determination or measurement of properties and qualitative observations were made in the laboratory or on a test conveyor rig installed at NCRR's Resource Recovery Laboratory at Upper Marlboro, MD. Engineering analysis and criteria development were done concurrently with the experimental work.

Within the scope of this first phase of the work, belt conveyors (horizontal and inclined), vibrating conveyors and apron conveyors were considered. Additionally, a test plan for a pneumatic conveyor rig was defined.

In the present paper, to allow more room for a discussion of the approach taken, its rationale and detailed results on six waste materials from MSW, it was decided to limit the discussion to two types of solids conveyors:

- belt conveyor (horizontal and inclined)

- vibrating conveyor.

DESCRIPTION OF FACILITY AND TEST RIG

Since, to some extent, materials properties and characteristics to be determined are linked to the particular type of conveyor system being studied, a description of the facility and test rig utilized might be in order at this point.

The conveyor test rig, designed and installed at the Upper Marlboro research facility was completed in 1979. Its design was based on several considerations:

- ability to circulate a constant (or quasi-constant) mass flow rate;

- easy access for sampling; and

- flexibility to incline or decline, or interchange test conveyors.

These led to the choice of a continuous loop, recirculating flow configuration, as shown in Figure 2. To maintain a constant mass flow rate, the mass of material on the loop was changed at different speeds of the conveyors. It was experimentally verified that a constant mass flow rate was indeed realized along the loop. An attempt had earlier been made to use a surge hopper with a variable speed conveyor to keep a constant feedrate, but this procedure was abandoned because it resulted in surging and poor feedrate control. The various components of the test rig are identified in Figure 2.

Table 1 lists the specifications for each conveyor. Worthy of note, conveyor 2a (Table 1), which is the test belt conveyor, was modified for testing with new idlers, belts and a variable drive motor to provide a range of speed from 0.20 m/s to 2.44 m/s (40 ft/min to 480 ft/min). Testing conveyor 2b, of vibrating type, was uipped with a variable speed ive and interchangeable cam afts to change stroke length. It was leased from Carman Industries, Inc., Jeffersonville, IN.

PROPERTIES AND CHARACTERISTICS OF MSW MATERIALS AFFECTING CONVEYABILITY

As pointed out earlier, engineering data on materials properties and handling interactions are available for most bulk solids (2), but not for those of interest here, namely MSW and its processed fractions.

Among the many properties affecting conveyability, some of the most important might be: bulk density, moisture, particle size, angle of surcharge, cohesiveness, angle of internal friction, etc. Table 2 shows a complete list of bulk material properties affecting conveyability, according to the Conveyor Equipment Manufacturers Association (CEMA) (3). Asterisks indicate those which were considered to be unrelated to the conveyability of waste on solids conveyors. Daggers refer to properties for which test

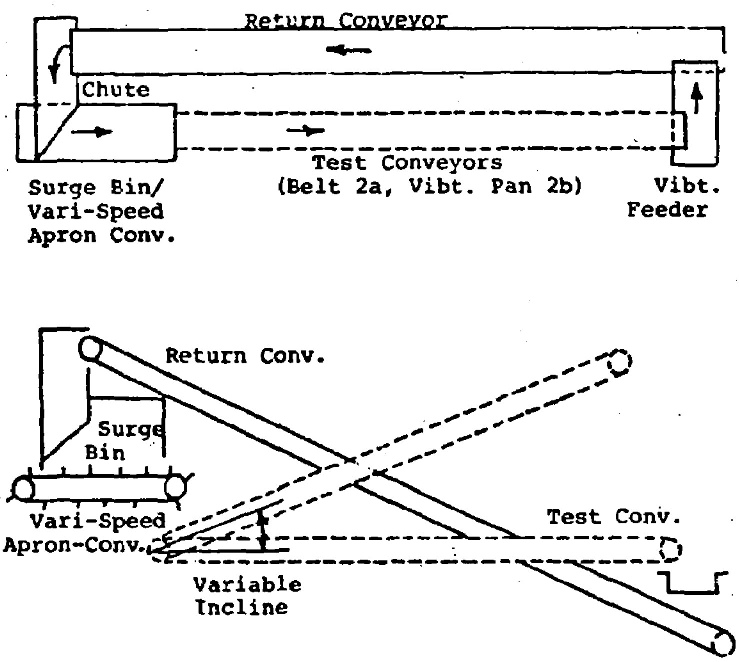


Figure 2. Recirculating test rig layout.

TABLE 1. TEST RIG CONVEYOR SPECIFICATION

Conveyor	Width m (in.)	Length m (ft)	Drive	Idlers angle	Stroke/ freq.	Incline	Speed	Manufacturer
Feed Apron	0.749 (29.5)	2.06 (6.75)	variable	N/A	N/A	0°	0.14 m/s (27 fpm)	Bonded Equipment
Test belt conveyor	0.457 (18)	7.63 (25)	variable	20°/ 35°	N/A	0°-32° max.	0.20-2.44 m/s (40-480 fpm)	Bonded Equipment
Vibrating conveyor	0.603 (23.75)	4.58 (15)	variable	N/A	12.7 mm (1/2 in.)/ 400-560 cpm 22.2 mm (7/8 in.)/ 470-545 cpm	0°	N/A	Carman Industries
Transfer vibrating conveyor	0.508 (20)	1.83 (6)	constant	N/A	4.8 mm (3/16 in.)/ 1300 cpm	0°	N/A	Meyer Machine Co.
Return conveyor	0.508 (20)	9.67 (31.7)	constant	35°	N/A	17°	1.04 m/s (205 fpm)	Bonded Equipment

TABLE 2. PROPERTIES AND CHARACTERISTICS OF BULK MATERIALS EFFECTING CONVEYABILITY

	Properties (measured)
1.	Abrasiveness*
2.	Angle of external friction*
3.	Angle of internal friction*
4.	Angle of maximum inclination (of a belt)
5.	Angle of repose
6.	Angle of slide
7.	Angle of surcharge
8.	Bulk density - loose
9.	Bulk density - vibrated
10.	Cohesiveness*
11.	Elevated temperature†
12.	Flowability - flow function*
13.	Lumps - size - weight
14.	Specific gravity†
15.	Moisture content
16.	Particle hardness*
17.	Screen analysis and particle size consist
18.	Sized and unsized material
	Characteristics (assessed).
1.	Aeration - fluidity†
2.	Becomes plastic or tends to soften†
3.	Builds up and hardens
4.	Corrosive
5.	Generates static electricity†
6.	Degradable - size breakdown
7.	Deteriorates in storage - decomposition
8.	Dusty
9.	Explosiveness
10.	Flammability
11.	Harmful dust, toxic gas or fumes
12.	Hygroscopic†
13.	Interlocks, mats and agglomerates
14.	Oils or fats present†
15.	Packs under pressure
16.	Particle shape
17.	Stickiness - adhesion
18.	Contaminable†
19.	Very light and fluffy - may be windswept

*Test methods for processed solid waste fractions yet to be developed.

†Considered unrelated to conveyability of solid waste.

methods for MSW and its processed fractions have yet to be developed.

Materials Tested

For the purpose of these tests, representative samples of the following fractions were obtained from the Baltimore County Resource Recovery Plant, Cockeysville, MD:

(1) shredded MSW; nominal size -102 mm (-4 in.);

(2) air-classified light fraction or refuse-derived fuel (RDF), nominal size -51 mm (-2 in.);

(3) densified refuse-derived fuel pellets (d-RDF);

(4) air-classified heavy fraction (HF);

(5) magnetic or "ferrous" fraction (MF); and

(6) blend of d-RDF and coal (1:1 on a volumetric basis).

Properties Measured and Results

A complete description of test methods and procedures is given elsewhere (4) and would be too lengthy to reproduce here. The discussion will be limited to general comments and results, and to applicable properties or characteristics.

Abrasiveness, Angle of External Friction, Angle of Internal Friction

It was determined that current CEMA methods (3) cannot be applied to measure these properties on solid waste. The development of new, reliable procedures was found to be outside the budget and time limits of this investigation. Some effort was spent on determining mass loss on two types of material - aluminum sheet and belt rubber lining - being impacted by the solids over a standard time interval; results were inconclusive. The angles of internal and external friction are doubtless of significance to the overall problem of conveying over the equipment lifetime, but were not needed in the engineering evaluation described below.

Angle of Maximum Inclination

On a belt conveyor, the angle of maximum inclination is that angle, in degrees to the horizontal, at which the empty belt successfully will elevate the material fed to it. It was observed to be dependent upon mass flow rate and belt speed. For a "central" value of mass flow rate - which we estimated to be the middle of the range for each of the materials listed and for a normalized belt speed of 0.51 m/s (100 fpm) - Table 3 lists the angles of maximum inclination. The belt was 457 mm (18 in.) wide, with 35° idlers. Angles are seen to increase with the bulk density of the material (see values following).

Angle of Repose

The angle of repose for bulk materials being stockpiled is that angle between a horizontal line and the sloping line from the top of the pile to the base. The results are shown in Table 4.

It is noted that, for each material, a range of values is reported. As should be expected, the angle of repose for a given material varies due to irregularities in particle shape, size and their relative distribution in the pile. Accordingly, the piles were never conical, and different angles of repose were measured at varying horizontal angles from the center of the pile. A qualitative observation is that narrower ranges are observed for relatively more homogeneous fractions, such as d-RDF or the ferrous fraction.

Angle of Slide

The angle of slide is that angle to the horizontal of an inclined flat surface on which an amount of

TABLE 3. ANGLES OF MAXIMUM INCLINATION

Solid waste fraction	Belt width mm (in.)	Belt idlers (°)	Belt speed m/s (ft/min)	Flow rate Mg/h (TPH)	Angle of maximum inclination (°)
MSW	457 (18)	35	0.51 (100)	0.9 (1.0)	19
RDF	457 (18)	35	0.51 (100)	0.9 (1.0)	21
d-RDF	457 (18)	35	0.51 (100)	4.5 (5.0)	30
Heavy fraction	457 (18)	35	0.51 (100)	4.5 (5.0)	28
Ferrous fraction	457 (18)	35	0.51 (100)	4.5 (5.0)	28
d-RDF/coal	457 (18)	35	0.51 (100)	9.1 (10.0)	27

TABLE 4. ANGLE OF REPOSE

Fraction	Range
MSW	25°-52°
RDF	29°-49°
d-RDF	27°-46°
Heavy fraction	30°-59°
Ferrous fraction	N/A
d-RDF/coal	40°-45°

material will slide downward due to its own weight. Repeatability in the experimental determination of the angle of slide is somewhat limited. The angle will vary with the:

- type of substrate (steel, belting, etc.);
- physical condition of the underlying surface;
- state of compaction of the material; and
- rate of change of slope as performed by an operator.

Tests were conducted on both a smooth steel plate and conveyor belting material (rubber). For each slide test, approximately 14.2 dm^3 (0.5 ft^3) were utilized. As could be foreseen, results given in Table 5 show higher values for the angle of slide on belting material than on the steel plate. The various fractions listed would, under static conditions, slide down a conveyor belt or chute at an angle equal to or greater than the value given in Table 5.

Angle of Surcharge and Maximum Angle of Surcharge

The angle of surcharge, α, is the angle to the horizontal which the surface of the material assumes while the material is at rest on a moving conveyor belt (Figure 3). For bulk solids listed in the CEMA handbook on belt conveyors, this angle is said to be in observed conditions of use from 5° to 15° lower than the angle of repose, although it may be as much as 20° lower for some materials (2). As observed, this angle is not an intrinsic property of the bulk solids, but rather an indication of operating conditions determined to be satisfactory; it should, therefore, be dependent on the conveyor velocity, configuration and mass flow rate. On a vibrating conveyor, the angle of surcharge is practically 0°.

TABLE 5. ANGLE OF SLIDE

Solid waste fraction	Angle of slide on steel plate	Angle of slide on conveyor belting
MSW	29.3°	30.0°
RDF	31.0°	35.0°
d-RDF	32.8°	34.5°
Heavy fraction	27.5°	28.5°
Ferrous fraction	17.5°	32.0°
d-RDF/coal	22.0°	24.0°

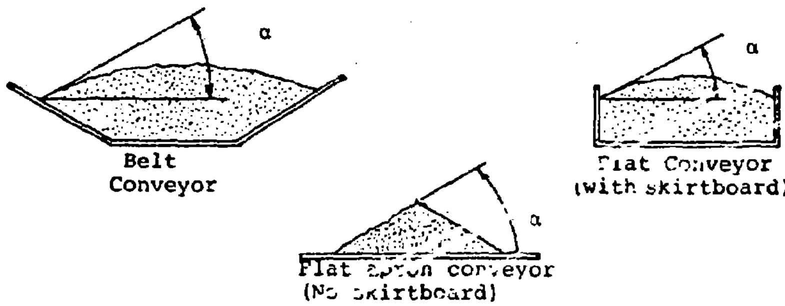


Figure 3. Angle of surcharge.

We have defined here the maximum angle of surcharge on a belt conveyor, α_{max}, as the experimentally determined angle at which the conveyor can be loaded to maximum capacity (or maximum cross-section) under static conditions (i.e., with the belt at rest).

Table 6 lists the observed values of the maximum angle of surcharges for six materials and two idler angles.

Loose Bulk Density

Under actual conditions of use, MSW or its processed fractions may be less compacted or "looser" than could be inferred from measurements on a vibrated or tapped mass of the material.

Accordingly, the loose bulk density, thought to be similar to the "as conveyed" density, was measured in a test in which the solid waste fraction is discharged from its container and piled in a cone, without any other compaction. Although there exist several published standards for determining bulk density (3), the American Society for the Testing and Materials (ASTM) methods suitable for aggregates and coke cannot be applied towards bulk density determination of solid waste fractions. The procedure developed by NCRR for this work is detailed elsewhere (4). Basically, the mass and volume of the cone were measured to determine the loose or "as conveyed" bulk density. Results are given in Table 7.

TABLE 6. MAXIMUM ANGLE OF SURCHARGE

Solid waste fraction	Maximum angle of Surcharge	
	20° Idler	35° Idler
MSW	55°	54°
RDF	51°	65°
d-RDF	not measured	49°
Heavy fraction	48°	59°
Ferrous fraction	not measured	52°
d-RDF/coal	not measured	40°

Relatively wider ranges are reported for the more heterogeneous fractions, due to the presence of discrete pieces of heavier or larger size materials. Also, higher average values for the bulk densities of HF or MF are due to the denser ferrous or glass components.

Vibrated Bulk Density

The vibrated bulk density is the weight per unit volume measured after the sample, in its container, has been compacted by vibrating or tapping the container. ASTM has recently recommended a standard for the bulk density determination of solid waste fractions (3).

Briefly, the various solid waste fractions were placed in a 28.4 dm^3 (1 ft^3) container, tapped several times. The material was thereby compacted, and its weight and volume recorded. Results are given in Table 8.

By comparing Tables 7 and 8, it can be seen that some vibrated bulk densities are higher by about 20% than the loose bulk densities. The vibrated bulk density is often used in specifying mass flow rates on a conveyor; however, the loose bulk density is more representative of the actual conditions in operation. It is proposed that this value be used for MSW and its processed fractions.

Cohesiveness, Flowability, Particle Hardness

No measurement techniques for solid waste fractions are available. However, these properties are obviously of importance in a number of applications, and future research work is warranted in this direction.

TABLE 7. BULK DENSITY (LOOSE)

Solid waste fraction	Bulk density (loose) kg/m^3 (lbs/ft^3) Range	Average
MSW	61 - 152 (3.8 - 9.5)	106 (6.6)
RDF	34 - 50 (2.1 - 3.1)	43 (2.7)
d-RDF	361 - 387 (22.6 - 24.2)	374 (23.4)
Heavy fraction	366 - 598 (22.9 - 37.4)	482 (30.1)
Ferrous fraction*		
d-RDF/coal	712 (44.5)	712 (44.5)

*Cannot be performed within reasonable accuracy on a small pile.

TABLE 8. BULK DENSITY (MAXIMUM)

Solid waste fraction	Bulk density kg/m³ (lbs/ft³) Range		Average	
MSW	66 - 200	(4.1 - 12.5)	134	(8.4)
RDF	37 - 72	(2.3 - 4.5)	54	(3.4)
d-RDF	402 - 486	(25.1 - 30.4)	445	(27.8)
Heavy fraction	334 - 451	(20.9 - 28.2)	435	(27.2)
Ferrous fraction	194	(12.1)	194	(12.1)
d-RDF/coal	590	(36.9)	590	(36.9)

Size and Weight of Lumps

According to CEMA, lump size is the maximum linear dimension (in inches) of a large particle (or a stable agglomeration thereof) of a bulk material. Its weight is expressed in pounds of the maximum size lump (2).

Whereas this definition might make sense for a brittle, blocky and/or homogeneous material, it is thought to be largely inapplicable to solid waste fractions, and should not be retained as such. Particle size distribution, determined by sieving, and weight distribution by component are more indicative of how "large" the conveyed material is compared to the belt width. Yet, pliable materials such as textiles and plastics might be much larger than the nominal grate or sieve size, and streams with significant amounts of these components are more prone to spillage. Considerable work remains to be done in characterizing MSW and its processed fractions as to the actual "size" of its components seen by the conveyor belt.

Moisture Content

In the moisture content, only the absorbed and adsorbed water, measured by drying and evaporation, are considered. Due to the variability of moisture in solid waste fractions, the values reported in Table 9 should be taken as no more than general indicators.

Those materials with high moisture content, such as MSW or HF, may prove over long periods of time to cause maintenance problems due to corrosion by salt and moisture. Moisture content in excess of 40%, while beneficial in limiting dust emissions, could contribute to stickiness and adhesion on the belts and chutes.

Screen Analysis and Particle Size Distribution (PSD)

A screen analysis was performed on each sample. The material was subjected to a standard shaking action, and the percentage by weight retained on each screen of a series of test screens was measured. The biggest opening screen was on top and the smallest on the bottom. Results of the particle size analysis for all five fractions are given in Figure 4. No particle size distribution analysis was performed for the blend of d-RDF pellets (diameter 13 mm) and coal (95% <35 mm).

The information contained in such PSD results, for example that RDF is relatively uniform in size (40% by weight between 13 mm and 19 mm (1/2 in. and 3/4 in.)),

TABLE 9. MOISTURE CONTENTS

Solid waste fraction	Moisture content (wt% as-received) Range	Average
MSW	18 - 30	21.8
RDF	9.1 - 19	14.2
d-RDF	20.5 - 22.7	20.6
Heavy fraction	9.2 - 20.8	15.9
Ferrous fraction	2.6	2.6
d-RDF/coal	9.3	9.3

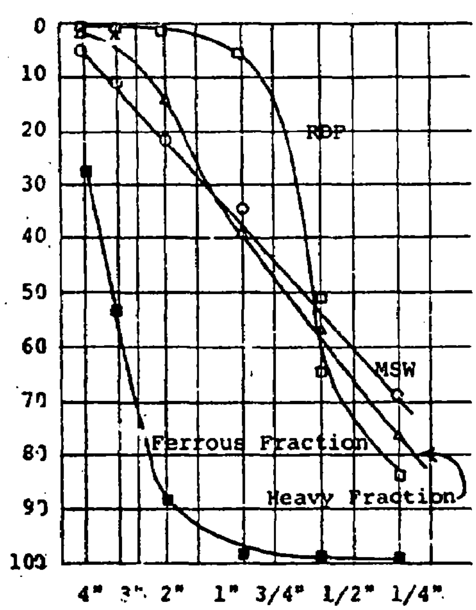


Figure 4. Particle size distribution of test samples.

should prove useful in selecting belt width, idler angles, height of trough and in the design of discharge and dribble chutes.

Sized and Unsized Materials

A sized material consists of particles passing through some defined square mesh screen opening and retained on some smaller mesh screen; a partially sized material is made of sized and unsized material.

Under that definition, solid waste fractions are unsized, with the possible exception of d-RDF, which is produced relatively homogeneously from RDF by an extrusion process.

Characteristics Assessed

Certain characteristics do not have defined measurement procedures, but still must be assessed in designing a conveyor system. Table 10 lists these characteristics with related properties in a material class description form. Conditions and materials are taken to be "average." Further details on these characteristics and their assessment are given by CEMA (2,3).

Using the above CEMA code of classification for MSW and its processed fractions, codes were devised for the six materials studied here and are listed in Table 11. It is recommended that they be used

TABLE 10. CEMA MATERIAL CLASS DESCRIPTION

	Material Characteristics	Code
SIZE	Very fine - less than 100 mesh	A_{100}
	Fine - 3.2 mm (1/8 in.) or less	B_6
	Granular - 76 mm (3 in.) or less	C_3
	Lumpy - containing lumps 406 mm (16 in.) and less	D_{16}
	Irregular - stringy, interlocking	E
FLOWABILITY ANGLE OF REPOSE	Very free flowing - angle of repose less than 19°	1
	Free flowing - angle of repose 20° to 29°	2
	Average flowing - angle of repose 30° to 39°	3
	Sluggish - angle of repose 40° and over	4
ABRASIVENESS	Non-abrasive	5
	Abrasive	6
	Very abrasive	7
	Very sharp - cuts or gouges belt conveyors	8
CHARACTERISTICS (ASSESSED)	Builds up and hardens	F
	Deteriorates in storace	H
	Corrosive	T
	Degradable - size breakdown	Q
	Dusty	L
	Explosiveness	N
	Flammability	T
	Harmful dust, toxic gas or fumes	R
CHARACTERISTICS	Interlocks, mats or agglomerates	V
	Packs under pressure	X
	Stickiness - adhesion	O
	Very light, fluffy	Y

TABLE 11. MATERIAL CHARACTERISTICS

Fraction	Avg. loose bulk density kg/m^3 (lbs/ft^3)	Angle of repose (degrees)	Angle of maximum inclination (degrees)	CEMA material code
MSW	106 (6.6)	25 - 52	19	E36HVO
RDF	43 (2.7)	29 - 49	21	E35HLTXY
d-RDF	374 (23.4)	27 - 46	30	$D_3$35HQL
Heavy fraction	481 (30.1)	30 - 59	28	E47HQVO
Ferrous fraction	192 (12.0) max.	N/A	28	$D_1$66
d-RDF/coal	712 (44.5)	40 - 45	27	$D_3$46HQL

with an awareness of their limitations, in view of the heterogeneity and variability of these fractions.

Belt Conveyors: Analysis of the Basis of Spillage Rate

Belt conveyors are widely used in mining, construction and processing plants. Compared to other types, they often have the advantage of being economical, relatively simple to operate and able to convey materials of varying composition, size and moisture. They can be operated in the horizontal, inclined or declined mode. In resource recovery plants, they are in common use to transport MSW or its processed fractions.

In spite of the simplicity of the operation and design of such systems, operating experience at resource recovery plants shows that many problems still beset belt conveyors: spillage, jams, blow-back or roll-back, dusting, etc. Some of these problems no doubt are due to properties and characteristics of the materials conveyed. Therefore, the variables or parameters on which some degree of control exists (at the design stage, or in operation) need to be "fine-tuned" for a specific location and type of material. These may include the belt speed and acceleration, its inclination, the idler angles and the loading and discharge configurations.

A rationale for the design and analysis of a systematic series of tests, run on a horizontal or inclined belt, was developed as part of this investigation. Based on the concept of maximum admissible spillage rate, it is described in general terms below. More details can be found in the Contract final report (4).

Rationale: Designing for a Rate of Spillage

In designing a series of tests to define the range of "good" or "best" operation of a belt conveyor carrying a given material, some thought should be given to the criteria by which such labels as "good" or "best" might be awarded.

Experience or observations gathered at a number of operating plants with belt systems to convey solid waste fractions strongly suggests that by far, the most undesirable feature in such systems is a high rate of spillage.

Spilled material on the sides of conveyor belts, or at transfer points, will fall on the floor, jam rotating pieces of equipment and be a cause of constant problems in maintenance, odor, sanitation and clean-up. To illustrate, assume a rate of spillage of 1% of the mass flow rate on a conveyor belt 30.5 m (100 ft) long. The belt carries 1.8 Mg/h (2 tons/h) of light fraction (fluff RDF) having a bulk density of 54 kg/m^3 (3.4 lb/ft^3). After an 8-hour shift, 0.14 Mg (0.16 ton) will have accumulated along the belt, representing a total volume of 2.7 m^3 (94 ft^3). On each side of the belt, this would be equivalent of a layer 30.5 cm (1 ft) wide and 15 cm (0.5 ft) high. Such rate of spillage would obviously be intolerable in steady operation.

Other desirable (although possibly less crucial) features of a belt conveyor system of known geometry, carrying a given material, are:

(a) high throughput for a given size (as measured by the width of the belt);

(b) low power consumption;

(c) high reliability and trouble-free operation;

(d) low levels of dust emissions; and

(e) ease of transfer of material to and from the belt.

In view of the extreme importance of limiting spillage to a low, admissible level, it was decided at the outset to assess conveyability on the basis of a criterion of acceptable spillage. Then, consideration was given to high throughputs - feature (a) above - by studying the dependence of throughput on belt speed.

Item (b) above, the power consumption, was measured at the various operating points, with no attempt made to modify the design of the belt being tested for lower power consumption. It should be kept in mind, however, that high power consumption might be one of the essential deciding factors when choosing between an open, skirted or covered conveyor belt system.

High reliability and trouble-free operation, item (c), can only be ascertained after much longer periods of time than would be possible in this test program. Still, whenever possible and justified, incidents of operation, jamming of equipment or other incidents were noted and documented.

As explained below, dust levels, item (d), were recorded and evaluated in a relative, and to some extent, absolute manner. These levels were obtained at various "typical" locations (near transfer points, in the middle of a straight run, etc.), thus allowing to compare the dependence of dust levels on location as well as on the operating parameters and the kind of solid waste fraction being conveyed.

Finally, the ease of transfer of the material onto and from the belt, item (e), will be highlighted in two principal ways. First, by observing and recording trajectories of the material at the discharge point from the conveyor belt, and comparing them to those predicted by methods conventionally used in applications for materials other than solid waste. Secondly, experimental observations, largely qualitative, and *ad hoc* improvements made during the course of the tests should serve as a guide for assessing the "proper" mode of feeding the belt with a variety of feedstocks. This is particularly true in the case of a steeply inclined belt, for which transfer and acceleration on the belt in the zone located directly under the chute or feeding stream are the mechanisms critically limiting throughput and/or producing surges.

Choice of Test Variables and Parameters

A schematic representation of the conveyor belt system is shown in Figure 5. The belt, of length L_B, can be either horizontal ($\alpha = 0$) or inclined at angle α on the horizontal. At the "inlet" point A, the input mass flow rate (of dimensions

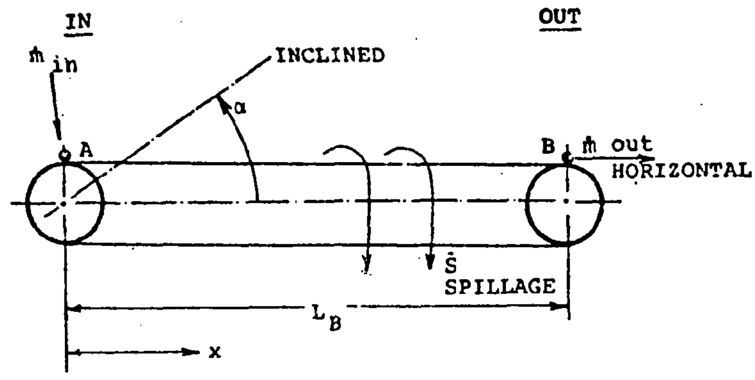


Figure 5. Schematic of belt conveyor system.

mass/time or $[MT^{-1}]$) is noted $\dot{m}_{in}$; the mass flow rate exiting the belt at point B is noted $\dot{m}_{out}$.

The spillage rate, s, is a relative measure of the mass of conveyed material being spilled per unit of mass flow rate conveyed and unit length of belt. This would appear as a logical definition, but it should be kept in mind it implicitly contains some assumptions or simplifications. First, the input mass flow rate, m_{in} defined above and shown in Figure 5, is assumed to be known and constant. Second, the rate of spillage is construed to be proportional to the belt length. For long, straight runs, this might be the case only after the "discreet" spillage at transfer points A and B, in Figure 5, has been subtracted from the total spillage. More will be said about these limitations when discussing the experiments and test results.

Let $\dot{m}_s$ be the mass flow rate of material spilled per unit length of belt. The formal definition of the spillage rate, as a fraction (p.u.) or percentage, will be, with the above qualifications,

$$\dot{s} = \frac{d\dot{m}_s/dx}{\dot{m}_{in}} = \frac{\dot{m}_{in} - \dot{m}_{out}}{\dot{m}_{in} \times L_B} \quad \text{(per unit)}$$

or

$$\dot{s}_{\%} = 100\ \dot{s} \qquad \text{(percent)}$$

Note that $\dot{s}$ and $\dot{s}_{\%}$ have dimensions mass/unit time and length $(ML^{-1}T^{-1})$. Example: A spillage rate of 10^{-5} or 0.01% per 0.3 m (1 ft) of belt, on a belt 30.5 m (100 ft) long fed at the rate of 1.8 Mg/h (2 tons/h), would amount to a total amount of mass spilled, over 1 hour, equal to $10^{-5} \times 10^2 \times 1.8$ Mg = 1.8 kg (4 lbs). This would represent 28 dm^3 (1 ft^3) of a material having a bulk density of 64 kg/m^3 (4 lbs/ft^3).

The concept of admissible (or maximum) spillage rate, $\dot{s}_{max}$, is introduced as that upper bound on the spillage rate which, over the time periods and lengths of belt considered, is deemed tolerable under the conditions of use. The designer should choose, for a given material and system geometry, an operating point leading to a lower spillage, $\dot{s}$, than the maximum tolerable one, $\dot{s}_{max}$.

Obviously, the absolute level of such spillage rate is partly a matter of judgment, partly specific to the material conveyed and the operating conditions at the site. By the same token, in designing a test procedure for the present investigation, the admissible (or maximum) spillage rate was selected on the basis of engineering judgment; not so small that it could not be measured with a good degree of accuracy, yet not so large that it would make the volumes physically interactable and the flow rates unsteady. Thus, to some extent, the choice of threshold "s_{max}" is influenced by the material conveyed, the characteristics of the experimental setup and the attainable ranges of test parameters, such as capacity, belt speed, etc.

In the discussion, the material being conveyed is assumed to be given, from among the fractions listed and described above. Its properties and characteristics, in the sense explained previously, have been measured and recorded.

The size and geometric characteristics of the conveyor belt are assumed to be known. In the present case, as shown in Figure 6, this amounts to giving the belt width w, part of which (w_1) is on the horizontal rollers, and part of which (w_2) is resting on the idlers. β is the idler angle. The spacing between idlers is ℓ.

The static capacity is determined as follows. Along a length of belt sufficiently long to be able to ignore end effects, the material under study is piled up on the belt, at rest, so that the edge of the pile, on either side, touches the edge of the belt. If a unit length (L = 1) of belt is considered, it has a cross-section similar to that sketched in Figure 6. The static capacity, C_{ST}, will be defined by the area of this cross-section, equal to

$$C_{ST} = \frac{h_1}{2} (w_1 + 2w_2') + w_2' \tan \beta \, (w_2' + w_1),$$

with $w_2' = 1/2 \, w_2 \cos \beta$.

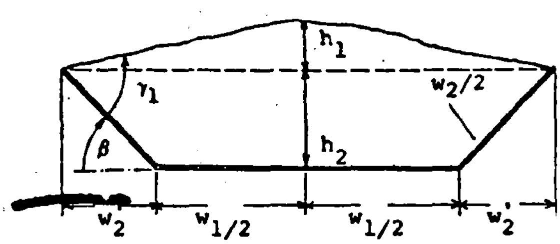


Figure 6. Cross-section of loaded belt (at rest).

In this formula, h_1 is measured. C_{ST} has the dimension of an area (L^2), and $C_{ST} \times L_B$ is the volume of material resting on a length L of the belt.

If in the experiment outlined above, we set the belt in motion, the material resting on the belt will tend to "crumble" along the sides of the (two-dimensional) pile, and the cross-sectional area occupied by the material will decrease below the value at rest, C_{ST}. In other words, the belt volumetric carrying capacity will not be that which would be realized if the cross-sectional area C_{ST} could be maintained without spillage under dynamic conditions (belt at speed V); namely, $Q_{ST} = C_{ST} V \quad [L^3T^{-1}]$.

To quantify this reduction, it is proposed that a prescribed degree of spillage (per unit time and unit length of belt) be specified in advance, s_*, say. Under such conditions, a measured (or computed) area, or "capacity," C_{DYN} is obtained experimentally. The reduction in capacity resulting from the motion is then assessed by a reduction coefficient:

$$k_{RED} = \frac{C_{DYN}}{C_{ST}}$$

which itself is a function of the dynamic parameters, as described hereunder, and of the prescribed degree of spillage. Intuitively, it is obvious that the dynamic capacity would, all other factors being equal, be expressed by a larger number if the allowed rate of spillage is larger.

One way to look at the last relationship is to consider k_{RED} as a measure of the "efficiency" with which the volume above the belt is occupied under dynamic conditions, compared to the maximum volume achievable at rest, for a prescribed degree of spillage.

After these preliminaries, it is now possible to state what the independent and dependent variables should be in the "basic" test proposed.

The geometry, size of the system, and the conveyed material are given. Among other properties, its loose bulk density (in the "conical" mode) has been determined. It is assumed that the variations of this density with the speed and loading of the belt are small and neglected (a fact confirmed by observations). The fundamental variables:

- mass flow rate, $\dot{m}$
- area of cross-section of the belt occupied by the material, or dynamic capacity, C_{DYN}
- V, belt speed

are related to each other and the measured bulk density, ρ_b, by

$$\dot{m} = \rho_b C_{DYN} V \quad (1)$$

We are at liberty to select V, the belt speed, as an independent variable. Increasing it might increase the conveyor carrying capacity, but this is not uniformly true. Excessive speeds would increase spillage beyond tolerable limits, due to blow-back and mechanical shocks and vibrations. Similarly, we could select C_{DYN} of the material on the belt, as an independent variable, and attempt to increase it (for fixed V) to increase the carrying capacity. Again, this might only be possible to a point, due to excessive "mass spillage" from the crumbling, sloughing slopes of the moving load.

Finally, the throughput $\dot{m}$ and belt speed V could be varied, but the dynamic capacity, calculated from equation (1) would still need to be related to the observed spillage rate.

Thus, in actuality, equation (1) should be used as an equation to compute C_{DYN}, given a spillage rate $\dot{s}$ related to the throughput and belt speed by

$$\dot{m} = F(\dot{s}, V) \quad (2)$$

or solving for $\dot{s}$,

$$\dot{s} = \mathcal{J}(\dot{m}, V) \quad (3)$$

In this preferred form, the choice of independent and dependent test variables is apparent:

- for one series of experiments, the mass flow rate $\dot{m}$ will be set at a fixed value $\dot{m} = \dot{m}_1$ (independent variable: $\dot{m}$)
- in that series of experiments, the velocity of the belt, V, will be varied over an operating range, $V_{min} \leq V \leq V_{max}$ (independent variable: V).

For every pair ($\dot{m}_1$, V), the spillage rate s will be measured as the dependent variable. As explained before, if $s = s_*$ (some chosen value) for some pair ($\dot{m}_*$, V^*) obtained from experimental or graphed results, C_{DYN}, the dynamic capacity for spillage rate s^*, is computed as

$$C^*_{DYN} = \frac{\dot{m}_*}{\rho_b V^*} \quad (4)$$

Dividing this expression by C_{ST}, previously defined, the dynamic coefficient of reduction in capacity, k^*_{RED} (corresponding to spillage rate $\dot{s}_*$) is

$$k^*_{RED} = \frac{C^*_{DYN}}{C_{ST}} = \frac{\dot{m}_*}{\rho_b C_{ST} V_*} \quad (5)$$

In summary, it appears logical to select the throughput $\dot{m}$ and belt velocity V as independent variables, and to measure the spillage rate $\dot{s}$ as a dependent variable. Other subsidiary quantities, such as the dynamic capacity or coefficient of reduction in dynamic capacity, can then be computed from the previous ones.

Functional Dependence of Spillage and Mass Flow Rate on Velocity

On physical grounds, the expected dependence of the spillage rate on belt speed and mass flow rate could be obtained.

(a) Fixed spillage rate: Indeed, consider, for given spillage rate, $\dot{s} = \dot{s}_*$, the dynamic reduction coefficient, k^*_{RED}. At very low speeds, this quantity is expected to be smaller than, but on the order of, 1. At very high speeds, on the other hand, the whole mass being conveyed will be spilled, due to aerodynamic effects, vibrations and shocks on the idlers. Ideally, $k^*_{RED} \to 0$ when $V^* \to V^*_1$, as shown in Figure 7. Thus, k^*_{RED} is conjectured, on physical grounds, to have the shape of a monotonously decreasing function, over the range of interest for V^*. But since the mass flow rate $\dot{m}_*$ corresponding to velocity V^* and spillage rate $\dot{s}_*$ is

$$\dot{m}^* = \rho_b C_{ST} k^*_{RED} V^* \qquad (6)$$

it follows that $\dot{m}^*$ should have a maximum, shown as point Z (belt speed V^*_{opt}) in Figure 7. Thus, for a given spillage rate, there should exist an optimal velocity, for which throughput is maximized.

(b) Fixed mass flow rate: Using Figure 7 in a plane of coordinates mass flow rate, velocity or $(\dot{s}, V)$, it is here possible to locate two points, or abscissa V_C, V_D, respectively, and ordinate $\dot{m}$, which are on a locus $\dot{m} = \mathcal{M}(\dot{s}_*, V)$, i.e., a curve of constant spillage rate, $\dot{s}_*$. If a number of plots such as Figure 7 are drawn, a family of curves corresponding to various mass flow rates can be obtained. From these, in turn, curves, giving the spillage rate vs. V, for given mass flow rate $\dot{m}$ are derived and given by equation $\dot{s} = \mathcal{S}(\dot{m}, V)$. For convenience, these curves will be labeled the "$\mathcal{S}$" curves shown in Figure 8.

(c) Use of the $\mathcal{S}$ curves in system design: On Figure 8, possible uses of the network of $\mathcal{S}$ curves are illustrated, such as:

(i) checking that a selected operating point, say P of coordinates $(V_P, \dot{m}_P)$ on Figure 8 corresponding to a combination belt speed and throughput, has a spillage rate $\dot{s}_P$ which is considered acceptable.

(ii) determining the maximum throughput $\dot{m}_Q$, and corresponding velocity V_Q, achievable at the prescribed maximum spillage $\dot{s}_{max}$ (Figure 8).

(iii) choosing a preferred operating point between the two points (P and R on Figure 8) corresponding to a rate of spillage $\dot{s}_P < \dot{s}_{max}$. If, for example, the range $(\dot{m}_P, \dot{m}_T)$ has to be covered in operation, then V_R would be preferable to V_P, since the rate of spillage corresponding to $(V_P, \dot{m}_T)$ exceeds the maximum admissible $\dot{s}_{max}$. Such is not the case for V_R, for which $\dot{s}_U$, corresponding to that speed and a mass flow rate $\dot{m}_T$, is lower than the maximum admissible spillage.

Inclined Belt: Analysis of Test Procedure and Variables

The geometry of the inclined conveyor belt is sketched in Figure 5. In the present case, the inclination, α, is not zero. If α is progressively increased until it reaches a threshold, α_{TH}, or angle

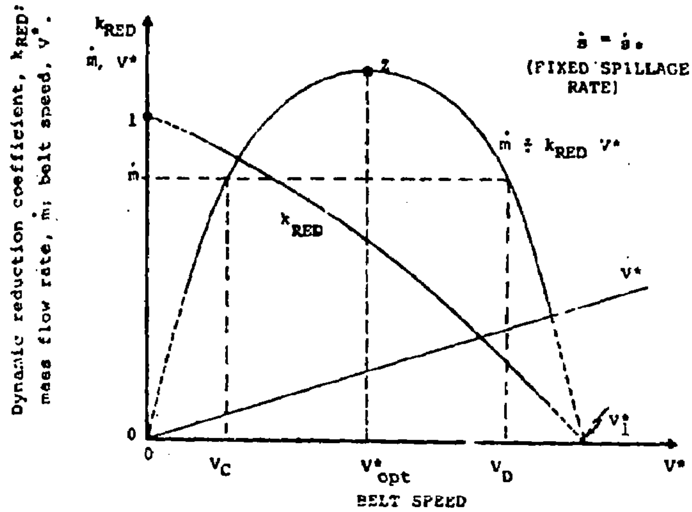


Figure 7. Shape of curves of dynamic reduction coefficient vs. speed, and mass flow rate vs. speed (fixed spillage).

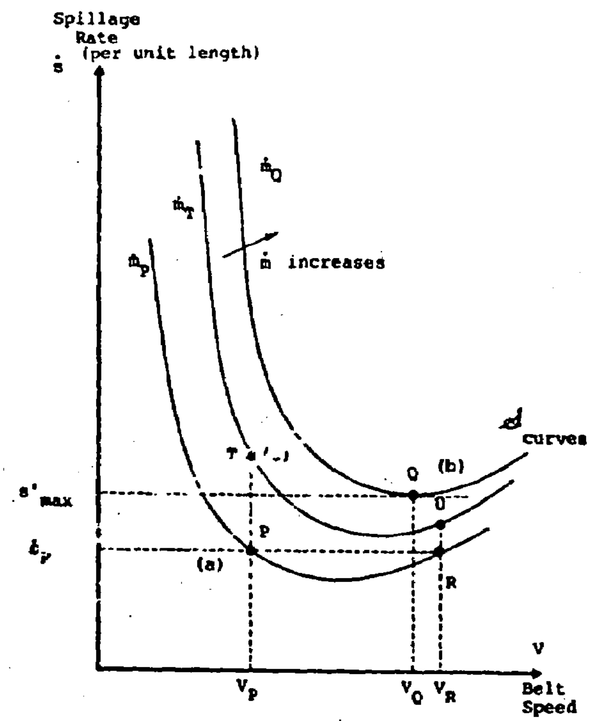


Figure 8. Examples of use of "$\mathscr{S}$" curves.

of maximum inclination, the material will roll back on the belt. The forward motion of the material on the supporting inclined belt becomes impossible.

From the results given above, it is observed that threshold α_{TH} is significantly lower than the angle of slide on the conveyor belting material. At angles equal to or larger than α_{TH}, backsliding becomes so pronounced that adequate, steady feeding cannot be maintained at the transfer point between the apron-feed/chute and the tail pulley section of the belt. Accordingly, the experiments were limited to an upper limit for the inclination angle, α, relatively close to but lower than α_{TH}. For example, as described in detail in the test results below, for MSW, the angle of maximum inclination on the belt was 19°. The angles selected for inclined conveying were 18° and 14°.

As explained above, the belt speed V and mass flow rate $\dot{m}$ were selected as independent variables. The dependent variable will again be: $\dot{s}$, spillage rate, per unit mass of throughput and unit length of belt (as previously defined).

In a grossly qualitative sense, the arguments given in the preceding pages to justify the dependence of the spillage rate on the belt speed, at given mass flow rate $\dot{m}$, and of the spillage rate on the mass flow rate, at given belt speed, are expected to remain valid for the inclined belt, provided the angle of inclination is not too close to that leading to generalized slip and rollback. If so, the curves giving the spillage rate vs. V, belt speed, given the capacity $\dot{m}$, would then look like the "$\mathscr{A}$" curves of Figure 8. The "steepness" of the sides, value of the optimum speed leading to minimum spillage and generally, position of the curve in the plane of representation are expected, obviously, to depart from those corresponding to the horizontal case.

Qualitatively speaking, an argument can be made that increasing the inclination, from zero, leads to vertical cross-sections A_V (instead of A_O, for $\alpha = 0$) which are larger and of steeper slopes (Figure 9). In the horizontal case, at relatively "low" V, the increase in carrying cross-section (or dynamic section) necessary to carry the same mass flow rate $\dot{m}$ at lower speed is accompanied by an increase in spillage rate. A similar effect can be presumed to exist if the belt is inclined: moderate for moderate inclinations, but extremely pronounced as α approaches the belt maximum inclination, α_{TH}. As a function of V, the effect should be less important at high speeds than at low speeds, since less of the belt width is utilized and the height of burden can be kept smaller for the same capacity (Figure 10).

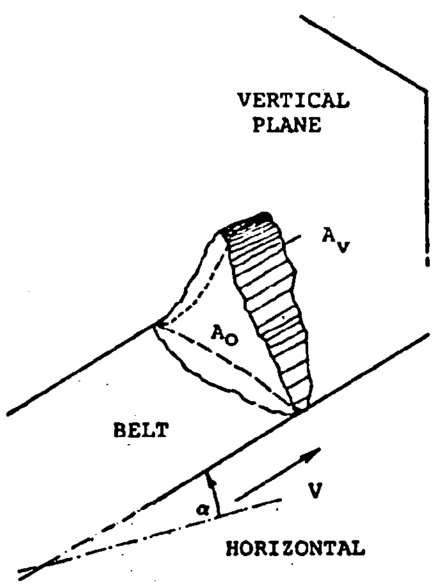
An increase in mass flow rate, when conveying a given material on a belt of given inclination α running at a given speed V, entails an increase in area of the cross-section on the belt occupied by material. This should cause an increase in spillage rate, as illustrated in Figure 10.

Assuming that the "$\mathscr{A}_\alpha$" curves giving: $\dot{s} = \mathscr{A}_\alpha(\dot{m}, V)$ for inclination α have the shape shown in Figure 11, then there exists a minimum spillage $\dot{s} = \dot{s}_*$ at given mass flow rate $\dot{m} = \dot{m}_*$, corresponding to an optimum operating belt speed equal to V_*.

Operating Point. At inclination α and mass flow rate $\dot{m}_P$, two operating points, P and Q, might exist corresponding to a spillage rate $\dot{s}$ not exceeding the admissible one, $\dot{s}_{max}$ (Figure 11).

In the example illustrated in Figure 11, point Q is preferable to point P, since it allows a larger increase in mass flow rate before the maximum admissible level, $\dot{s}_{max}$ is reached.

Operating Range. The experimental results described as follows show that, in most instances, the sensitivity of the spillage rate to an increase in flow rate and/or inclination is, for the same level of spillage, much smaller in the upper range of belt speeds (i.e., to the right of the point). In such cases, it would be more efficient to operate in this range, for lower spillages under deliberate or accidental variations of belt speed and mass flow rates about the nominal design conditions. Figuratively speaking, at any practical



A_0: normal to belt trough and belt speed

A_V: vertical $\cdot$ $A_V = \dfrac{A_0}{\cos\alpha} > A_0$

Figure 9. Increase in vertical cross section with inclination.

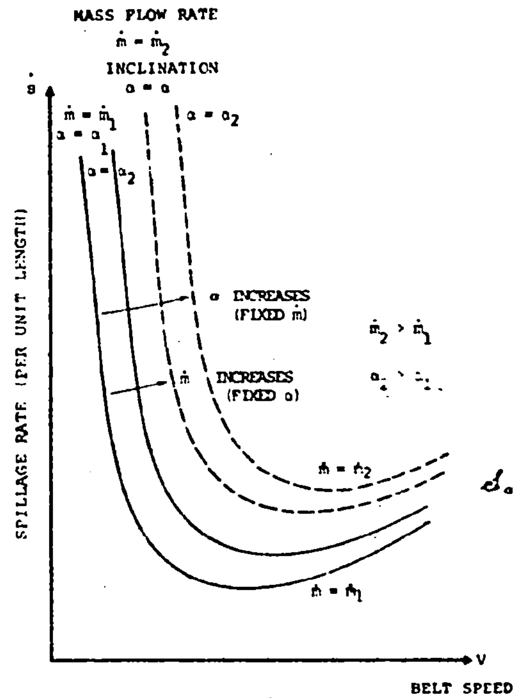


Figure 10. Family of curves "$\mathcal{S}_\alpha$".

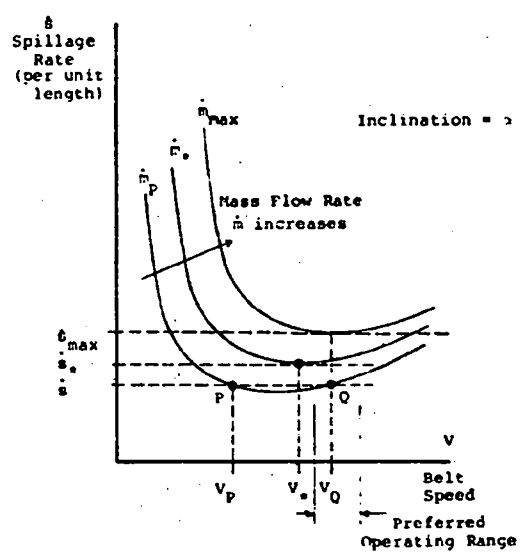


Figure 11. Optimum Speed V_* and preferred operating range, at inclination α.

inclination, the belt should be operated "fast and lean" rather than "slow and loaded."

Other Comments

At high speed, the increase in spillage rate is due to aerodynamic "blow-back" and vibrations and shocks on the rollers and idlers. Physically, aerodynamic "detachment" and "vibrations" should not depend to any degree on inclination at small angles to the horizontal. Thus, the level of spillage, all other factors being equal, should not vary much with the inclination if the material is flat and self-compacting, as is the case with RDF. However, waste or fractions thereof containing a fair percentage of spherical or cylindrical pieces likely to roll down the inclined belt, should show a rapid increase of spillage with speed, in the upper range of speeds.

BELT CONVEYOR: SUMMARY OF EXPERIMENTAL RESULTS

The 7.63 m (25 ft) long, 0.457 m (18 in.) wide test belt conveyor, in the closed loop rig sketched in Figure 2, was equipped with a variable drive motor, allowing a feed range from 0.20 m/s (40 fpm) to 2.44 m/s (480 fpm). Two sets of similar idlers were used: either 20°, or 35°. To guide the material fed to the belt, a feed chute and 1.1 m (3.5 ft) of skirting were assembled at the tail pulley. Test results are given and discussed below. Complete details on these tests may be found elsewhere (4).

Horizontal Mode Test Results

A certain fixed mass was placed on the test conveyor, at the chosen belt speed, providing a quasi-constant mass flow rate, over sufficiently short test durations and in the absence of excessive spillages (4). All spillage from the test belt (including its frame and pulleys) and from the floor was accumulated over approximately 30 minutes and weighed. The sides of the test conveyor were isolated with plastic sheets to avoid including spillage caused by the return and feed conveyors. Troughing belt idlers at 20° and 35° were investigated.

Sample results are given for:

- shredded MSW, for three mass flow rates and two idler angles (20°, 35°) (Figure 12)

- RDF, also for three mass flow rates and two idler angles (Figure 13)

- the ferrous fraction (MF) for 35° idlers and three mass flow rates (Figure 14)

The whole set of result curves appears in the final report of this project (4).

Based on these complete results, the analysis performed prior to the tests and outlined above was indeed confirmed. High spillage rates are observed at lower belt speeds. Upon increasing the belt speed from a very low value, the rate of spillage (for a constant mass flow rate) decreases to a minimum value, then gradually increases. Higher mass flow rates, for a given material and belt speed, lead to higher spillages, and the location of the minimum spillage point moves towards higher belt speeds.

Although all the solid waste fractions show similar patterns of behavior, the specific values of spillage rates for each individual fraction are dependent on its properties and characteristics. For example, it was observed that d-RDF, being relatively uniform, showed a much lower spillage, all other factors being equal, than more coarse, heterogeneous fractions (4).

Noteworthy is the fact that, except at negligible throughputs, conveying will always generate <u>some</u> spillage. Also, the results <u>clearly</u> indicate, as shown in Figure 13, that the utilization of 35°

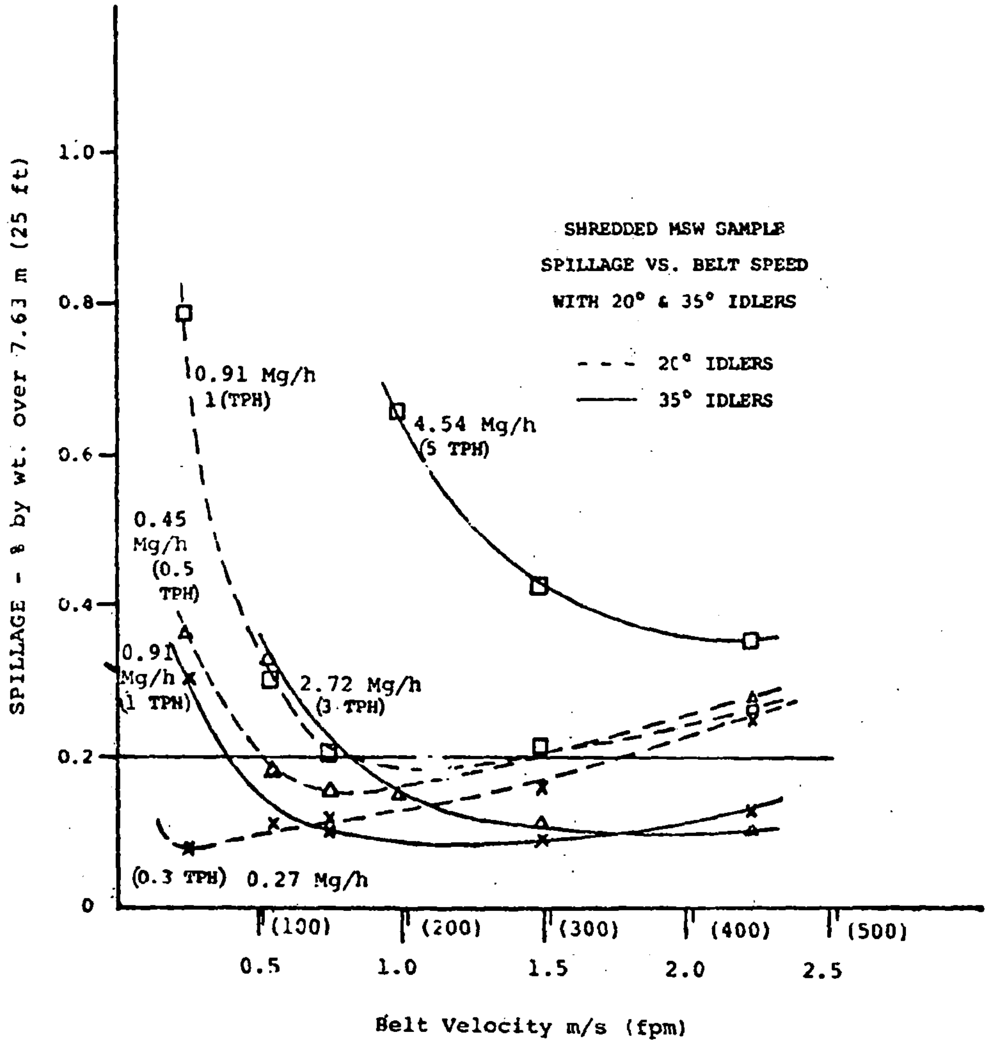


Figure 12. Shredded MSW. Spillage vs. belt speed.

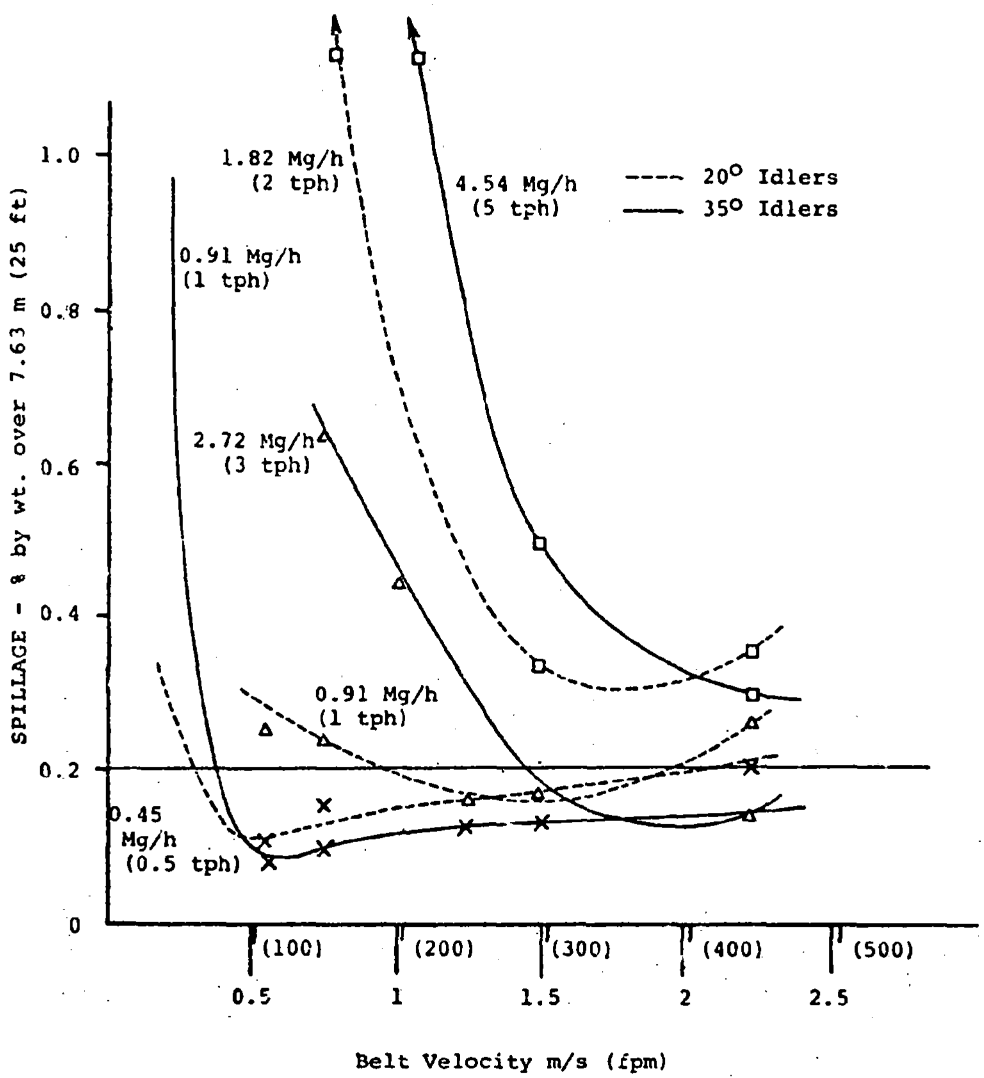


Figure 13. RDF sample. Spillage vs. belt speed.

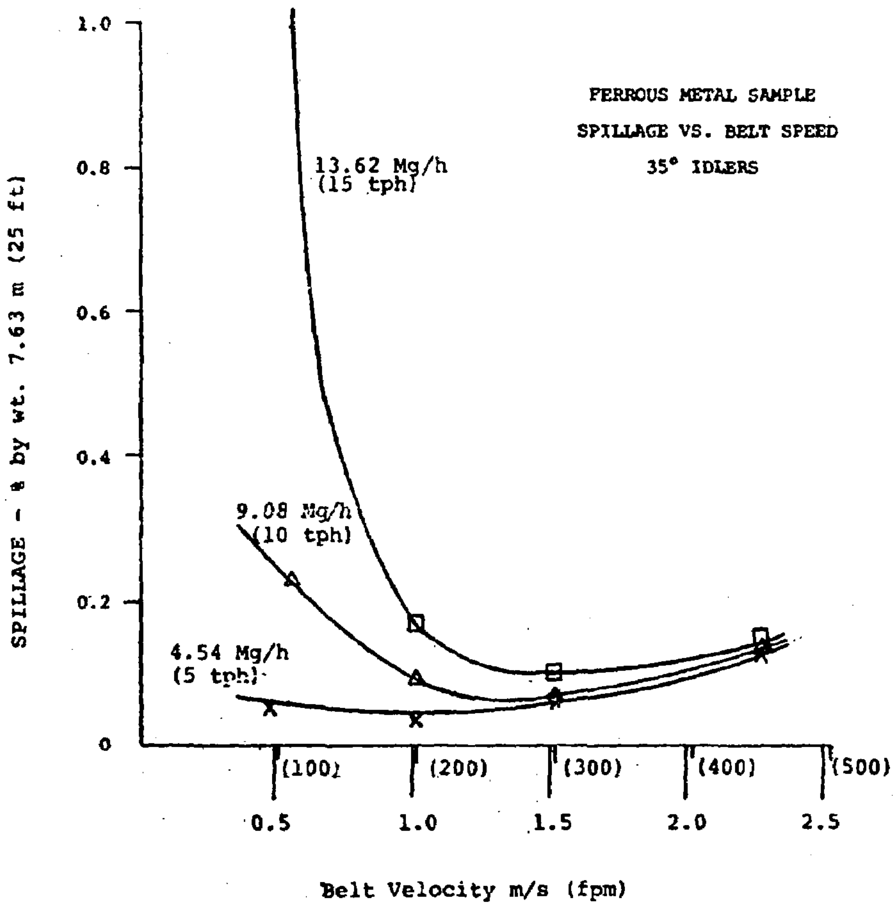


Figure 14. Ferrous metal sample spillage vs. belt speed.

troughing idlers allows higher throughputs, for the same amount of material spilled over a given time.

The distribution of the spilled material along the section length was also recorded. The test conveyor was divided into four sections (labeled 1 to 4) of length 1.1 m (3.5 ft), 1.7 m (5.5 ft), 3.7 m (12 ft), 1.2 m (4 ft) respectively, counted from the tail pulley towards the head pulley. Spillage was separately collected and weighed for each of these sections at a given mass flow rate and for different belt speeds. Table 12 is an example for each of this distribution for RDF conveyed at the rate of 2.7 Mg/h (3.0 tph) (4).

It is seen that at 0.76 m/s (150 fpm), for example, most spillage occurs from the first two sections. In section 1, the 37.5% spilled are a result of RDF fines, inert, inorganic particles, wedging between the belt and its skirting, and being squeezed and spilled out. The spillage in section 2 (43.0%) is, at this relatively low operating speed, the result of crumbling and troughing of the RDF material from the sides of the conveyor. At a higher speed of 1.53 m/s (300 fpm), the amount of spillage at section 2, 9.5%, is considerably lower than at 0.76 m/s (150 fpm), which is due to the lower belt loading. On the other hand, a higher percentage (52.4%) of the spillage is observed at section 4, probably due to the higher centrifugal forces acting at the head pulley. In summary, the amount and distribution of spillage area result from non-uniform feed, very low or very high belt speed, improper feed and skirting arrangements, and carryover of adhesive, sticky material around the head pulley.

Trajectories, or discharge paths of the material after the end pulley, were m sured at a given capacity and different speed by a direct observation technique, recording the fall height vs. fall distance (4). In actuality, the material, depending on the belt velocity, is discharged from the head pulley in the form of a band. The trajectories in these figures have been derived from plotting from the band's mid-stream points. An example is given in Figure 15. The experimental values were compared to the theoretical discharge trajectory, also plotted in Figure 15.

The theoretical and experimental values correspond reasonably well. This suggests that the method, provided by CEMA, for theoretical trajectory calculations, could be successfully used to predict solid waste trajectories accurately.

As regards power consumption, and contrary to what was expected, results indicated negligible measurable change in the belt motor current for a wide range of velocities, capacities and materials. This negligible change in power consumption - despite extreme variations in such conveying conditions as speed, gravitational load, etc. - was probably due to the utilization of a motor which surpassed required design and capability. The disadvantage of using a skirtboard across the whole length of a long belt conveyor would be to increase the frictional resistance and, therefore, the horsepower requirement. Specific information for detailed horsepower calculations can be obtained from reference (2).

Inclined Mode: Test Results

The tests measured spillage vs. mass flow rate and speed, for a given material and belt inclination (4). Inclinations of 14° and 18° were tested. Overall experiments corroborated the speculation, from analysis, that higher spillages will be encountered on increasing the belt inclination, and that a preferred speed exists at given mass flow rate and inclination. An example in point is shown in Figure 16 for MSW and 35° idlers.

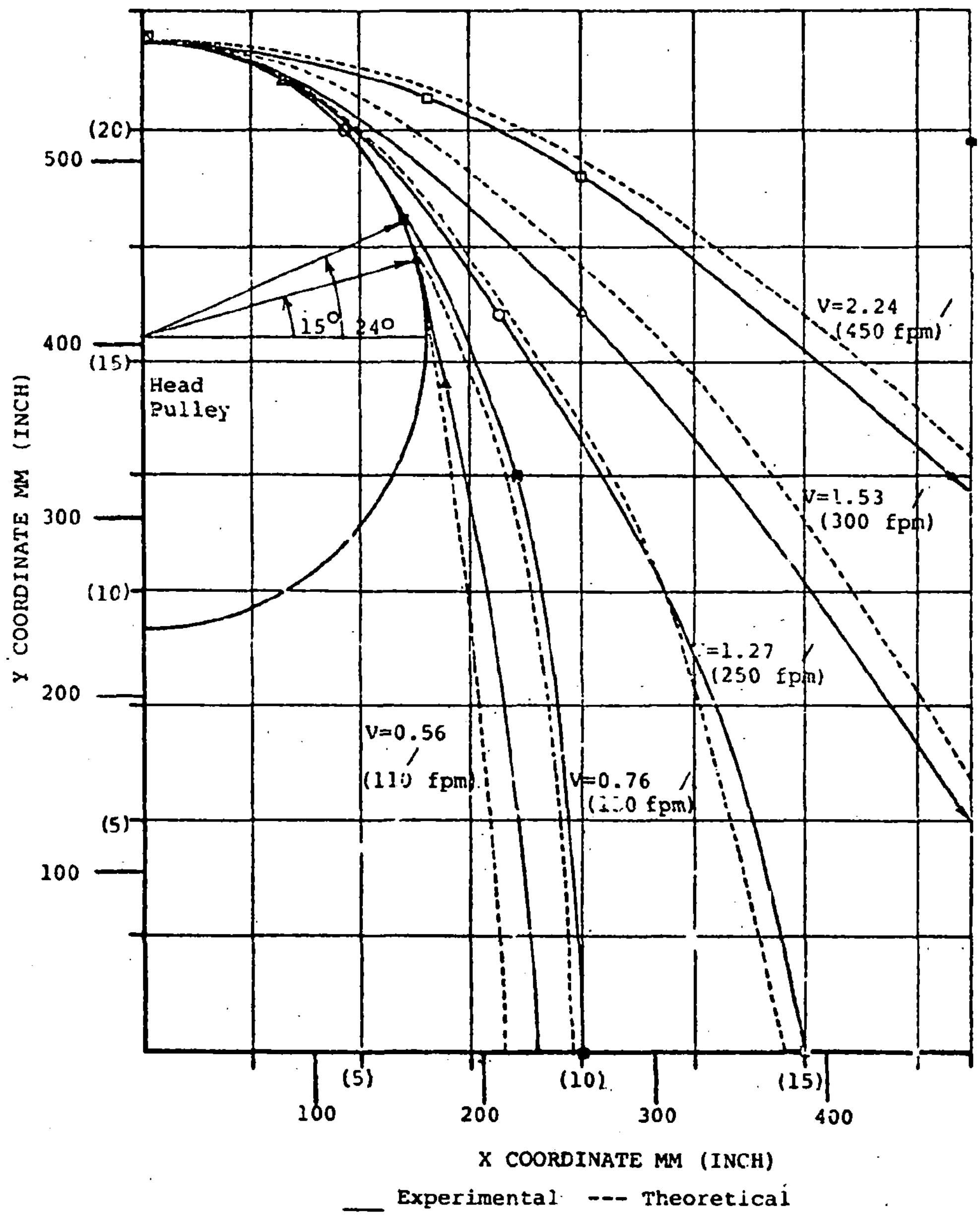


Figure 15. Trajectories for RDF at 0.91 Mg/h (1 tph) and 20° idlers.

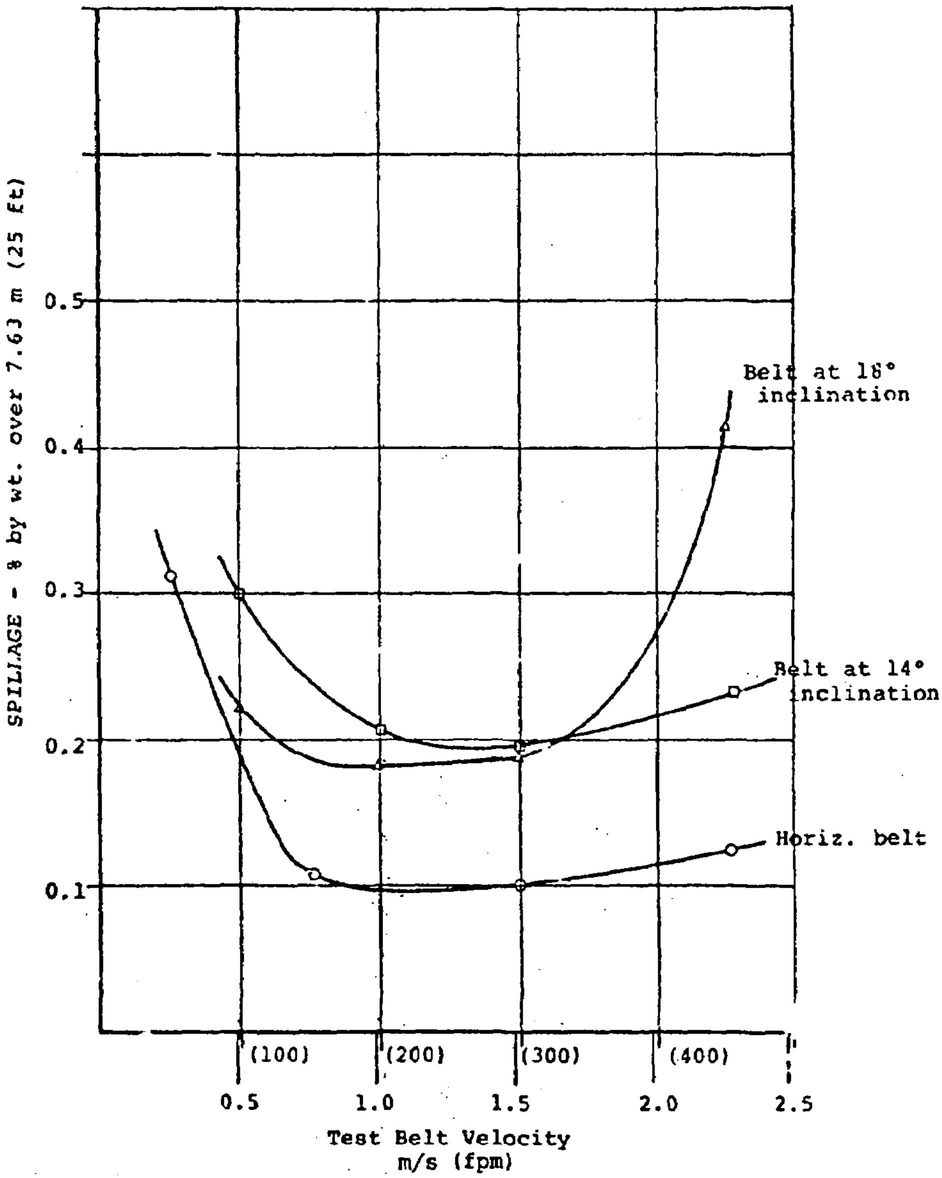


Figure 16. Dependency of MSW Spillage on test belt velocity for a fixed mass flow rate of 0.91 Mg/h (1.0 tph), 35° idlers.

TABLE 12. SECTIONAL SPILLAGES MEASURED AND REPORTED AS A PERCENT OF THE TOTAL SPILLAGE

RDF conveyed at 2.7 Mg/h (3.0 TPH)

Section	Percent of total spillage Test conveyor velocity m/s (fpm) 0.76 (150)	 1.53 (300)	 2.29 (450)
1	37.5	23.5	24.2
2	43.0	9.5	13.1
3	13.2	14.6	13.6
4	6.3	52.4	49.1
Total	100.0%	100.0%	100.0%
Spillage rate, kg/h (lbs/h)	17.5 (38.5)	3.87 (8.52)	3.63 (8.00)

Dust Levels Generated

Sierra high volume dust samplers (Model 305-2050H) were used to determine the magnitude of dust generated, during transportation of the solid waste fractions, on the inclined test belt conveyor. An attempt was made to determine if any relationship between the extent of dust generated for parameters such as the test belt's angle of inclination, its velocity and mass flow rate of the material existed. One dust sampler was placed approximately 5 feet away from the tail pulley, next to the inclined belt. This sampler measured the quantity of dust generated at the turbulent feed end of the belt conveyor. A second dust sampler was located approximately 6.1 m (20 ft) away from the conveyor system. The results of the second sampler were inconsistent and unreliable, possibly due to background dust interferences in the testing area. It was not possible to reduce or completely remove the laboratory dust levels within a reasonable time on completion of a test run; therefore, only the dust loadings measured by the sampler located at the conveyor feed end were reported.

The test results provided the total suspended dust (4). Particle size distribution or any further characterization of the dust was not attempted. The test method and calculations are described elsewhere (4).

For more complete details on dust sampling methods and procedures, the reader should refer to ASTM D2009 and D1356 standards.

No consistent trends were readily apparent, but a tendency towards greater dust concentration was indeed observed for higher mass flow rates and belt conveyor inclinations. For RDF, d-RDF and the d-RDF/coal blend, the experiments strongly suggested the use of a dust collection system at the conveyor's feed end. For MSW and the heavy fraction, relatively lower dust loadings were recorded, in fact much below OSHA's threshold limit of 15 mg/m^3, time-weighted average (5).

VIBRATING CONVEYORS: CARRYING CAPACITY VS. FREQUENCY AND STROKE

Another part of the NCRR investigation dealt with vibrating conveyors, and measured the dependence of the carrying capacity for different waste fractions as a function of the vibration frequency and stroke amplitude. Only the main results and conclusions of the work described in reference (4) will be reported here.

Vibrating conveyors - having relatively few moving parts and designed to operate with minimum maintenance - have found a number of applications in the resource recovery industry for the feeding and/or discharge from such units as air classifiers, shredders, etc. The theoretical principle of their operation, illustrated in Figure 17, shows that during the first part of the acceleration of the pan, a particle resting on it will be thrown up and away from it, and then fall back onto it during the next vibration period (one-cycle jump). A higher stroke (amplitude) might accelerate the material in a two-cycle jump, but this would require a much higher energy input.

The test vibrating conveyor, 4.6 m (15 ft) long by 0.6 m (2 ft) wide with a pan height of 205 mm (8 in.) was manufactured by Carman Industries. This conveyor was driven by an eccentric rotating cam linked mechanically to the pan at 30° (4).

The conveyor was tested at 400 and 570 cycles/min (cpm), utilizing a variable drive motor. Two replaceable, eccentric cams allowed the stroke to be changed either 12.7 mm (0.5 in.) or 22.2 mm (0.875 in.). Dynamical balance also requires a balancing weight and the removal or addition of leaf springs, for a fixed stroke and frequency (Figure 18). Test results show that considerably more work is needed to rationally design a conveyor of appropriate stroke length and frequency for a given solid waste fraction.

Within the finite scope of the program, it was not possible to undertake a systematic study of this complex mechanical system and its dynamics. The operating range was selected on an empirical basis, adopting as a reasonable operating criterion that the measured vibration of the base not exceed 3.2 mm (1/8 in.). All points corresponding to a pan vibration of 12.7 ± 3.2 mm (1/2 ± 1/8 in.) were considered "12.7 mm" (1/2 in.) stroke tests, and all points for which the amplitude was 22.2 ± 3.2 mm (7/8 ± 1/8 in.) were considered "22.2 mm" (7/8 in.) stroke tests. This limited the range of operating frequencies to 430 - 545 cpm (22.2 mm stroke) or 90 - 550 cpm (12.7 mm stroke).

The tests conducted determined for the two values of the stroke specified, the maximum carrying capacity and conveying speed (for fixed mass flow rate) vs. frequency; the energy consumption vs. burden depth, at a given frequency; the compaction and segregation of material along the length of the pan; the dust level generated vs. pan stroke; the conveying speed vs. material moisture content. These results are graphed in reference (4). A sample set of result curves is given in Figure 19.

The following conclusions could be drawn from the complete series of tests:

- For all fractions examined, over the range of frequency investigated, the carrying capacity increases with both frequency and stroke. However, on physical grounds, the capacity curve is expected to reach a saturation level at some higher, undetermined frequency. At 540 cpm, increasing the amplitude from 12.7 mm (1/2 in.) to 22.2 mm (7/8 in.) increases the capacity by a factor of from 1.7 to 2.6, depending on the material.
- At a given mass flow rate, the conveying speed increases with increased frequency. This increased speed might be beneficial

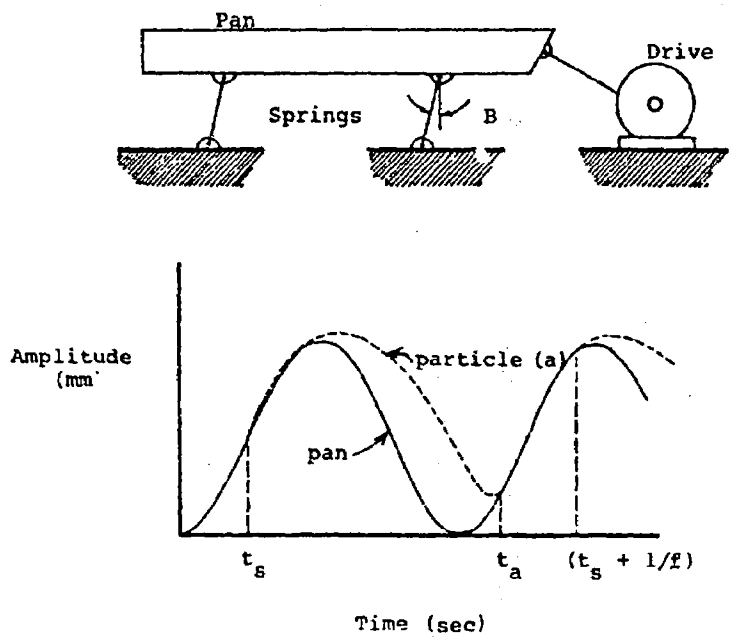


Figure 17. Vibrating conveyor principle.

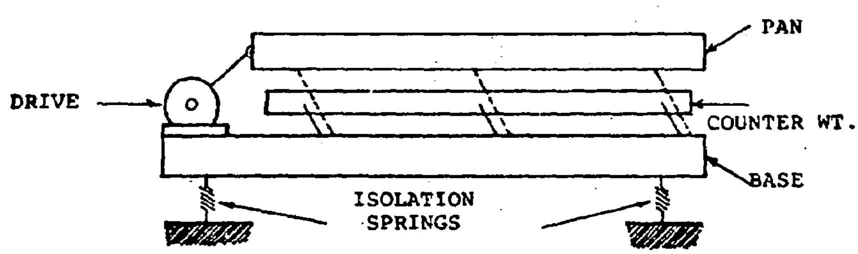


Figure 18. Schematic of vibrating conveyor.

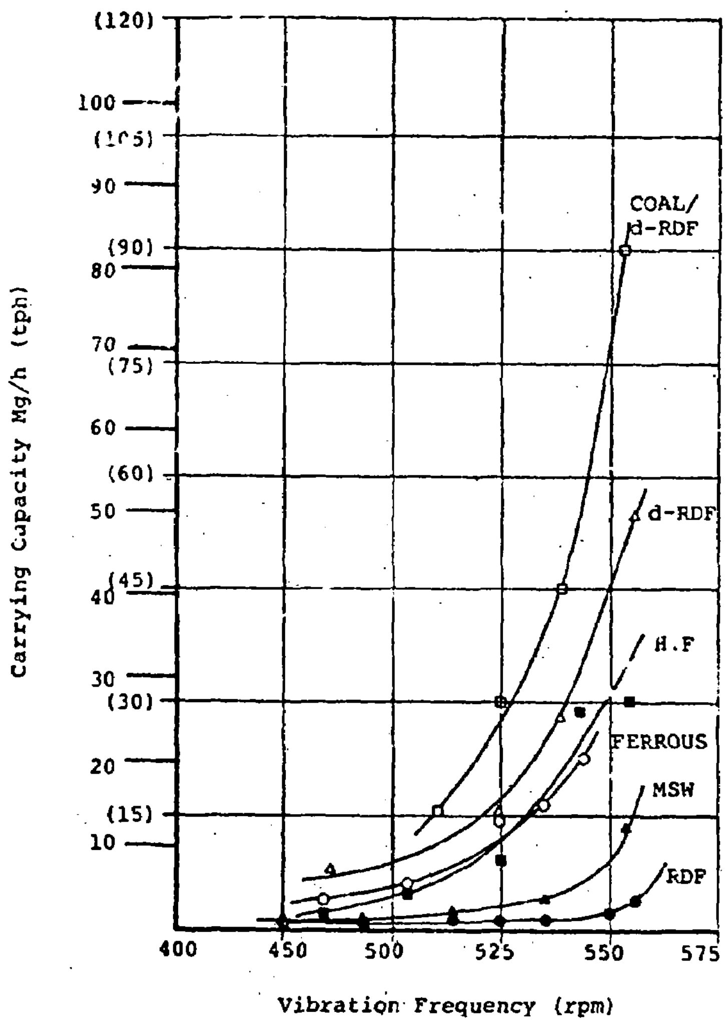


Figure 19. Carrying capacity of test vibrating conveyor vs. vibration frequency for 13 mm (1/2 in.) stroke.

in reducing the chances of buildups, jams and spillages. At 540 cpm, speeds on the order of 0.20 to 0.25 m/s (40 to 50 fpm) were observed for a 12.7 mm (1/2 in.) stroke and from 0.46 to 0.51 m/s (90 to 100 fpm) for a 22.2 mm (7/8 in.) stroke.

- No significant difference in energy consumption, at a given frequency and amplitude, was observed for different bulk solids (d-RDF/coal vs. RDF, for example).

- At a fixed frequency, chosen equal to 510 cpm, the vibrating conveyor was uniformly loaded with the solid waste material, at three burden depths, ranging from 25.4 to 152.4 mm (1 in. to 6 in.). Experiments were carried out for the 12.7 mm (1/2 in.) and 22.2 mm (7/8 in.) strokes (Figure 20). For the six fractions, a decrease in conveying speed with increasing burden depth was observed. Negligible for the heavy fraction (HF), it is observed to be 32% for RDF, when the stroke length is 22.2 mm (7/8 in.) and the height of burden increases from 51 mm (2 in.) to 152 mm (6 in.). This indicates that the energy imparted by the vibrating pan is absorbed rather than transmitted, as is the case for denser fractions.

- The tendency for the material to compact as it progresses down the pan was measured, at a fixed frequency (520 cpm), stroke length (22.2 mm) and initial height of burden (76.2 mm). The percent lowering of burden height over 4.58 m (15 ft) of conveyor varied from 18.3% for HF to 44.1% for MSW. Thus, there is a definite tendency for the solid waste fraction to compact due to the vibrational activity of the pan. MSW and RDF, relatively more compressible, showed the highest degree of compaction.

- The segregation of material along the depth of the burden was also evaluated. Most solid waste fractions are composites of varying bulk density components. For example, RDF, which is rich in paper and plastics, could have an inert or fines content (ceramics, silicates, glass) as high as 20%. A test was conducted to determine if varying components of a solid waste fraction segregate out, due to vast bulk density differences. A particle size distribution was performed on a "top" and a "bottom" layer to determine the extent of segregation. The frequency was fixed at 510 cpm, and two strokes (12.7 and 22.2 mm) were studied. Without reproducing detailed results given elsewhere (4), and to summarize, it was observed that the smaller particles in MSW and HF did indeed concentrate in the bottom layer. Such was not the case for RDF, presumably due to the tendency of fine particles to adhere on paper flakes.

- A slight decrease (less than 10%) in conveying speed (for a given material, frequency, stroke and height of burden) was generally observed when moisture was increased from about 10 to 15 wt% to the 30 to 40 wt% range. This was true for MSW, HF and the d-RDF/coal blend, and was attributed to enhanced adhesion characteristics. A slight

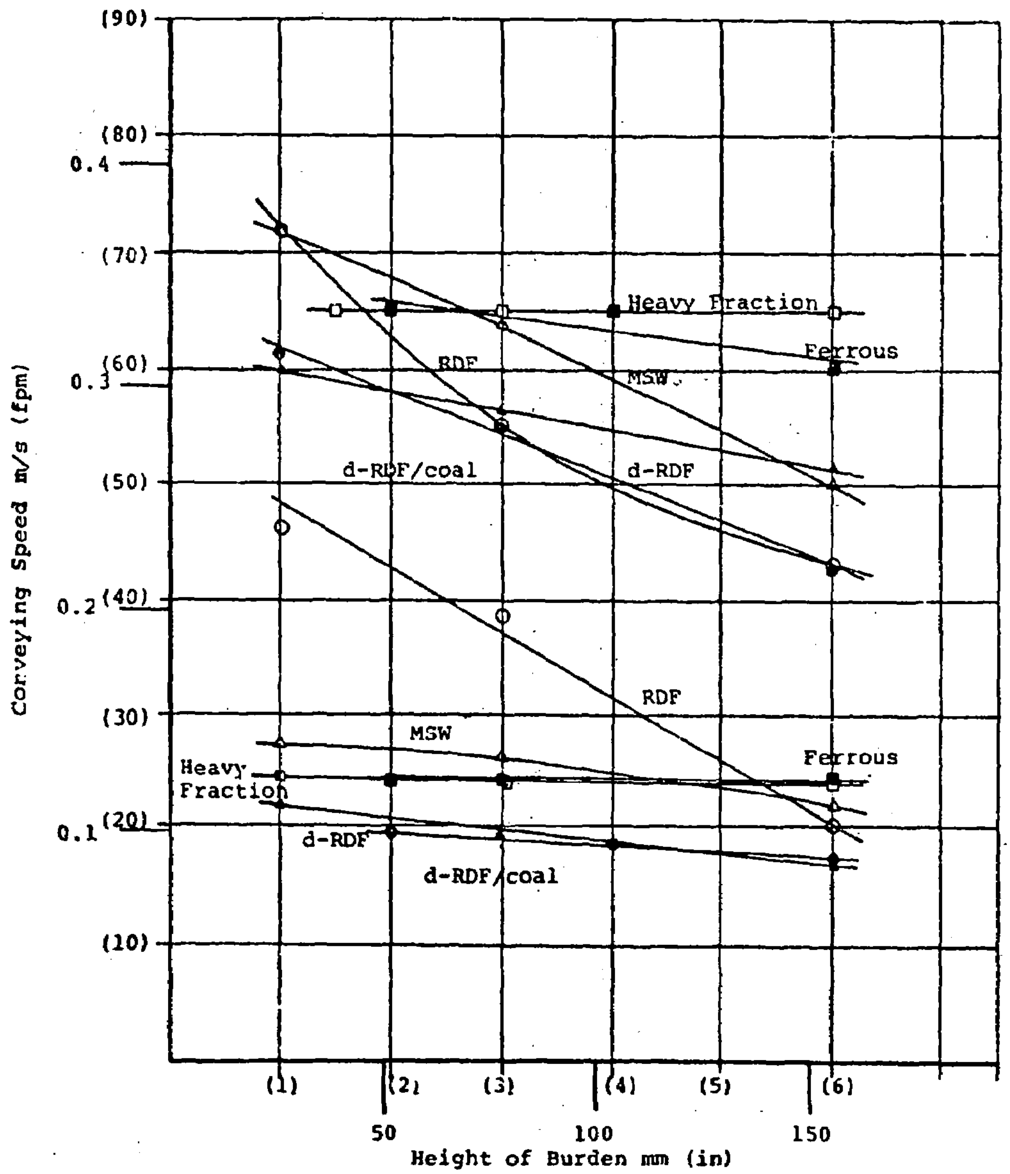


Figure 20. Conveying vs. speed vs. height of burden (f = 510 cpm).

increase, from 0.10 m/s (20 fpm) to 0.14 m/s (2. fpm) was observed for d-RDF, however, when the moisture content increased from 18 wt% to 43 wt%. This was probably due to a loss in physical integrity and gain in bulk density with increased moisture content.

- Measurements of dust generation at 1.5 m (5 ft) from the discharge end were carried out for fixed stroke length, mass flow rate and frequency (510 cpm). For most materials, dust levels were higher for the larger stroke (22.2 mm) than for the smaller stroke (12.7 mm). For HF and d-RDF, they were practically the same. They ranged from a low of 0.9 mg/SCM of air (HF) to a high of 31.2 mg/SCM (d-RDF), for all materials but the d-RDF coal blend. For the latter, due to the presence of coal fines and without any dust control in place during the experiment, high dust levels (235 mg/SCM) were recorded for the 22.2 mm stroke.

SUMMARY AND CONCLUSIONS

An investigation was made of the material properties and operating parameters of importance in assessing the conveyability of municipal waste and its processed fractions. In the present paper, the emphasis was put more specifically on belt conveyors and vibrating pan conveyors. The main results and conclusions of the study are:

- Properties and characteristics deemed to be relevant to MSW and its processed fractions were analyzed. Where sensible and feasible, these properties or characteristics were measured or assessed. The experimental values are reported.
- An analysis was made of the dependence to be expected, on a belt conveyor, between spillage rate, capacity and belt speed. Experimental results on six waste fractions confirmed these predictions. A procedure for a rational choice of operating conditions at various flow rates was defined, in which the maximum admissible spillage is selected as the design criterion.
- Finally, the results of an experimental study of conveying on a vibrating pan are described. Within the range of parameters investigated, they underline the importance and show the effects of frequency, stroke amplitude, bulk density, moisture content on carrying capacity, conveying speed, segregation in the depth and dust emissions. The results indicate trends and sensitivities and should prove useful in practice. However, they strongly suggest that significantly more analytical and experimental effort is called for to establish a material-specific design basis for vibrating conveyors handling solid waste fractions.

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COMPARATIVE STUDY OF SEVEN AIR CLASSIFIERS UTILIZED IN RESOURCE RECOVERY PROCESSING

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ABSTRACT

This paper presents the results of an extensive air classifier field test program conducted for the U.S. EPA. Methods of testing, criteria for evaluation, operating conditions, and assessment of air classifier performance are described. Topics that are germane to the design and operation of air classifiers are also covered. The results of the testing program show that there are criteria that can be applied to air classifiers such that their performance can be compared under equitable conditions. Comparisons presented herein enable judgements to be made as to the relative performance of air classifiers and the tradeoffs that require consideration when describing air classifier performance.

Introduction

Seven air classification systems with nominal throughputs ranging from 4 to 91 Mg/h have been field tested and evaluated under a two-year program sponsored by the U.S. EPA [1]. The purpose of the testing program was to characterize and compare the operation and performance of air classifiers located in the field. During the course of the work, characterization parameters were developed that enabled the comparison of all air classifiers on an equivalent basis. Due to the fact that the best air classifier performance was found to exist only for sufficiently dilute air/solids mixtures within the air classifier column, the air/solids ratio was chosen as the means for establishing the performance parameters. For each set of operating conditions, the performance parameters were found to be relatively invariant when the air/solids ratio was greater than a critical value, that value being defined by the point where the constant light fraction split fell off by 1 percent. Constant light fraction split is defined as that value of the light fraction split which does not change at a given air flow and independent of the air/solids ratio. The invariant nature of material characteristics above the critical air/solids ratio has been documented previously [2].

The seven air classifiers tested in this study, their locations, and their general descriptions are given in Table 1. Further details concerning the geometrical configuration of the air classifiers are available in the final report to the EPA.

An examination of some of the key characteristics of the solid waste encountered during the air classifier testing program shows the importance of normalizing the performance parameters in terms of the air classifier infeed composition. As can be seen from the entries in Table 2, there are wide variations in the waste characteristics from site to site. For example, the paper and plastic content of the infeed to the Los Angeles air classifier averaged 30.2 percent while that of the other six air classifiers exceeded 50 percent.

Two of the air classifiers were fed shredded and screened solid waste (Ames

TABLE 1. SUMMARY OF AIR CLASSIFIERS TESTED

Site	Type of Air Classifier	Design Throughput (Mg/h)	Cross Sectional Shape of Column
Tacoma, WA	Horizontal	73	Rectangular
Baltimore Co., MD	Vertical	91	Circular
Richmond, CA	Vertical	4	Rectangular
Ames, IA	Vertical	45	Rectangular
Los Angeles, CA	Vertical	4	Rectangular
Akron, OH	Vibratory, inclined	64	Rectangular
Pompano Beach, FL	Vibratory, inclined	6	Rectangular

and Pompano Beach), while the other five air classifiers processed waste that had been shredded only. Consequently, normalizing the performance parameters in terms of the infeed composition was essential in order to allow comparisons between the air classifiers that processed shredded refuse and those that processed waste that had been shredded and screened. It is worth noting that the ash content of the screened air classifier feed material at Ames and Pompano Beach was in the range of 13 to 14 percent, while the range was 31 to 40 percent at the five sites not employing screening prior to air classification.

Terminology

Due to the fact that little terminology had been developed for describing and characterizing air classifier operation and performance, certain terms and definitions were developed as part of this study. Some of these terms and definitions have been presented previously [2] but are repeated in Table 3, along with terms subsequently developed during the course of the study, in order that the reader may understand the shorthand notation used in presenting the operating and performance data.

Test Procedures and Methods of Analysis

For each air classifier, the test program consisted of collecting samples of heavy and light fraction under a specified set of operating conditions. Samples were collected at three discrete air flow settings (denoted as high, medium, and low) over as wide a range of material flowrates as was possible within the physical constraints imposed by the facility or the air classifier system. One of the three air flow settings was the operating mode used by the plant under normal processing conditions. Reasons for the selection of three air flows and a full range of throughputs were the reality that there is not a generally accepted definition of optimum air classifier operating condition or setpoint in the industry. In addition, manufacturers' data or recommendations as to an air classifier setpoint are not typically available.

A total of five simultaneous samples of heavy and light fractions were collected for each air flow setting. Prior to the actual test runs, "dry test runs" were used to determine the necessary time intervals to be observed in order that simultaneous samples of heavies and

TABLE 2. AVERAGE AIR CLASSIFIER FEED PROPERTIES

Site	Air Dry Moisture Content (%)	Charac-teristic Size (cm)	Percent Ferrous Metals (air dry)	Percent Non-Ferrous Metals (air dry)	Percent Paper and Plastic (air dry)	Percent Fines (-14 mesh) (air dry)	Percent Ash (oven-dry)	Heating Value (oven-dry) (Btu/lb)
Tacoma	27.1	2.8	8.8	2.1	54.2	14.2	39.7	6141
Baltimore	26.6	1.6	5.4	1.5	51.6	15.7	33.9	4609
Richmond	14.4	1.7	6.7	1.4	53.2	13.9	32.5	4897
Ames	15.0	3.6	2.3	0.6	69.4	4.6	13.7	7557
Los Angeles	13.2	1.4	3.8	1.0	30.2	25.4	34.0	7058
Akron	17.8	2.5	6.9	2.1	50.5	19.7	31.4	5546
Pompano Beach	11.2	1.7	1.9	2.1	80.9	7.1	12.5	8455

TABLE 3. NOMENCLATURE FOR AIR CLASSIFICATION

Term	Definition
Light Fraction Split	The percentage of air classifier feed material reporting to the light fraction discharge (as-processed weight basis).
Air Classifier Split	The relative breakdown of air classifier feed material into light and heavy fractions. Generally reported as (mass fraction of light material)/(mass fraction of heavy material), on an as-processed weight basis.
Specific Energy	The energy required by a unit or system and reported on an as-processed ton basis (kWh per metric ton).
Air Classifier Column Area (Syn: column area, air classifier cross-section)	The cross-sectional area of the zone of separation of light and heavy materials. The column area is perpendicular to the air stream and generally is reported as the maximum column area up-stream of the lights discharge.
Average Column Velocity	The volumetric air flow through the separation zone divided by the column area.
Light Fraction Quality	The percentage of paper and plastic in the light fraction (on an air-dry weight basis). Light fraction quality is a measure of the amount of the primary combustible constituents in the light fraction.
Combustible Yield	Defined as the product of the light fraction quality and the light fraction split (both on an air-dry weight basis). Combustible yield is a measure of the amount of paper and plastic recovered in the light fraction and reported in terms of a unit input of feed material to the air classifier.
Air/Solids Ratio	A dimensionless term defined as the mass flowrate of air divided by the as-processed mass flowrate of refuse. The air/solids ratio is a fundamental parameter utilized widely in the pneumatic conveying industry to characterize two-phase mixtures of gas and solids.
Constant Light Fraction Split	That value of the light fraction split which remains relatively constant for a given air flow and independent of the air/solids ratio.
Critical Air/Solids Ratio	That value of the air/solids ratio where the constant light fraction split falls off by 1.0 percent, denoted by a "knee" in the curve of a graphical plot of light fraction split versus air/solids ratio.

(continued)

TABLE 3 (continued)

Term	Definition
Critical Throughput	The throughput corresponding to the critical air/solid ratio for each air flow setting.
Critical Column Loading Factor	Defined as the mass flowrate of refuse at the critical air/solids ratio divided by the column area. A low value of the critical column loading parameter indicates the need for relatively large air classifiers for a given material flowrate.
Recovered Paper and Plastic	Defined as the weight of paper and plastic (on an air-dry basis) recovered in the light fraction divided by the weight of paper and plastic present in the air classifier feed. A high recovery percentage of paper and plastic is desirable to provide high heating value components for the light fraction.
Recovered Energy	Defined as the energy recovered in the light fraction (oven dry basis) divided by the energy content of the air classifier feed.
Retained Ash	The weight of ash in the light fraction divided by the weight of ash in the air classifier feed material (on an oven dry basis). Being a qualitative parameter, retained ash is a measure of the ability of an air classifier to drop out in the heavy fraction components that are high in ash content.
Retained Ferrous Retained Nonferrous	The weight of a particular metallic component in the light fraction divided by the weight (on an air dry basis) of that component in the air classifier feed.
Retained Fines	The weight of -14 mesh fines in the light fraction divided by the weight of fines in the air classifier feed, on an air dry basis.
Choked Condition	The area marked by the distinctive rolloff in light fraction split and denoted by air/solids ratios less than the critical value.

Abbreviation	Definition
A/S ratio	air/solids ratio
L.F. or LF	light fraction
H.F. or HF	heavy fraction
Fe	ferrous metals
NonFe	nonferrous metals
PP	paper and plastic

lights could be collected. Particle size of the heavy and light fractions was used to determ... the quantity of material to be used for the size distribution and composition analyses. Materials used for size distribution and composition analyses consisted of subsamples from the samples of heavy and light fractions collected for mass flowrate measurements. The size of the latter samples generally ranged from 10 to 50 kg. The sample sizes for the size distribution and composition analyses were in the range of 2 to 10 kg.

The general procedure involved setting a particular air flow through the classifier, which was accomplished through varying the rpm of the air classifier fans or adjusting a damper. Subsequently, samples of heavy and light fractions were collected simultaneously for a number of different ... feed rates to the air classifier. Samples of heavy and light fractions were collected from conveyors downstream of the classifier. These samples served the dual purpose of allowing calculation of the flowrate of heavy and light fractions while providing the material from which representative samples were chosen for later laboratory analyses. All material was completely removed from a given length of conveyor belting, thus alleviating the problem of stratification of components in the flow stream which might have skewed the results had only "grab" samples been collected.

Laboratory analysis consisted of air drying, screening, and manually sorting the light and heavy fractions, except for the Ames air classifier testing in which it was only possible to collect infeed and heav samples. In addition, heating value determinations and ash analyses were carried out on light and heavy fractions collected at each site following the procedures proposed by the ASTM for RDF-3. Both manual and mechanical screening were used to determine the size distribution of the samples. Size distribution analyses were carried out in order to determine the amount of fines (minus 14 mesh) in the heavy and light fractions and also to provide a quantitative means of describing the particle size of the shredded air classifier feed material. Manual sorting of the samples consisted of separating ferrous, paper and plastic, and nonferrous components from the heavy and light fractions. The composition and size data were used subsequently to develop the characterization parameters.

Also as part of the test program, both air flow and system power requirements were measured for each operating setpoint (i.e. air flow setting).

Results and Discussion

A summary matrix of the operating parameters determined for each air classifier is shown in Table 4. Data are shown for each of the three air flow settings used during the test program at each site. The air flow settings used during the test program at each site are denoted as "High", "Medium", and "Low". The volumetric air flows corresponding to the high, medium, and low air flow settings are reported in the final report.

Critical throughputs have been reported in Table 4 instead of the maximum tested feedrates due to the fact that for feedrates greater than the critical throughput value the air classifiers were operating in a choked condition. Consequently, they were not exhibiting their best performance for each air flow setting.

The air classifier performance parameters were calculated from data for which the air/solids ratios exceeded the critical value. These parameters, all based upon material characteristics, are reported in Table 5 in absolute and normalized terms. For reasons previously discussed, the normalized values (reported as percent of component retained in light fractions, Table 5) are the significant parameters. Due to the differing characteristics of the air classifier infeed material among the different sites, the absolute values of the performance parameters (colums A through K) are only of value when used to judge individual air classifier performance and not to compare air classifiers among different sites. In addition, the use of the absolute values for evaluating air classifier performance at a particular site presupposes that the waste composition is invariant over the duration of the tests, a questionable assumption.

TABLE 4. SUMMARY OF OPERATING PARAMETERS.

	Air Flow Setting	Critical Specific Energy kWh/Mg	(kWh/t)[a]	Critical Column Loading (Mg/h)/m²	(tph/ft²)	Critical A/S Ratio	Average Column Velocity m/s	(fpm)	Heavys Throat[b] m/s	Constant L.F. Split (%)	Critical Throughput Mg/h	(tph)[a]
Tacoma	High	≤1.1	(≤1.0)	≥46.0	(≥4.7)	≤1.6	17.29	(3,404)	NA[c]	80	≥120	≥132
	Medium	1.0	(0.9)	37.2	(3.3)	1.7	15.26	(3,005)		75	99	109
	Low	0.9	(0.8)	36.2	(3.7)	1.7	14.36	(2,826)		62	95	104
Baltimore	High	5.9	(5.4)	9.8	(1.0)	3.5	8.18	(1,610)	NA	80	36	40
	Medium	9.0	(8.2)	5.9	(0.6)	5.5	7.31	(1,440)		78	21	23
	Low	13.2	(12.0)	3.9	(0.4)	7.5	6.35	(1,250)		77	13	14
Richmond	High	5.1	(4.6)	8.8	(0.9)	5.1	6.38	(1,257)	NA	84	3.3	3.6
	Medium	9.2	(8.4)	4.9	(0.5)	6.8	4.48	(881)		78	1.7	1.9
	Low	9.4	(8.5)	2.0	(0.2)	8.5	3.43	(676)		61	0.9	1.0
Ames	High	≤7.6	(6.9)	≥18.6	(≥1.9)	≤2.6	11.42	(2,248)	NA	86	≥21.0	≥23.1
	Medium	≤7.6	(6.9)	≥17.6	(≥1.8)	≤2.5	10.74	(2,115)		78	≥20.5	≥22.5
	Low	≤4.6	(4.2)	≥27.4	(≥2.8)	≤1.5	11.52	(2,268)		88[d]	≥31.6	≥35.0
L.A.	High	8.2	(7.5)	8.8	(0.9)	6.6	11.29	(2,223)	NA	89	3.2	3.5
	Medium	9.5	(8.6)	7.8	(0.8)	5.9	8.75	(1,722)		86	2.8	3.1
	Low	11.4	(10.4)	4.9	(0.5)	5.6	6.19	(1,218)		62	2.0	2.2
Akron	High	14.1	(12.9)	16.7	(1.7)	6.4	26.21	(5160)	18.41	96	19.9	21.9
	Medium	10.5	(9.6)	21.6	(2.2)	4.7	24.70	(4862)	18.46	95	26.7	29.4
	Low	11.4	(10.4)	20.6	(2.1)	4.6	22.36	(4401)	16.05	93	24.9	27.4
Pompano Beach	High	11.2	(10.2)	11.8	(1.2)	5.6	15.51	(3055)	3.33	86	4.4	4.8
	Medium	15.0	(13.6)	3.8	(0.9)	6.3	12.89	(2538)	2.20	86	3.3	3.6
	Low	14.6	(13.3)	8.8	(0.9)	5.2	11.08	(2182)	1.97	84	3.4	3.7

a) t = ton, tph = ton per hour
b) air velocity in the vicinity of the heavy fraction discharge point of the Triple S air classifiers
c) NA = Not Applicable
d) re-adjustment of the air bleed of the air classifier caused an increase in the column velocity despite a decrease in the air flow control setting

TABLE 5. PERFORMANCE PARAMETERS FOR A/S RATIOS GREATER THAN OR EQUAL TO CRITICAL

Column	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
	Heavy Fraction			Light Fraction								Percent of Component Retained in Light Fraction					
Air Flow Setting	MC (%)[c]	PP[b] (%)[d]	Heating Value (kJ/kg)[b]	MC (%)[c]	Fe (%)[d]	NonFe (%)[d]	Ash (%)[d]	Fines (%)[d]	Quality (%)[d]	Heating Value (kJ/kg)[b]	PF Combus Yield (%)[d]	Ash[b]	Fines[d]	Fe[d]	NonFe[d]	Recov. PP[d]	Recov. Energy[b]
Tacoma																	
High	18.3	29.4	9624	25.1	3.3	1.1	32.7	19.6	58.8	15773	44.9	62.7	94.6	26.0	34.7	86.7	87.4
Medium	20.9	38.6	11907	26.3	1.0	1.5	28.6	16.3	62.8	14608	47.5	61.9	86.5	9.4	53.5	83.4	77.9
Low	28.7	42.8	11435	30.7	1.8	1.3	32.2	17.5	66.7	16303	41.5	45.6	83.1	14.2	43.4	69.5	68.2
Baltimore																	
High	12.8	7.3	5768	32.7	0.2	0.3	23.8	29.1	56.4	10440	46.0	66.0	95.8	2.8	44.0	98.5	90.6
Medium	17.7	5.0	4687	27.6	0.0	0.0	18.8	16.0	70.0	12628	55.0	58.0	98.5	0.0	0.0	95.0	73.1
Low	16.0	16.5	9060	32.0	0.0	0.2	20.7	19.9	63.0	12791	46.4	57.0	92.0	0.0	39.7	92.1	85.8
Richmond																	
High	13.0	6.3	1513	20.8	3.0	1.2	21.2	12.4	63.8	13434	52.8	56.0	97.0	26.4	55.4	98.3	97.2
Medium	13.6	12.4	4942	20.4	0.3	0.7	19.1	20.1	59.7	13031	47.0	45.0	93.2	5.8	43.2	93.8	68.6
Low	17.1	28.0	9927	15.3	0.0	0.2	16.0	16.1	76.2	12422	45.1	29.3	68.4	0.0	7.2	79.1	65.2
Ames																	
High	8.0	9.1	7450	15.0	I	I	11.1	7.3	69.3	17100	58.5	[illegible]	97.2	I	I	97.8	93.0
Medium	10.0	23.7	9546	10.9	I	I	10.9	4.0	79.6	19000	70.4	70.4	87.4	I	I	96.2	86.0
Low	23.7	11.4	11846	19.2	I	I	8.4	5.3	84.0	17107	72.4	[illegible]	95.7	I	I	97.7	91.1

(continued)

TABLE 5 (continued)

Column	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
	----Heavy Fraction----			------------------Light Fraction- ---------------								---------Percent of Component Retained in Light Fraction----------					
Air Flow Setting	MC (%)[c]	PP[f] (%)[a]	Heating Value (kJ/kg)[b]	MC (%)[c]	Fe (%)[a]	NonFe (%)[a]	Ash (%)[a]	Fines (%)[a]	Quality (%)[a]	Heating Value (kJ/kg)[b]	PP Combus Yield (%)[a]	Ash[a]	Fines[a]	Fe[a]	NonFe[a]	Recov. PP[a]	Recov. Energy[b]
Los Angeles																	
High	14.2	2.9	10762	19.8	0.1	0.7	34.3	35.4	22.9	18362	20.2	85.2	93.9	2.5	66.4	98.2	95.5
Medium	9.9	2.5	7362	8.6	0.2	0.8	26.8	21.0	36.9	17875	31.4	74.6	99.7	8.5	71.3	99.0	90.8
Low	11.3	16.2	10647	6.8	0.1	0.8	23.1	37.5	44.0	19598	28.5	42.2	[illegible]	0.9	46.2	87.8	74.8
Akron																	
High	13.3	0.8	2273	15.6	0.6	0.6	21.4	25.0	55.2	14343	53.6	88.1	100.0	15.6	96.7	99.5	99.3
Medium	10[e]	2.7	I	16.5	0.6	0.6	25.2	29.0	94.7	13430	52.0	67.7	99.1	8.1	58.6	99.0	99.9
Low	9.8	22.8	6397	18.7	1.0	0.5	26.8	28.6	51.4	15913	45.3	76.3	99.8	25.5	28.6	98.0	93.3
Pompano Beach																	
High	11.9	43.9	12060	13.8	0.4	0.9	11.5	8.7	80.1	18038	69.7	64.6	91.2	15.8	34.3	92.3	93.3
Medium	13.8	63.4	18303	8.4	0.0	0.7	8.9	5.8	87.8	21171	79.6	80.2	95.1	0.0	51.1	93.2	91.4
Low	14.2	71.6	19287	10.9	0.2	1.4	8.9	7.2	34.1	19978	74.9	81.2	93.9	32.1	64.4	90.5	83.9

a) air dry basis
b) oven dry basis
c) MC = average moisture content
d) I = Insufficient data
e) one sample only
f) PP = paper and plastic

Key parameters for both heavy and light fractions are reported in Table 5. Many comparisons and conclusions can be drawn from the data. For example, an examination of the data in the table shows that approximately 70 to 99 percent of the input energy content (column Q) can be recovered in the light fraction, and in addition for most air classifiers near their normal operating points, recovered energy is in the range of 90 to 99 percent. As a second example, it may be noted that the percentage of paper and plastic in the heavy fraction (column B) ranged from 0.3 to 42.8 percent, excluding the Pompano Beach data which were skewed due to the significant amount of preprocessing of the waste prior to air classification.

Also from Table 5, it can be seen that the light fractions obtained in Ames and Pompano Beach have a relatively high heating value (Column J). This may be due to the composition of the raw waste and/or the effect of screening prior to air classification. The light fraction obtained in Los Angeles also has a relatively high heating value. However, the high value can not be attributed to screening inasmuch as this unit process is not employed at the site. An examination of the heating value of the air classifier feed at Los Angeles (Table 2) shows that the waste also has a relatively high heating value. Hence, the heating value of the Los Angeles light fraction is partly a consequence of the relatively high heating value of the parent waste.

From the standpoint of establishing criteria for air classifier evaluation, two key ratios can be suggested. The ratios are: recovered paper and plastic/retained fines and recovered energy/retained ash. These criteria are shown in Tables 6 and 7, respectively, for each air classifier and air flow setting. The former ratio (recovered PP/retained

TABLE 6. VALUES OF RECOVERED PP/RETAINED FINES FOR A/S RATIOS GREATER THAN OR EQUAL TO CRITICAL

Site	Air Flow Setting	Recovered PP (%)	Retained Fines (%)	Recovered PP / Retained Fines
Tacoma	High	86.7	94.6	0.92
	Medium	84.4	88.5	0.95
	Low	69.5	83.1	0.84
Baltimore	High	98.5	95.8	1.03
	Medium	95.0	98.5	0.96
	Low	92.1	92.0	1.00
Richmond	High	98.3	97.0	1.01
	Medium	93.8	93.2	1.01
	Low	79.1	68.4	1.16
Ames	High	97.3	97.2	1.01
	Medium	98.2	87.4	1.12
	Low	97.7	95.7	1.02
L.A.	High	98.2	98.9	0.99
	Medium	99.0	99.2	1.00
	Low	82.0	82.2	1.00
Akron	High	99.9	100.0	1.00
	Medium	99.0	99.1	1.00
	Low	98.0	99.8	0.98
Pompano Beach	High	92.3	91.2	1.01
	Medium	93.2	95.1	0.98
	Low	90.5	93.9	0.96

TABLE 7. VALUES OF $(ENERGY\ RECOVERED_{LTS})/(ASH\ RETAINED_{LTS})$ FOR A/S RATIOS GREATER THAN OR EQUAL TO CRITICAL

Site	Air Flow Setting	Sample No.	% Energy Recovered in LTS (A)	% Ash Retained in LTS (B)	$\frac{\text{Avg \% Energy Recovered}_{LTS}}{\text{Avg \% Ash Retained}_{LTS}}$[a]
Tacoma	High	7	89.8	67.8	1.29
		8	84.9	67.5	
	Medium	11	80.5	69.4	
		12	77.9	57.8	1.26
		13	75.3	58.5	
	Low	1	68.8	48.4	1.47
		3	67.6	44.5	
Los Angeles	High	12	96.2	91.6	1.12
		18	94.7	78.3	
	Medium	20	94.1	74.9	1.38
		22	87.5	57.0	
	Low	5	73.0	42.3	1.86
		6	76.6	38.0	
Pompano Beach	High	5	93.6	83.2	1.51
		6	92.9	40.7	
	Medium	22	93.1	84.1	
		23	89.4	76.0	1.14
		25	91.6	80.5	
	Low	1'	86.5	78.1	1.07
		18	91.3	87.6	
Richmond	High	1	96.7	45.2	2.25
		2	97.6	41.1	
	Medium	9	84.7	40.3	
		11	87.7	46.5	2.07
		14	93.3	41.6	
	Low	16	78.5	28.8	2.25
		17	51.8	29.2	

(continued)

TABLE 7 (continued)

Site	Air Flow Setting	Sample No.	% Energy Recovered in LTS (A)	% Ash Retained in LTS (B)	Avg % Energy Recovered$_{LTS}$ / Avg % Ash Retained$_{LTS}$ [a]
Baltimore	High	12	90.6	53.0	1.83
		14	90.9	46.1	
	Medium	30	73.1	57.1	1.28
	Low	2	83.8	59.6	1.50
		3	87.7	64.5	
Akron	High	15	98.6	92.5	1.13
		19	100	83.7	
	Medium	7	99.9	85.8	1.16
	Low	9	88.9	57.9	1.33
		12	97.7	82.1	
Ames	High	1	--	73.4	
		2	92.7	50.7	
		3	93.2	19.3	
		4	--	41.5	
		Avg	93.0	46.2	2.01
	Medium	6	91.0	ID[b]	
		7	--	93.7	
		9	81.0	ID	
		11	--	47.1	
		Avg	86.0	70.4	1.22
	Low	13	92.4	71.3	
		15	94.9	ID	
		17	95.7	36.8	
		18	--	59.5	
		19	81.4	13.7	
		Avg	91.1	45.3	2.01

a) Average (A)/Average (B)
b) ID = insufficient data due to negative values calculated for light fraction ash content

fines) could be used for determining optimum air classifier performance for selectively separating paper and plastic components from fine inorganic contaminants, for instance when fiber recovery is the intent of a resource recovery process. On the other hand, for recovery of a refuse derived fuel (RDF), the ratio of recovered energy (RE) to retained ash (RA) is of significance and has been chosen for use in this study as the key criterion for establishing the performance characterization of the seven air classifiers that were tested.

The selection of the ratio of RE/RA as the key criterion is based upon the fact that both recovered energy and retained ash in the light fraction are normalized on an infeed basis, thus eliminating the effects of variation of refuse composition on air classifier performance. By means of an explanation, large values of this ratio imply that an air classifier is recovering (in the light fraction) a significant percentage of the energy available in the infeed material while simultaneously dropping out into the heavy fraction a significant percentage of the ash-carrying components.

The data in Table 7 show a range of values for the ratio of RE/RA for each air classifier, depending upon the air flow setting. Due to the fact that for each air classifier only selected samples of heavy and light fractions were analyzed for heating value, average values of RE/RA were calculated by dividing the average value of RE by the average value of RA for each air flow setting. This method of obtaining values of RE/RA was deemed to be the most reasonable given the amount of data available. Where possible, only heating value and ash data for the same samples were used in the calculations (as shown for all sites except Ames). Due to the procedure used for determining the properties of the Ames light fraction samples and the attendent inconsistencies of the data, as much of the Ames ash data as possible were used for calculating the values of of RE/RA. Consequently, the values listed in Table 7 generally will differ from those that would be calculated by using the RE and RA values listed in Table 5, except for the Ames air classifier.

If the maximum values of RE/RA for each air classifier are chosen as the criterion (or premise) for determining the optimum operating point for recovery of a "high quality" RDF, then other performance parameters can also be chosen for comparison based upon the air flow setting resulting in the maximum value of RE/RA for each air classifier. Some key parameters for characterizing each air classifier's performance at its optimum air flow setting are shown in Table 8.

Using the parameters listed in Table 8 and two additional judging criteria, namely "System Complexity" and "Cost", a comprehensive assessment can be made of the various air classifiers under their respective optimum air setting for RDF recovery. Such a summary of the key operating and performance parameters for each air classifier is shown in Table 9. This table shows the judging criteria and the key parameters that are used to quantify each judging criteria. The first three parameters (specific energy, column loading, and RE/RA) were determined from field measurements. The last two parameters (system complexity and 1980 costs) are of a qualitative nature. The judgment of system complexity was based upon visual observation of the total air classifier system, including number of conveyors, blowers, cyclones, and mechanical equipment required, the engineering and structural complexity, and an engineering judgment of the degree and type of control necessary to maintain the air classifier in operating order. Costs were determined by escalating reported capital costs (10 percent per annum) to 1980 levels and dividing them by the critical throughput for each air classifier at its optimum air flow setting, as detailed in Table 10.

A comparison of air classifiers is possible using the data presented in Table 9. For example, the Tacoma air classifier uses the least energy per ton, has the highest column loading, and has the least capital cost on a ton per hour basis. However, the RDF quality suffers, as evidenced by the relatively low value for the ratio of RE/RA (1.5); and the air classifier system is complex when compared to the others tested. This example illustrates the fact that the tradeoffs

TABLE 8. KEY PERFORMANCE PARAMETERS FOR AIR CLASSIFIERS USED IN THE RECOVERY OF HIGH QUALITY RDF

Air Classifier	Air Flow Setting for Max. RE/RA[a]	E_0 (kWh/Mg)	Column Loading (Mg/h)/m^2	Avg. Recov. Energy / Avg. Retained Ash
Tacoma	Low	0.9	36.2	1.5
Baltimore	High	5.9	9.8	1.6
Richmond	High	5.1	8.8	2.3
Ames	High	$\leq$7.6	$\geq$18.6	2.0
Los Angeles	Low	11.4	4.9	1.9
Akron	Low	11.4	20.6	1.3
Pompano Beach	High	11.2	11.3	1.5

a) Max. = Maximum determined from field test analyses of samples collected under test conditions exceeding the critical air/solids ratio.
RE = Average Recovered Energy
RA = Average Retained Ash

must be considered when evaluating and judging the performance of air classifiers.

As mentioned previously, the use of RE/RA to form the basis for evaluating and comparing air classifiers represents only one means of forming such comparisons. However, for recovery of RDF the choice of RE/RA seems a natural one. All subsequent parameters were determined after the air settings for the maximum values of RE/RA were established. As previously discussed, other starting points are possible. For example, if fiber recovery is the object of air classification, the natural starting criterion might be the ratio of recovered paper and plastic to retained fines. The subsequent determination of the performance parameters would then follow similarly to that previously described for the case of characterizing RDF recovery, i.e., the use of the ratio of recovered energy to retained ash.

Conclusions

The testing and performance characterization of seven air classifiers has shown the ranges of operating conditions and performance that can be expected for each air classifier. In addition, methods have been presented for comparing different types of air classifiers operating under different air and material flows and handling shredded refuse of differing composition. There is no absolute means of comparing air classifier performance. As the data in Table 8 show, positive and negative points exist for all air classifiers. However, it is now possible to judge air classifier performance on a relative basis if the judging parameters are judiciously chosen so as to allow an equitable comparison, i.e. normalization of the system outputs to eliminate the effect of varying infeed composition. Hopefully, the methods and data presented here will prove useful in the evaluation of other air classifiers.

Since the field tests covered a number of different air classifiers, analysis of the test data allows the establishment of the magnitudes of a number of quantities that should be of interest to the resource recovery industry, for example, the percentages of ferrous metals, nonferrous metals, retained fines, and

TABLE 9. OPERATING AND PERFORMANCE PARAMETERS[a] OF SEVEN AIR CLASSIFIERS FOR RDF RECOVERY

JUDGING CRITERIA ➔	ENERGY REQUIREMENT	UNIT SIZE	RDF QUALITY	SYSTEM COMPLEXITY	COST[a]
Key Parameter ➔	Specific Energy	Column Loading	Avg. Recovered Energy / Avg. Retained Ash	Design Simplicity	1980 Cost Basis
	(kWh/Mg)	$(Mg/h)/m^2$	(Ratio)	(Ranking[b])	$(\$/Mg/h_{crit})$
Air Classifier					
1. Tacoma	(0.9)	(36.2)	(1.5)	6	5,800
2. Baltimore	(5.9)	(9.8)	(1.8)	3	12,600
3. Richmond	(5.1)	(8.8)	(2.3)	1	4,300
4. Ames	(7.6)	($\geq$18.6)	(2.0)	4	$\leq$14,000
5. L.A.	(11.4)	(4.9)	(1.9)	2	8,200
6. Akron	(11.4)	(20.6)	(1.3)	6	6,600
7. Pompano Beach	(11.2)	(11.8)	(1.5)	5	6,200

a) Estimated capital cost (equipment and engineering) for air classifier system, costs exclude operating and maintenance expenses
Mg/h_{crit} = throughput at the critical A/S ratio.

b) 1 = simplest system; 6 = most complex system

TABLE 10. COST OF SEVEN AIR CLASSIFIER SYSTEMS[a]

Air Classifier	System Cost ($)	Construction Year	Escalation Factor[b]	1980 Cost ($)[e]	Critical Feedrate	1980$ / (Mg/h)[d,e]
Tacoma	452,500	1978	1.21	548,000	95	5,800
Baltimore	310,000	1976	1.46	453,000	36	12,600
Richmond	9,750	1976	1.46	14,200	3.3	4,300
Ames	182,854	1975	1.61	294,000	≥21	≤14,000
L.A.	12,250[c]	1977[c]	1.33	16,300	2.0	8,200
Akron	125,000	1977	1.33	166,000	25	6,600
Pompano Beach	18,756	1976	1.46	27,400	4.4	6,200

a. The system costs in general represent cost of materials and installation. However, for some of the air classifiers, engineering design costs were almost certainly part of the total system cost, although this conclusion can not be documented.
b Construction year cost escalated at 10 percent per year to establish 1980 cost.
c These entries are estimated.
d In light of the peculiarities of the manner of cost accounting as described in footnote a), the $/Mg/h values presented should be viewed with caution, bearing in mind that there are a myriad of factors that may or may not be accounted for in the total system costs.
e) Rounded costs.
f) Calculated maximum feedrate corresponding to the critical air/solids ratio for the air flow setting resulting in the maximum value of recovered energy/retained ash.

paper and plastic in the light fraction. Results of all seven field tests taken collectively enable an overall, or average, value of certain parameters to be calculated as shown in Table 11. Such average values subsequently can be used for calculation of mass and energy balances on an air classifier system. For example, the mass on of nonferrous metals in the light action can be computed from the mass fraction of nonferrous metals in the air classifier feed and the percentage of nonferrous metals retained in the light fraction.

Certain other factors involving the calculation of mass balances can also be gleaned from the test data. For example, the data in Table 11 show the probable values for various operating and performance parameters that characterize air classifiers. For design purposes, the data in the table allow an estimation of typical levels of performance. For example, the minimum and maximum values of paper and plastic in the heavy fraction can be seen to be 0.8 and 42 percent, respectively, although an average value of 5 to 30 percent appears to be possible with properly tuned air classifiers. Other noteworthy findings include typical ranges of: 1) 2 to 20 percent and 45 to 65 percent, respectively, for retained ferrous and retained aluminum in the light fraction; 2) specific energy requirements of 1 to 11 kWh/Mg; 3) RE/RA values of 1.2 to 2.1; and 4) system capital costs of $5,800 to 8,200 per Mg/h.

It is readily apparent after testing these air classifiers that a standard method of testing and evaluation is needed by the resource recovery industry not only to allow comparison of performance among different air classification systems but also to establish the correct operating settings for producing a specified output. Presently there is little control exercised over the air classification process. Consequently, the quality of the output (i.e. RDF) oftentimes suffers. As with most of the processes in resource recovery, air classification is but another that has not yet progressed from an art to a controlled process.

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TABLE 11. SUMMARY OF OPERATING AND PERFORMANCE CHARACTERIZATION OF AIR CLASSIFIER SYSTEMS

	High	Low	Typical Range[a]
Critical Air/Solids Ratio	8.5	≤1.5	2 - 7
PP in Heavy Fraction (%)	42.8	0.8	5 - 30
Light Fraction Composition (%)			
Ferrous metals	3.3	0.0	0.1 - 1.0
Non-ferrous metals	1.5	0.0	0.2 - 1.0
Fines	37.5	4.0	15 - 30
Paper and plastic	87.8	22.9	55 - 80
Ash	34.3	5.8	10 - 35
Percent of Component Retained in Light Fraction			
Ferrous metals	32.1	0.0	2 - 20
Non-ferrous metals	96.7	0.0	45 - 65
Fines	100.0	[illegible]	80 - 99
Paper and plastic	99.9	69.5	85 - 99
Ash	85.2	29.3	45 - 85
Recovered Energy	99.9	65.2	73 - 99
Specific Energy (kWh/Mg)	15.0	0.9	1 - 11
Column Loading (Mg/h)/m²	≥46.0	2.0	5 - 40
Recovered PP/Retained Fines	0.9	1.1	1.0
Recovered Energy/Retained Ash	2.3	1.1	1.2 - 2.0
1980 $/(Mg/h)	≤14,000	4,300	5,800 - 8,200

[a] Typical range to be expected.

PRODUCTION PROCESSES FOR RDF AND d-RDF, WITH APPLICATION TO A d-RDF SYSTEM FOR SMALL COMMUNITIES

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ABSTRACT

Production systems for refuse-derived fuel (RDF) and densified refuse-derived fuel (d-RDF) are composed of a number of processing steps. An understanding of the operations and inter-relations of these various pieces of equipment is critical to proper design and functioning of the entire system. Five of the most common unit processes in waste fuel production systems are shredding, air classification, screening, densification and material handling. A review of recent and ongoing research and evaluation programs for each of these processes is provided in this paper. In a second section, analysis is made of the technical and economical feasibility of a d-RDF system for small community. The approach first defines the affordable cost, on a breakeven basis, for the equipment and plant needed to provide a RDF feedstock to a densification module. A RDF production scheme is outlined and a preliminary facility layout and cost discussed. This cost is then compared to the front-end capital affordable for various fuel values and landfill avoidance costs.

This discussion of preparation processes for refuse-derived fuels (d-RDF) will be divided into two parts. The first is a brief summary of equipment research and evaluation programs on five unit processes common to production systems for RDF and d-RDF; the second is to examine, as an example, the technical and economic feasibility of a d-RDF system for a small community. This example will illustrate one possible approach to planning, selection and analysis of a waste processing system, and will serve to point out the sort of information still lacking on unit process performance and products and needed for sound technical and economic analysis of a processing system.

PROCESS RESEARCH AND TESTING

Depending on the requirements of the fuel user and the design of the preparation system, RDF may take a number of forms: fluff (coarse or fine size), pulped, powdered or densified. In turn, there are a large number of process flows that have been applied or proposed for RDF production. Five of the most common process steps - unit processes - that are applied in these systems are shredding, air classification, screening, densification and material handling.

The early processing systems for recovery of fuel (RDF) and/or recyclable materials from mixed municipal solid waste (MSW) generally utilized unit process equipment adapted from other conventional industries or applications. These unit processes are scaled-up, and combined in a number of commercial-scale RDF preparation plants. However, in the first applications to solid waste, these systems generally have not functioned well and have fallen short of meeting operating expectations and product specifications. Subsequent efforts to evaluate, trouble-shoot or improve the performance of individual processes or plants as a whole were complicated by the fact that outputs of one process affected the performance of other processes as well as the rest of the system. The difficulties appear attributable to a lack of understanding of capabilities and limitations of the individual unit processes and to absence of significant bench, pilot or commercial operating experience using solid waste feedstock with this equipment.

In recognition of the need for basic knowledge of unit processes to advance the understanding and application of RDF preparation systems, the Environmental Protection Agency (EPA) had initiated a number of fundamental and experimental research programs. The following sections summarize descriptions, status and results of these research programs in the areas of shredding, air classification, screening, densification and material handling. While funding has been limited and priorities shifting (in fact, the Department of Energy (DOE) now has sole responsibility for RDF process research), these research activities (or in some cases the absence of such activities) are highlighted to emphasize the type of analytical and experimental programs necessary to develop more basic knowledge on unit processes. This could permit improved design, scaling, operations, costing and evaluation of waste-to-energy systems, and specification and pricing of RDF products.

It is beyond the scope of this paper to cover the results of all these projects in detail; the reader is directed to the references cited in this paper for additional information.

Size Reduction

Shredders are applied to unprocessed or processed solid waste to produce a smaller, more uniformly sized, homogeneous product which is more easily handled and separated in follow-on processing. Primary shredding refers to size reduction of unprocessed MSW utilizing hammermill (horizontal and vertical axis), shear or flail mill types of shredders. Secondary shredding refers to the size reduction, usually by a hammermill or knife mill, of a processed waste fraction - typically air-classified light fraction.

The earliest shredder performance testing was in EPA-supported field studies in the late 1960's and early 1970's in Gainesville, Florida and Madison, Wisconsin (1,2). A more fundamental pilot plant program by Cal Recovery Systems, Inc., established the key parameters which characterize refuse comminution and developed the criteria for evaluating size reduction equipment (3). A comprehensive follow-on field test program by the same firm (again under EPA support) was then initiated to make comparative performance evaluations of nine large commercial shredder installations (4). More recently, a field test program concerned with production capacity and product characteristics from parallel and sequential shredding of trommeled, air-classified light fraction was run with a vertical shaft shredder and horizontal shaft shredder at the Maryland Environmental Service facility in Cockeysville, Maryland (5). Results on dependence of particle size, throughput, power consumption and the effects of moisture and hammer wear for a vertical shaft hammermill were obtained at the Pompano Beach, Florida solid waste facility and reported recently (6).

Significant information and data on comminution parameters, energy consumption and hammer wear have been developed and documented in these studies. This work is representative of the combination of analytical and pilot-scale investigations, coupled with field evaluations which are lacking for most other unit processes, and for three other types of shredders - flail and knife mills and shear shredders. The first two of these devices are of particular interest for the type of small-scale RDF processing systems considered in the example below.

In a typical application, a flail mill is used to coarsely shred raw waste to break bags and liberate contents prior to separation or screening. No reported equipment investigations and only minimum experimental data on flail mill product characteristics are available to assist designers in using this equipment for waste-processing systems.

A primary-shredded, air-classified light fraction must be further reduced in size prior to densification in order to minimize milling action on the densifier, attendant increases in power consumption and wear and decreased mill capacity. Knife mills have recently been applied (particularly in Europe) or considered for size reduction in preparation of densifier feedstock (7,8). The presumed benefits of the knife mill have been the positive size control of textiles and the increased product density (less de-fiberized or fluffy). However, data are not available to answer these or other questions such as capacity of existing models, sensitivity to damage from tramp metals and wear on the knives and grates.

Shear shredders have two slow-speed, counter-rotating rotors with intermeshed hammers. They have found a growing market for industrial residues such as waste rubber and wood and are frequently mentioned as alternatives to hammermills for primary shredding. The advantages cited for the shear shredder are reductions in power consumption, wear and explosion hazard, but no documented investigations verify or disprove these claims.

Air Classification

Air classification is an aerodynamic process to separate loosely-mixed fractions of material based on individual component size, shape and density in relation to the equipment configuration and air flow parameters. There are several styles of air classifiers including straight column, zig-zag, horizontal vibrating, rotary drum and concentric tubes. As applied to solid waste, the air classification process is most frequently employed on shredded waste to produce a light, combustible fraction consisting mainly of organic materials (paper, plastics) and a heavy fraction consisting mainly of inorganic, noncombustible materials. In general, the expectations and predictions for separation efficiency and reliability have not been met in actual operation.

Unit process research on air-classification equipment has primarily been in the form of field evaluations of pilot- and full-scale equipment. Midwest Research Institute has reported on an extensive field test on 7 air classifiers of various styles and sizes (9). The tests documented performance and operating characteristics at several operating conditions.

At the National Center for Resource Recovery (NCRR), the performances of a Vibrolutriator® and a vertical zig-zag air classifier were assessed as part of an EPA process testing research program (10). In particular, experiments were run at varying air flows on both units and with varying internal geometry in the case of the zig-zag unit.

These types of field studies have provided interesting comparative data but due to the dissimilarity of designs, changing feedstock characteristics and feedrates, the data do not provide a basis for improving designs or for predicting performance for varying feedstocks. Few investigations directed at more basic understanding of the air-classification process, the principles for design, scaling and operation have been undertaken or reported. Along these lines, the work by M. Tels and M. Senden (11,12) should be cited. Also, the aerodynamic characterization of elements in air-classified light fraction was studied at NCRR in analyzing inertial separation during pneumatic conveying of fine inorganics from RDF (13).

One beneficial use of such fundamental and basic process knowledge and test data is in developing programs for new or improved equipment. An example of such a device is a tramp material separator. The recent move away from shredder and air-classification systems and the increased use of flails and screening has reduced cost and complexity of waste processing systems, but it has not eliminated the need for a device to separate dense, potentially damaging materials from the RDF. The application of such a tramp material separator is illustrated in this paper in the example of a small facility processing system. The efforts at development of such a device, which is the subject of an upcoming research task at NCRR sponsored by DOE (14), unfortunately, cannot benefit from the extensive operating and performance data logged on nearly a dozen air classifier systems in the test programs cited above. Rather, for example, information on the applicability of theoretical and analytical models for air classifier performance should be assessed; a controlled pilot-scale parametrical test program should be undertaken; and data obtained on characterization of waste components by size, shape and mass relationships. Topical discussion and outlines of a number of these more fundamental types of unit process research programs are provided in a report on research goals prepared by NCRR for EPA (15).

Screening

Flat (or vibratory), rotary (trommel) or disc screens have been considered or applied for size separation of unprocessed waste and a variety of processed fractions. Recent interest in preparation of RDF has been in the use of a rotary screen ahead of the primary shredder. The objective is to remove undersize material, particularly abrasive inorganics, prior to shredding to reduce the loading wear and power consumption. Flat, rotary or disc screens may also be placed after the shredder or air classifier to remove ash-causing inorganic fines and potentially troublesome oversize material from RDF. For either location or screen type, screening has the promise of offering a relatively inexpensive, efficient approach to upgrading RDF.

Few reports of analytical or experimental efforts on flat screening of solid wastes have been published. In an experimental program at NCRR, some operating experience was gained, and associated data were reported on flat screening of shredded MSW and air-classified light fraction. The testing, however, was aimed at characterizing the particular devices being used and not at evaluating the screening process for various pieces of equipment and a range of input conditions (10). The results indicated that, due to the presence of flat and flexible materials that ride on the screen and block the openings, flat screens would have to be unusually large for effective MSW or RDF processing. A tumbling action, as occurs in rotary screens, appears to offer improvement. A similar conclusion was reached by Trezek in an investigation of flat screening of light fraction (16).

The use of modified flat screens for two focused applications in waste fuels processing - the separation of textiles and other wrappables and removal of dense inorganics - will be considered in a modest research task just started at NCRR (17).

DOE recently initiated an extensive research effort on the mechanism and performance of rotary screens applied to RDF preparation. Three contractors - NCRR (18), Cal Recovery Systems, Inc. (19) and Midwest Research Institute (20) - will be conducting analytical studies and pilot- and full-scale testing and evaluations. Studies of the trommel hardware systems (the structure and drive), the economics of full-scale trommels and an evaluation of trommels for small-scale systems are all part of the DOE program.

The particular approach which NCRR has adopted to develop predictive relationships on trommel operation and performance was developed as part of an aforementioned study for EPA on processing research topics (15,21). Concurrent to that study, the first evaluation of a full-scale trommel was conducted as part of an EPA test and evaluation program at the Resource Recovery Demonstration Facility in New Orleans, Louisiana (22). An additional ten full-scale tests in New Orleans, as well as an evaluation of the trommels at the Browning-Ferris facility in Houston, the Maryland Environmental Service plant in Cockeysville, and two plants in the United Kingdom are to be conducted as part of the new DOE research program.

A disc screen is a horizontal assembly of rotating shafts with circular or elliptical interlocking discs arranged to form an aperture through which undersize material may pass. Oversize material is carried across and off the screen by the rotating discs. In one of the first applications to waste fuel processing, disc screens were installed in the RDF production plant in Ames, Iowa, for removal of grit (fine inorganics) to reduce the load and wear on the secondary shredder and materials handling equipment and reduce the ash content of the RDF. The performance of the disc screens, as they affect fuel characteristics and plant operations, has been reported as part of an EPA-sponsored evaluation of the entire Ames facility (23). Unfortunately, data could not be obtained to indicate the change in fuel yield after the installation of the disc screens and show the proportion of organics loss with the grit product. This important operating facility information, as well as an evaluation of the relationships between machine parameters (speed, disc screenings, disc shapes) and feedstock characteristics, is necessary to more fully understand and consider application of disc screening.

Densification

For reasons of combustion, feeding, handling or storability, a densified form of RDF may be required for a particular fuel market. Such applications are typically in stoker-fired boilers burning lump or particle coal. Densified RDF or d-RDF is formed by the mechanical compaction of a processed waste fraction into particles. Equipment types include pelletizers, cubers, extruders and briquetters.

Some of the earliest and most extensively report experiences on the preparation, properties, handling and economics of densification occurred at NCRR between 1976 and 1979, under EPA's sponsorship (8). This project covered an operation and performance evaluation of a shredder and pelletizer subsystem designed to produce d-RDF from shredded, air-classified light fraction. Over 1300 Mg of pellets were produced for test firing in two different stoker-boiler facilities (24,25). Other experimental activities at the NCRR densification plant included an investigation of the effect on throughput, power consumption and pellet quality from addition of waste oil to the densifier feedstock (26) and evaluation of the operations and products from processing 125 Mg of high paper content (office waste) feedstock into d-RDF (27).

A series of pilot-scale evaluations of a commercial pellet mill and a fundamental investigation of densification of RDF utilizing a single die arrangement were carried out at the University of California (28). The bench-scale testing was the first of its kind and provided insights into the dynamics of pellet formation and elements of the energy requirements for pelletization. The results determined the effects of die configuration and suggested explanations for excessive die wear and decreasing specific energy requirements for increasing mass throughput as observed in commercial pellet mills.

Material Handling

Material handling processes in RDF preparation systems include mechanical and pneumatic conveyors. Although not contributing directly to the RDF refinement process, proper selection, design and operation of this equipment is vital to reliable, clean and economical operation of the system. Although problems with material handling equipment have been prevalent in most of the first generation RDF processing plants, it was not until recently that a research effort on material handling systems has been initiated.

At NCRR, the first phase of a research project studying the parameters affecting conveyability of waste fractions and testing various processed waste fractions on a series of belt and vibrating conveyor test rigs was just completed (29). Unfortunately, the additional phases which included field testing at full-scale commercial installations were a casualty of EPA's shift out of waste processing research programs.

Pneumatic conveying systems are found at nearly every RDF facility, yet little knowledge of operating parameters and performance is available. As part of the first phase conveyor project, the scope, facility requirements and cost of a pneumatic test rig experimental program have been assessed. Implementation of the program, however, was not covered in the first phase funding and is not planned at this time.

APPLICATION TO A d-RDF SYSTEM FOR SMALL COMMUNITIES

After this review of present research and experimental evaluation on the preparation and densification of RDF, the second part of this paper will examine, in an example, the technical and economic feasibility of a d-RDF system for a small community generating from 100 to 200 Mg/d (110 to 220 ton/d) of municipal solid waste.

It is reasonable to assume that small communities, as just defined, can ill afford the capital investment and operational and managerial complexities entailed by high technology, capital-intensive approaches to resource recovery taken in large metropolitan areas (1000 Mg/d of waste, or more). The relative cost of scaling down system size and the requirements for a variety of skilled labor might be seen as serious impediments.

In the following discussion, an example will be treated in which the technical and economic aspects of producing d-RDF in a small community plant are analyzed. This example follows the general approach and procedures developed by the authors in a more detailed contract report (8).

By reference to the densification of d-RDF and its uses given above, it is assumed at the outset that a customer or customers have been found in the community and are willing to purchase d-RDF for use as a substitute or supplemental fuel in a particle coal stoker-fired boiler. The sale price of the d-RDF is based on its energy content, presumably discounted from that of the displaced fossil fuel.

From previous NCRR work (8), realistic projections for capital, labor and operating and maintenance (O&M) costs of a densifying operation can be made. The approach cited in Reference 8, and applied here), is to define the flow process, upstream of the densifier, based on the question: "How much can be afforded for the plant and equipment, other than the densifier and the associated structures, given the quantity of d-RDF produced, its sale price and the cost of densifying?"

This being determined, a RDF production scheme will be outlined which would fit the technical and economic constraint. A preliminary layout and costing for the facility in the example under study will be discussed. The cost will be compared to the projected front-end capital affordable for various fuel values and landfill avoidance costs.

Cost of Densification

Projections for the capital, operation and maintenance costs have been made for the densification subsystem shown schematically in Figure 1. The system would have a design capacity of 9 Mg per hour of nominal 75 mm feedstock. Accounting for start-up transients, occasional jams and blockages, an 80% availability is assumed yielding a realized capacity of 7.2 Mg/h. Over two shifts (14 hours) the daily capacity would be 100 Mg.

Table 1 provides a list of equipment and other costs (1979 basis). A ring extrusion-type densifier, as was used in the production program at NCRR, is suggested here. However, auxiliary equipment, O&M costs, capacity and product characteristics would not be expected to vary greatly for other types of densifiers.

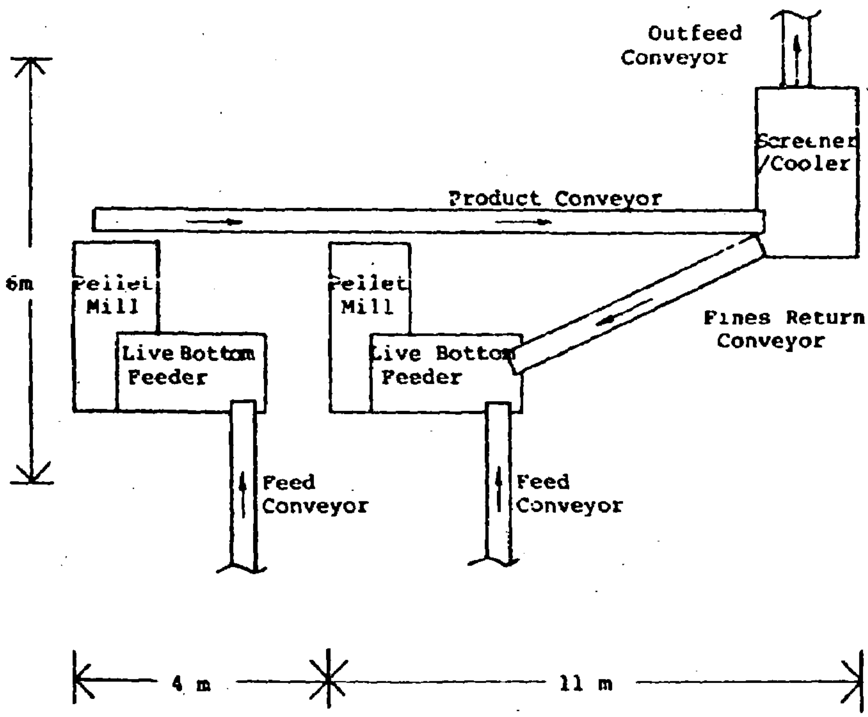

Figure 1. Densified-refuse derived fuel module layout schematic for two densifiers.

TABLE 1. DENSIFICATION MODULE EQUIPMENT COST DETAIL (REF. 8)
TWO DENSIFIERS - 1979 COSTS

Item	Cost
Equipment	
Conveyors (4) - feed and product	$ 32,700
Densifiers (2) - w/surge bin, spare die and rolls, motor	184,600
Pellet cooler	14,500
Pellet screener	6,200
Motor control center	5,000
Freight and taxes	17,000
Installation	65,000
Building allocation - 75 sq m	20,000
Engineering	27,600
Contingency	17,300
Total Capital Cost	$389,900

An estimate of the O&M costs for a two-shift operation are provided in Table 2. The operating costs include the proportioned time of an equipment operator and power requirements on a unit throughput basis. The maintenance costs include die rehabilitation (regrinding) or replacement, roller shell replacement and estimates for nominal maintenance on the pellet mill drive, conveyors and screens.

Table 3 summarizes these costs yielding a total of $9.20/Mg ($8.28/ton) for the capital and operating costs of the densification module.

For details on the presumed maintenance schedule and costs, the reader is directed to the EPA final project report (8).

Allowable Processing System Costs

The capital investment, upstream of the densification unit just described, is said to be allowable if the options of landfilling or processing and densifying are economically indifferent.

The projected costs of densification were detailed earlier. Other estimates or assumptions used in the analysis are listed below:

- Densifier capacity (nominal): (9 Mg/h, 80% availability) 7.2 Mg/h for 2 densifiers
- Operating time: 2 x 7 hours, 250 d/y (2 shifts)
- Equipment life: 10 years
- Fuel heating value: 13.94 MJ/kg (6000 Btu/lb), as-received, or 13.94 GJ/Mg (12 x 10[6] Btu/ton)
- Sale price of fuel: k_f = $1.42/GJ ($1.50/M Btu) or $2.37/GJ ($2.50/M Btu)

TABLE 2. DENSIFICATION MODULE OPERATING AND MAINTENANCE COST DETAIL (REF.8)
TWO DENSIFIERS - 14 h/d - 250 d/y 7.2 Mg/h
NOMINAL THROUGHPUT - 25,200 Mg/y

	Annual	Unit Throughput
Labor	$30,000	$1.19
Materials, supplies	12,000	0.48
Utilities	32,250	1.28
Maintenance		
Dies	50,400	2.00
Rollers	32,250	1.28
Miscellaneous (densifier, conveyors, cooler, screen)	15,900	0.63
	$172,800	$6.86/Mg

TABLE 3. DENSIFICATION MODULE CAPITAL AND OPERATING COST SUMMARY (REF. 8)

Item	Annual
Capital costs	
Total cost	$389,900
Annual 8%, 10 years	58,485
Unit cost	2.34/Mg
Operating costs	
Labor	1.19
Materials, supplies	0.48
Utilities	1.28
Maintenance	3.91
Total Operating Costs	6.86/Mg
Total Capital and Operating Costs	$9.20/Mg

- Ferrous sale price: $33/Mg ($30/ton), F.O.B. plant
- Ferrous material recovered: 0.06 Mg recovered/Mg of input waste
- Landfill avoidance cost: variable "x" (ranging from 0 to 15 $/Mg)

As mentioned, the front-end available capital (F.A.C.) is the amount that can be afforded in order to balance costs and revenues, for buildings, equipment, O&M and installation costs upstream of the densifier. The revenue per Mg of d-RDF or $/Mg, in short, is noted R.P.T. and is equal to:

R.P.T. = revenue from sales of fuel/Mg + revenue from sales of ferrous/Mg - cost of densifying/Mg + x (landfill avoidance, $/Mg)

The front-end available capital is equal to

$$F.A.C. = \frac{(RPT \times TPY)10}{1 + \beta + \alpha} \qquad (1)$$

$$\alpha = 10k_y$$

in which α, k_y are the estimated fraction of the capital investment spent over a period of 10 years and 1 year, respectively, for O&M of the front-end equipment and facilities. For example, $k_y = 0.2$, the value adopted in this example, corresponds to 20% of capital cost on a yearly basis. The term $1 + \beta$ in the denominator corresponds to the cost of financing the capital costs (F.A.C.). Here β was assumed to be the capital recovery factor at 8% over 10 years, or β = 0.4903.

Equation (1) is plotted in Figure 2 against x, and landfill avoidance cost (a variable), for the case of two densifiers, with ferrous recovery.

The yield of d-RDF per input ton of waste, Y, is taken to be 50% for these examples (see discussion in next section).

In Figure 2, it is seen that for realistic landfill costs ($2 to $15/Mg of waste) and the lower price of energy ($1.42/GJ), a range of $1.2 million to $2.1 million can be defined for the front-end available capital. For the higher price of energy ($2.37/GJ), the range is $2.1 million to $3.0 million.

At the assessed d-RDF module capacity of 7.2 Mg/h (8 ton/h), 14 h/d, 250 d/y, the recovery plant handles 100 Mg/d (112 ton/d) of shredded RDF (fluff) feedstock to the densifier module.

In the above-referenced general study (8), it was obtained that all alternate schemes examined for the production of this RDF have

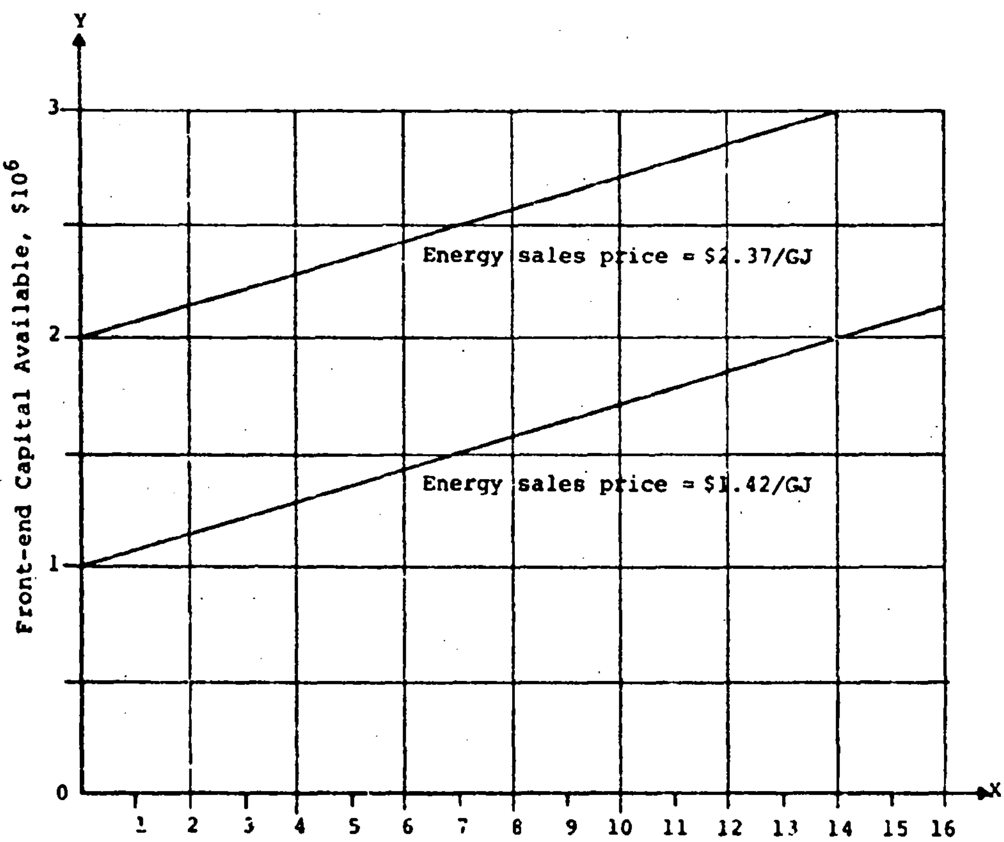

Figure 2. Front-end affordable capital vs. landfill avoidance cost for energy sale price of $1.42/GJ ($1.50/M Btu) and $2.37/GJ ($2.50/M Btu).

yields "Y" (in Mg RDF/Mg input waste) somewhat smaller than or equal to 50%. The size of the facility, in Mg/d of input, is obviously 100/Y (112/Y ton/d). As explained in the following section on plant layout and costing, a recirculation of trommel oversize could be implemented, if necessary, to achieve a figure of 50% for the yield in RDF (Y = 0.50).

Proposed Process Flow

In choosing one of many feasible schemes for producing, from raw municipal solid waste, an "acceptable to good" RDF feedstock, the emphasis was placed primarily on:

- simplicity of operation
- low capital and O&M costs
- production of a feedstock having a moisture level between 12 and 25%, having low inorganic fines (extrinsic ash) and being free of tramp metals

Some of these requirements (such as requiring a low ash content) might conflict with the objective of a high yield. Therefore, compromises might have to be made which relatively increase the quantity, and thus the disposal cost, of process residuals.

Basic Building Blocks

The "building blocks" which would appear to be well suited to small systems are:

- the trommel (or rotary screen) which will effect the removal of glass and small organic materials with high efficiency
- the magnetic recovery system, with a suspended drum or belt magnet. Efficiencies on the order of 85 to 90% are expected.
- the size reduction device, which only handles that fraction of the input waste to be densified as a fuel.

The principal size reduction mechanism called for is a cutting action on materials such as paper, plastics and fabrics. Throughputs are only a fraction (on the order of 50%) of the total input rate. Incidentally, the reliable and continuous operation of such a knife shredder, if it is not designed to be tolerant of pieces of hard metal, would possibly require the installation, immediately ahead of the shredder. of a device yet to be developed, whose function would be to remove large pieces of metal (possibly non-magnetic) present at that stage. It is schematized, in Figure 3, as an optional unit, called a "tramp metal separator" here. As already mentioned, the analysis of an aerodynamic device for separation of tramp material is the subject of a project currently underway at NCRR (14).

These building blocks are the basic components of the scheme described below.

Process Flow: Flail-Milling and Two-Hole Trommeling

The basic process flow is shown in Figure 3. The raw waste is flail-milled first, then trommeled. Magnetic recovery is effected on the 203 mm (8 in.) hole undersize product. Aluminum picking (by hand) is optional. The remainder of this fraction is size-reduced before densification. Again, the option of removing tramp metals prior to size reduction is sketched on Figure 3, but not included in the sample calculations.

Based on a survey of available data and results from Recovery 1, the City of New Orleans' resource recovery plant, a reasonable composition is given in Table 4. Starting with this composition and the size distribution in Figure 4, a computed size distribution for the flail-milled product is obtained and given in Figure 5. (As

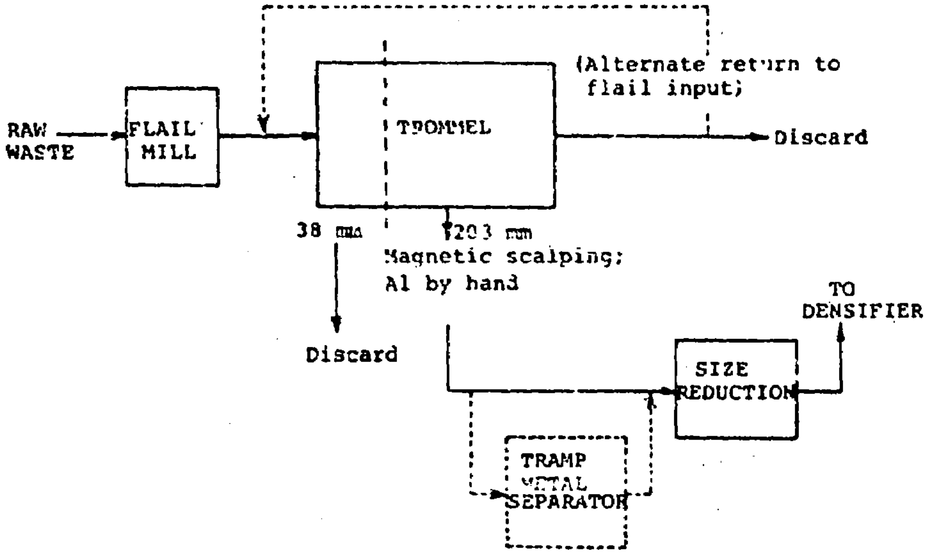

Figure 3. Process flow schematic.

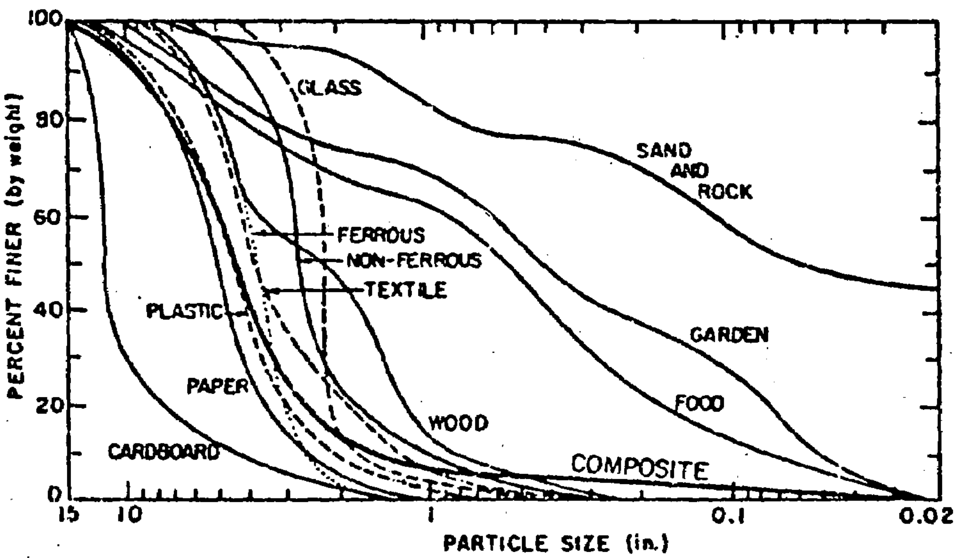

Figure 4. Cumulative distributions of raw waste.

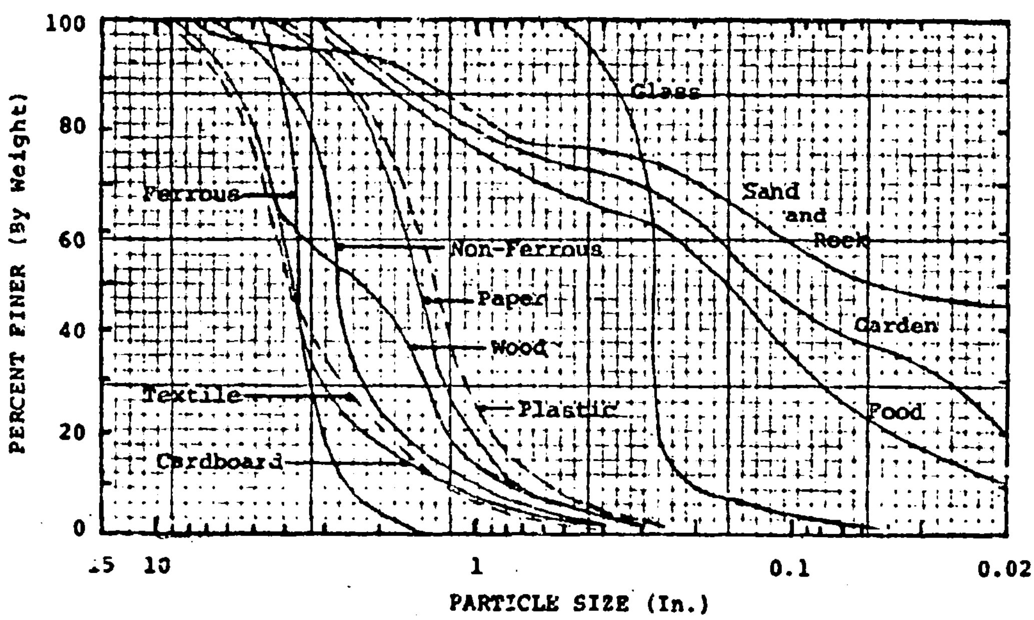

Figure 5. Computed particle-size distribution of flail-milled raw waste.

TABLE 4. ASSUMED COMPOSITION OF INPUT WASTE

Material	Wt% as-received	Of which moisture is wt% as-received	HHV, MJ/kg (Btu/lb) dry basis
Paper	30	5	17.43(7,500)
Cardboard	13	3	16.36(7,040)
Glass	9.2	0.3	-
Garden & Food Wastes	25	12	17.43(7,500)
Ferrous	8	-	-
Stones	3	0.9	-
Fines (<1/4 in.)	4	0.1	-
Non-ferrous	0.3	-	-
Textiles	2.5	0.5	23.24(10,000)
Plastic	2	-	37.18(16,000)
Wood	3	1.5	20.22(8,700)
	100.0	23.3	

pointed out by A. Scaramelli et al., (30), very little experimental information exists and has been documented on flail mill product sizing.) It is observed that the graphs for individual components show a horizontal translation (towards the smaller sizes), the magnitude of which depends on the material considered. Bond's theory as applied to municipal waste (31) was used to compute the specific power (kWh/Mg) required to effect the size reduction of glass from the initial size (80% under 68.6 mm (2.7 in.) to the desired size (80% under 8.4 mm 0.33 in.)). The power is then allotted to the other components in the proportion of their weight fraction in the mixture. The prediction is that paper will be reduced in size from -203 mm (-8 in.) to -56 mm (-2.2 in.), whereas the size of stones, wood and metals remain unchanged.

Based on the New Orleans trommel evaluation (Bernheisel et al. (22,31)) and other relevant data (Woodruff (32), Woodruff and Bales (33)), Table 5 presents values for the trommel screening efficiencies, which were adopted in the calculations. It is well realized that these figures do not apply regardless of hole sizes, screening sections length, trommel dynamic parameters and feedrate. It is one of the objectives of a detailed investigation underway at NCRR, under DOE support (18), to develop detailed and more widely applicable data for the screening efficiency matrix, in terms of components and sizes. Overall, however, the values of Table 5 are thought to be realistic and conservative.

A detailed mass balance is reported elsewhere (18). A five-point moisture loss is allowed for drying during processing. The yield and fuel specifications are listed in Table 6.

TABLE 5. ESTIMATED SCREENING EFFICIENCIES OF TROMMEL

Component	η_S, Screening Eff., %
Paper	70
Cardboard	70
Glass	99
Garden & food waste	90
Ferrous	85
Stones	100
Fines	98
Non-ferrous	92
Textiles	35
Plastic	78
Wood	60

TABLE 6. YIELD AND SPECIFICATION

Fuel: 38 to 203 mm (1.5 in. to -8 in.) with ferrous extracted

Yield: Y_S = 36.2 (%) (Figure 2)

Composition*	Wt% (dry basis)*
Paper	52.2
Cardboard	24.0
Glass	0.3
Garden & food waste	10.7
Ferrous	2.2
Stones	1.2
Fines (<1/4 in.)	0.3
Non-ferrous	0.8
Textiles	2.3
Plastics	3.3
Wood	2.6

*Percentage might not add up to 100% due to rounding

Moisture: 21.0%

Higher heating value: HHV = 13.56 MG/kg (5,835 Btu/lb), as-received

HHV_d = 17.16 MG/kg (7,385 Btu/lb), dry basis

Ash content: 9.6% (dry basis)

The oversize (+203 mm) product represents 16.2 wt% of the incoming product, and has a moisture content, as-received of 19.0 wt%. Of this fraction, 92.5 wt%, or 15.0 wt% of the input waste, is essentially combustible, and consists of 71.2 wt% paper and cardboard, 3.6 wt% garden and food wastes, 6.4 wt% wood and 11.2% textiles and plastics. The moisture content of the combustible fraction, as-received, is 20.5 wt%. Therefore, flail milling of the oversize would ultimately raise the yield of the processed RDF. After removal of the ferrous materials (practically the only non-combustible component) by a magnetic pulley, the yield is calculated to be 15.1 wt% of the input waste. Since the moisture is comparable and the heating value is in excess of the value in Table 6, it is therefore realistic and conservative to adopt the above fuel characteristics, with a yield Y equal to 50% of the input waste.

Facility Layout and Costing

A layout of the front-end system based on the flail milling and two-hole trommeling process described in the previous section is shown in Figure 6. Some details on equipment specification and estimates of engineering, equipment, installation and building costs (all 1979 basis) are presented in Table 7.

Note that for purposes of the subsequent analysis, the total front-end plant cost of $1,687,700 does not include the d-RDF module costs. The layout and cost of the d-RDF module ($389,900) has been detailed previously (see Table 1) and discussed in an earlier section.

The front end loader illustrated in Figure 6 is sized to process up to 20 Mg/h of MSW and produce up to 20 Mg/h of feedstock for the d-RDF module. Actual hourly throughputs are expected to be somewhat lower. Waste is received and tipped on a 800 m^2 tipping area with a storage capacity of 200 to 250 Mg of material. A front-end loader pushes the waste into a shallow apron conveyor. The flail feed conveyor is inclined in such a manner that material roll-back controls the feedrate to the flail mill. The flailed product is conveyed to the trommel.

As detailed elsewhere, the -38 mm material from the first section of the trommel contains nearly all of the glass and inorganic fines; it is discarded. The intermediate -203 mm fraction from the second trommel section contains the bulk of the paper and organics and passes on for further processing. The quantity of the +203 mm product, expected to be composed primarily of cardboard and smaller quantities of wood, textiles, plastics and paper, will be a function of the flail mill product size. Figure 6 shows this fraction conveyed to a residue container for disposal. If, in fact, there is a significant level of paper and cardboard present in this fraction, minor equipment modifications would permit recouping these losses. This would involve an increase in hole size in the second trommel section or rerouting the trommel overs to the flail mill infeed. For either case, the impact on the cost estimates developed here would be negligible.

The -203 mm middling fraction is conveyed to a tramp material separator. This device would most likely be a form of air knife, designed to remove dense materials such as non-ferrous metals, wood or large rocks and stones. The objective is to keep such materials

TABLE 7. FRONT-END PROCESSING SYSTEM CAPITAL COST ESTIMATE-1979 COSTS (REF. 8)

Equipment description		Cost estimate
Front-end loader		$25,000
Receiving conveyor #1 - 25 m x 2 m		37,500
Feed conveyor #2 - 12 m x 2 m		18,000
Flail mill		60,000
Outfeed conveyor #3 - 4 m x 1 m; #4 - 10 m x 1 m		10,000
Trommel 8 m L x 3 m Ø - 38 mm and 203 mm openings		85,000
Overs conveyor #5 - 3 m x 2 m		3,000
Residue conveyors #6 - 18 m x 1 m; #7 - 6 m x 1 m #8 - 10 m x 1 m; #9 - 8 m x 1 m		30,000
Feed conveyor #10 - 10 m x 1 m		7,000
Tramp material separator		60,000
Outfeed conveyors #11 - 3 m x 1 m, #12 - 9 m x 1 m		8,500
Magnetic separator		8,000
Ferrous conveyor #13 - 8 m x .5 m		5,000
Secondary shredder		125,000
Outfeed conveyor #14 - 3 m x 1 m		2,500
d-RDF module - not included here (see Table 1)		---
Dust control system		30,000
Motor control center, operator panel & stations		50,000
Miscellaneous tools/spares		25,000
	Equipment Sub-Total	$589,500
Taxes & freight - 7% equipment		41,300
Installation mechanical/electrical-30% equipment		176,900
Building - 1680 m^2 @ $360/$m^2$		600,000
	Installed Sub-Total	$1,407,000
Engineering @ 10%		140,000
Contingency @ 10%		140,000
	Capital Cost Total	$1,687,700

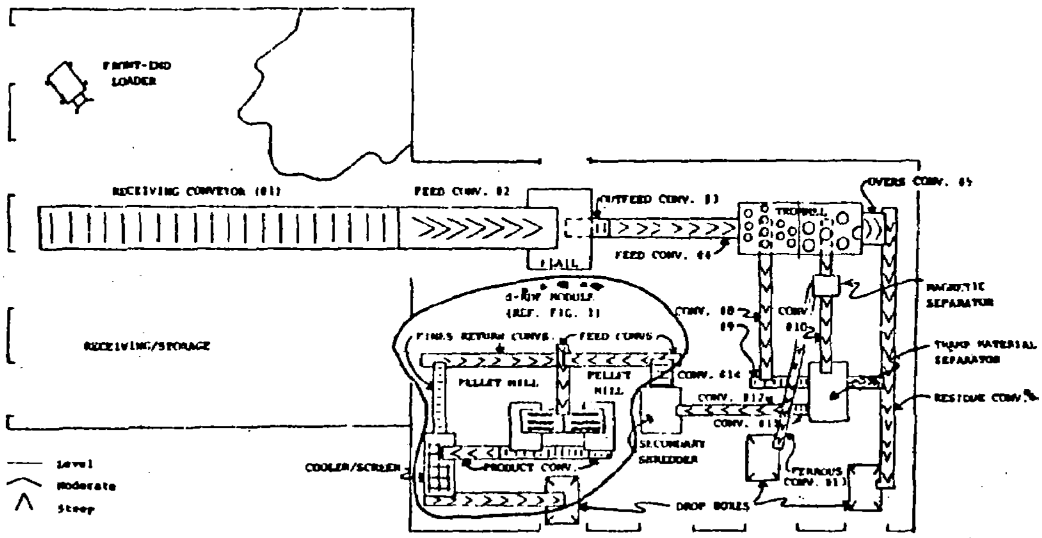

Figure 6. Small community d-RDF system layout.

out of the secondary shredder or densifier.

Residues from the tramp metal separator are combined with the -38 mm trommel undersize fraction and conveyed past a magnetic separator. The ferrous metals are separated and conveyed to one bin and the non-ferrous residue is discharged into another bin (or truck) for hauling to a landfill.

Two conveyors carry the remaining organics to a secondary shredder where they are reduced to a nominal -30 mm size. This product is then fed into the densifier module feed conveyors and on through a splitter into two parallel live-bottom metering bins and densifiers. The d-RDF product is screened to remove fines (which are recycled to the densifier feed) and then cooled in a pellet cooler.

Not represented in the equipment layout but included in the costs is a dust control system, the operator control room, motor control center, local control stations and office facilities. The installation costs (mechanical and electrical) are estimated at 30% of the equipment cost and taxes and freight at 7%. The building costs are estimated on a unit area basis at $\$360/m^2$. Land costs are not included. Contingency and engineering costs are based on a percentage of total installed cost and are projected at 10% each.

Economic Viability

In the previous section, a tentative layout and costing are developed for a d-RDF plant using two densifiers and recovering the ferrous materials.

We now refer to Tables 1 and 7 for anticipated costs of

C(D) = $389,000 for the densification unit, "D"

C(R) = $1,687,700 for the remainder of the plant, "R"

Breakeven (i.e., economic indifference between landfilling or fuel production) will occur at a combination of values of landfill cost, x^*, sale prices of energy, k_f, and fraction k_y of the plant capital cost (not including the densification unit) to be spent yearly in O&M of that part of the plant. This dependence is illustrated below, for $k_y = 0.2$. If k_f = \$1.42/GJ (\$1.50/M Btu), then x^* = 9.34 \$/Mg. If k_f = \$1.90 GJ (\$2.00/M Btu), x^* = 2.74 \$/Mg. The latter value of x^* = \$2.74/Mg shows that in this case, the plant should produce a net revenue, N.R., if the actual cost of landfill exceeds x^*, equal to N.R. = 25,000 (x - 2.74) (\$/y).

More generally, given k_y and the corresponding line x^* (k_f), for a set value $k_f = k_f^{(1)}$ of the sale price of energy, the value x^* (1) = x ($k_f^{(1)}$) is read on the graph. The net yearly revenue is a function of the actual landfill cost, x (\$/Mg), expressed here as N.R. = (25,000) (x - x^*) (\$/y).

Figure 7, where x^* at breakeven has been plotted versus the sale price of energy, for $k_y = 0.2$, would allow a preliminary determination of the economic viability of the proposed solution, in a particular case, for planning and analysis purposes.

Note that, since the yield in this example is 50%, the cost of disposing of the process discards is taken to be x (\$/Mg) per Mg of RDF. Therefore, the overall operation (d-RDF plant and landfill operations for the total input waste) will be self-supporting or profitable if net revenues from the d-RDF plant balance or exceed the cost of disposal of the remainder, or since $x > 0$, if $x^* \leq 0$ or $k_f \geq k_f (x^* = 0)$. This is realized for all values of (x, k_f) in the quadrant defined by the horizontal axis and the vertical axis drawn through the intercept of line $k_f = k_f (x^* = 0)$ with the horizontal axis, for the assumed value of k_y (here 0.2) (Figure 7).

ACKNOWLEDGMENTS

The evaluation of d-RDF systems for small communities reported in the second part of this paper was carried out by the National Center for Resource Recovery, Inc., as part of Grant No. R804150 from the U.S. Environmental Protection Agency's Municipal Environmental Research Laboratory, Cincinnati, Ohio (Carlton Wiles, EPA Project Officer). The support of many colleagues at the Center who were involved with that project is acknowledged.

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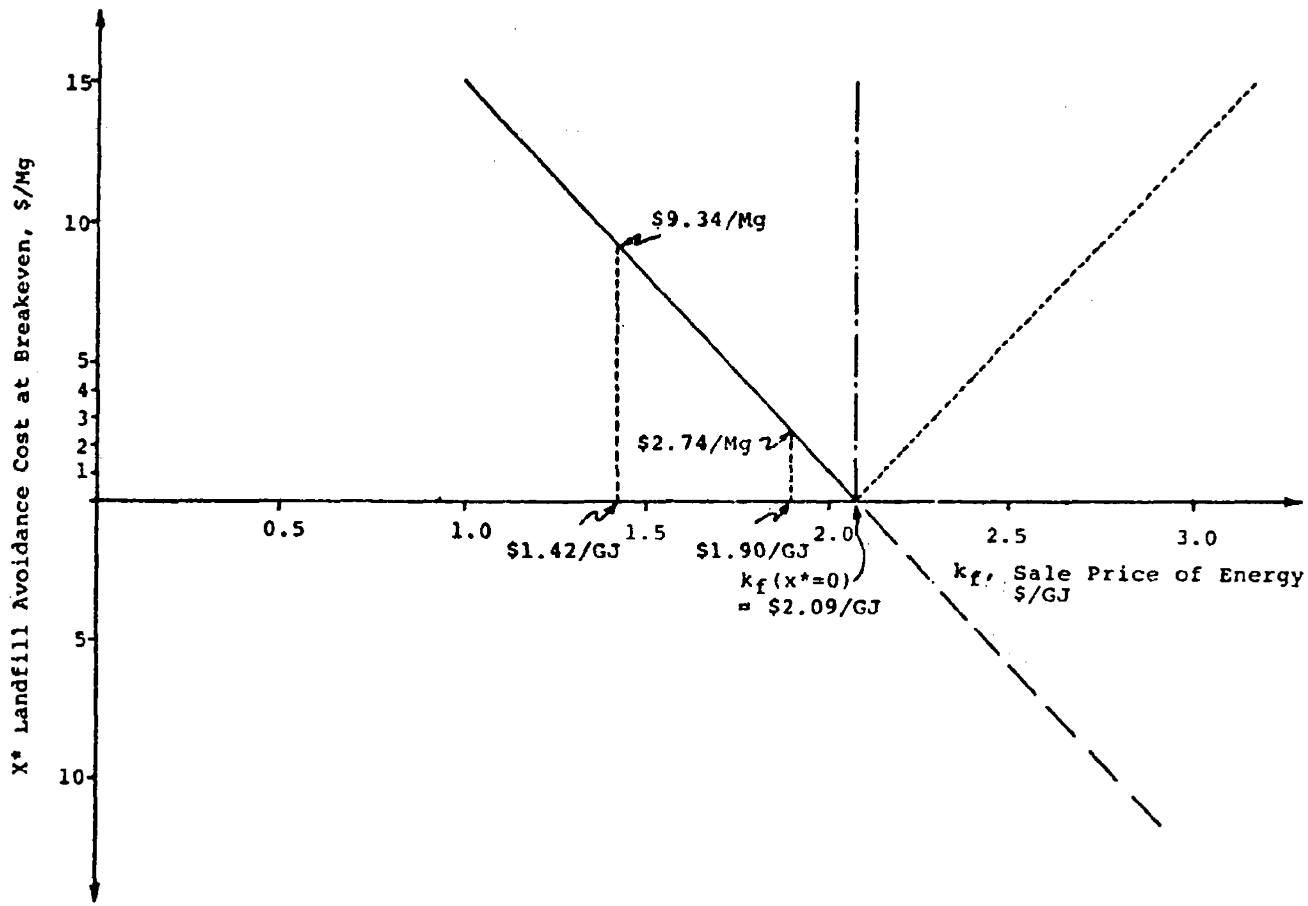

Figure 7. Breakeven landfill cost versus sale price of energy, k_y=0.2.

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TEST AND EVALUATION AT THE NEW ORLEANS RESOURCE RECOVERY FACILITY

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ABSTRACT

For the three years since the completion of the Recovery Module at Recovery 1, NCRR has been testing and evaluating equipment. This has been done concurrently with operation and modifications. These efforts have resulted in a facility which recovers ferrous metal, aluminum, and glass, each of which meets the rigid specifications of its purchaser. This paper summarizes these efforts. It covers the performance of the three recovery systems. In addition, the major modifications to each system are discussed.

INTRODUCTION

Project Background

The National Center for Resource Recovery (NCRR), Waste Management, Inc. (WMI), and the City of New Orleans agreed in the early 1970's to undertake the construction and operation of a materials recovery system as an adjunct to the City's then-contemplated shredded waste landfill disposal program. The City's program called for the construction and operation of a shred and landfill facility capable of processing 650 tons per day (tpd) of municipal solid waste (MSW), about half the daily waste generated in Orleans Parish [1].

The construction and operation of the materials recovery facility by WMI were subject to a number of conditions which limited the financial risk of WMI. The cost of this initial, large-scale venture into the recovery of magnetic metals, aluminum, and glass was shared by WMI and NCRR. The various commitments made in this initial agreement were fulfilled in July 1980, and a new agreement between WMI and NCRR for the continued use of the site for test and evaluation has been effected.

This report describes the experience gained in two and one-half years of equipment testing and shakedown. The data presented in this report were obtained in the NCRR test program for the equipment in the New Orleans facility. This test program was funded by two sources. First, by NCRR's internal funds. Second, by a contract for testing of equipment with the Municipal Research Laboratory of EPA located in Cincinnati, Ohio. This contract called for ten equipment tests which were completed, documented, and accepted by EPA in October 1980. These tests are described in some detail in the Test Report Series [2]. In order to present a coherent picture, this report covers the test and evaluation activities conducted by NCRR in New Orleans without regard to the source of funds. The effort - currently on-going - is anticipated to continue for the near future.

During the period covered by this report, the principal areas of activity were in (1) establishing what was in the waste - how much ferrous, glass, and aluminum - and what their characteristics were; (2) evaluating the performance of the trommel in processing MSW - the first and largest such unit installed in the U. S.; (3) delineating the operating parameters of the initial ferrous recovery system and its modified successor; (4) performing system and unit process testing of the aluminum and glass concentrating equipment and the aluminum recovery and product cleanup devices; and (5) debugging the operation of the equipment installed for glass recovery in order to establish its operating parameters.

The Recovery Module was completed February 28, 1978; the three-year test and evaluation period began on March 1, 1978. During this period, WMI and NCRR attempted to shake down the facility. It has been during this period that NCRR has conducted this series of tests on the individual equipment items mentioned above. Concurrent with these efforts to complete the facility, NCRR documented the plant as-built. The equipment, projected flows, and actual construction costs were summarized in the New Orleans Resource Recovery Implementation Study [3].

In July 1980, NCRR took over responsibility for the operation of the aluminum and glass recovery systems. NCRR has gotten the systems to function, and has produced 330 tons of glass and 29 tons of aluminum product which met the specifications of the customers.

Facility Description

The following paragraphs give a summary description of the facility (more detailed descriptions of each equipment item are included in later sections).

Incoming refuse is delivered to Recovery 1 in collection and transfer trucks. After weighing, it is deposited on the tipping floor of the Receiving Building, and pushed by a front-end loader into a pit conveyor. In the primary line, the refuse is first channeled through a 45-foot-long, 10-1/2-foot-diameter trommel (rotary screen), with 4-3/4-inch-diameter holes in the barrel. The rotating trommel breaks open plastic and paper bags, and sorts out most of the glass containers and metal cans. The separation of this trommel underflow material enhances later recovery of the glass and metal, and reduces wear on the shredder hammers and other components. The trommel underflow material also includes small-sized organic wastes, which are separated out in subsequent processing operations.

The remaining refuse, or trommel overflow material, enters the primary shredder, which reduces it to smaller, more manageable sizes. The secondary shredder provides a backup to the primary line.

Ferrous Recovery

Ferrous metal recovery begins as the trommel underflow, and shredded materials are conveyed separately under rotating magnetic drum separators. Recovered ferrous metals are directed to an air knife for cleanup and separation into two ferrous fractions: a light metal, consisting of cans and other light-gauge metals; and a heavy metal, made up of castings, forgings, and rolled stock. Light, non-ferrous materials, such as paper and plastic, are also discharged as a residue. The heavier ferrous is discharged directly from the air knife, while the lighter ferrous drops into a ferrous metals shredder. After shredding, the material is scalped by a belt magnetic separator and conveyed to either a railcar or the storage bin.

Following extraction of the ferrous product, the residue from the shredded material conveyor is moved to the landfill loadout area for disposal. In the future, this material may comprise a refuse-derived fuel product, but no market has been secured as yet. Material remaining in the trommel underflow line enters a trifurcated chute for metering into the air classifier.

The Recovery 1 air classifier uses a controlled column of turbulent air to separate the light (primarily organic) waste from the heavy (primarily inorganic) material. The "lights" are discharged to the landfill loadout area, and the air-classified heavy material is conveyed to the Recovery Building for extraction of aluminum and glass.

Aluminum Recovery

Aluminum recovery is initiated as the air-classified heavy material is deposited on a two-deck, 4 by 2-inch vibrating screen for separation into sizes larger than 4 inches, smaller than 2 inches, and between 4 and 2 inches. The plus 4-inch material is conveyed to the landfill loadout area, the minus 2-inch fraction enters the glass-rich processing stream, and the 4 by 2-inch material is introduced into the aluminum recovery cycle.

This aluminum-rich fraction is carried by an elevator to a 2-inch vibrating screen, where particles smaller than 2 inches, which were missed in the previous screening, are separated out and chuted onto the residue conveyor to the landfill. Material larger than 2 inches continues over a rotating drum magnet to remove residual ferrous metals before the stream enters the eddy current separator.

The eddy current separator, or "aluminum magnet," incorporates a series of electromagnets set precisely above and below a belt conveyor. The electromagnetic field and the resulting field in the conducting aluminum cause the aluminum product to be repelled into a collecting chute.

The separated aluminum then enters an air knife for further separation into aluminum canstock, other metals, and organic contaminants. The aluminum canstock - the primary output of this subsystem - is reduced in size and compacted by a hammermill to increa_ shipping density.. After being conveyed onto a 12-mesh vibrating screen to remove any fine materials, the recovered aluminum is pneumatically transported out of the building and into a trailer truck for shipment to market.

Glass Recovery

Glass recovery starts with the separation of a glass-rich fraction from the air-classified heavy fraction by the 4 by 2-inch vibrating screen.

An elevator carries the crushed glass up and onto a 1-inch vibrating screen. All material larger than 1 inch is conveyed to the landfill loadout area. The smaller than 1-inch fraction passes through a surge bin to a vibrating feeder and into a minerals jig, where a vertically pulsed water flow separates the light organic waste from the heavy (primarily glass) material. The jig produces a glass fraction that contains a small amount of contaminants.

The glass fraction is then pumped as a slurry to a 20-mesh vibrating screen for "sizing." Larger particles are transported to a rod mill for further size reduction, and piped back to the 20-mesh vibrating screen for a second screening. The flow of the minus-20-mesh material proceeds to a hydrocyclone for the first step in glass cleanup. The centrifugal force created in this process rejects the finer particles and removes the water from the glass stream.

This material then enters the final separation process, the froth flotation unit. In this operation, the glass and remaining contaminants are mixed with a chemical reagent, which adsorbs to the surface of the glass. The coated glass attaches to air bubbles formed in the tank, rises to the surface of the fluid-filled tank, and is "floated off." The recovered glass slurry is dewatered in another hydrocyclone and a vacuum filter before being dried in a spiral dryer. After drying, the glass is conveyed to one of two glass storage silos for shipment.

Residues are extracted throughout the various recovery processes. Although this material is currently being landfilled, it could be processed into a fuel product if a suitable, nearby market could be developed. Most of the residue is separated by the air classifier and its connecting cyclone, which serves to de-entrain the air flow within the system. The air handling equipment and conveyors provide similar functions in the Recovery Building, depositing the various residues on a conveyor leading to the loadout area. From the landfill loadout area, the shredded residues are carried to the adjoining landfill by a tubular conveyor and distributed in heavy-duty trailer trucks.

RECOVERY FEED PREPARATION

The purpose of the feed preparation section of the system - from the recovery standpoint - is to (1) concentrate metals and glass for materials recovery, and (2) produce an organic fraction for conversion into refuse-derived fuel (RDF). As no RDF market has been secured in New Orleans, this material is currently landfilled.

Mass Balance

Figure 1 depicts the unit operations performed in preparation of the MSW (consisting of size separation in trommel shredding, and air classification) prior to entering the individual recovery systems: ferrous metals, aluminum, glass, and RDF (as mentioned, no RDF process has been implemented). The rectangles represent the unit processes. Each flow from a process is shown by an arrow, with the mass of material given in figures adjacent to the arrow. The mass flows, shown in tph, correspond to the design rate of 62.5 tons

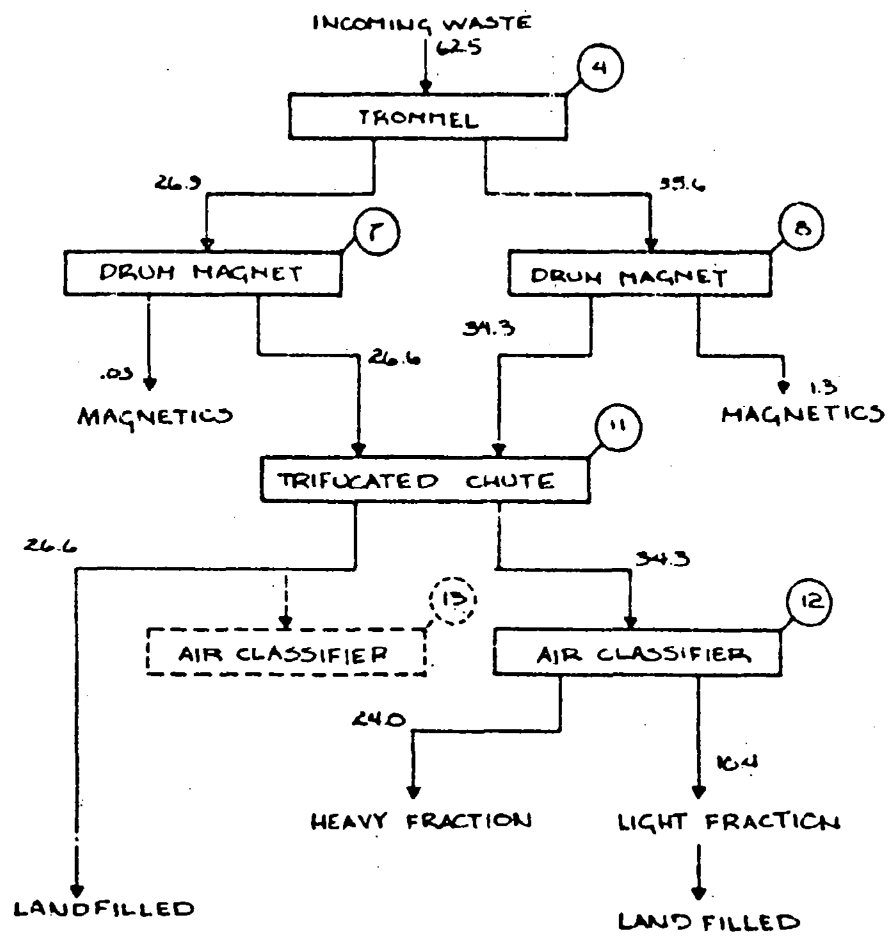


Figure 1. Feed Preparation Flow and Mass Balance

per hour (tph) of MSW feed to the plant. Most separation equipment is sensitive to its feed rate; increasing the rate for a given equipment will alter its performance. In addition to data on mass flows developed by the NCRR testing program, some data concerning the composition of these streams has been developed, and are presented in the following paragraphs.

Municipal Solid Waste Composition

Early in the City's planning for what developed into the Recovery 1 project, a large (32,000 pounds) sample of five days' raw waste was sorted and evaluated for its recovery potential by a consultant. The approach used was to cone and quarter, following standard sampling procedures. The results showed 7.5% ferrous metal, 1.2% aluminum, and 10.9% glass in the waste [4]. These percentages were calculated on an "as-received" basis. There was no decontamination of the metals or glass; for example, a can containing some organic matter was not washed, but was weighed with the contaminants.

This accounts for a portion of a difference between this early sample and the extensive raw waste evaluation that took place during the shakedown period.

During the trommel testing conducted in 1978, three samples were taken which form the basis for an estimate of the composition of the New Orleans waste. These samples were sorted by hand into a selected set of categories, and the results tabulated. These data are available in the original test report [5].

These tests reported a higher percentage of recoverable ferrous metal and aluminum than was being realized by the operation of the recovery system, but lower than the initial sample mentioned above. Therefore, it was decided to undertake a long-term - at least one year - sampling effort. This effort was aimed specifically at the recoverable materials for which Recovery 1 had markets.

The metals values found in the trommel test were approximately 28% higher than those obtained from the long-term sample. However, the values are within the variation that was experienced in the long-term sampling program, and the sample analysis techniques were comparable. The difference is therefore attributed to the normal variation in MSW.

During the 14-month sampling period, methods and analysis procedures changed, incorporating the usual learning process and, more importantly, feedback from the equipment test and evaluation activities also on-going and described later in this paper. For example, categories were established and definitions developed to match the market specifications. Also, certain standardizations were formulated to fortify the scientific basis for the program and add to its replicability.

Table 1 shows the measured concentrations of ferrous metals, aluminum cans, and glass which resulted from this program. These figures represent each constituent as free of contaminants as possible, using washing, scraping, and firing techniques. The ferrous and aluminum data presented represent the average character of the waste from December 1978 through January 1980. Twelve samplings per month were taken. The glass data came from a lesser number of samples. These were limited because the physical analysis of samples for glass is both time-consuming and expensive.

Light ferrous - primarily canstock is the principal magnetic metal target. The market for this material is Proler International, a secondary metals processor. It is detinned and then used in the copper precipitation process. Heavy ferrous

TABLE 1. CONCENTRATIONS OF FERROUS METALS, ALUMINUM, AND GLASS IN MUNICIPAL WASTE

	Metal (%)	Attached Contaminant (%)	Total Material (%)
Light ferrous			
<4 inches	2.40	1.05	3.45
>4 inches	0.32	0.20	0.52
Heavy ferrous			
<4 inches	0.35	0.25	0.60
>4 inches	0.67	0.52	1.19
Total	3.74	2.02	5.76
Aluminum cans	0.31	0.12	0.43
Glass			15.2

material, such as a piece of automobile brake shoe, is not desirable. A limited amount of this is allowed by specification. The 4-inch size distinction is the screen standard made by the 4-3/4-inch-diameter holes in the trommel upstream of the magnets [6]. This is the basis for the efficiency information given in the trommel discussion.

The data in Table 1 show a distinction between metal and attached contamination. This was obtained in the following manner. In sorting the MSW sample, each metal object removed was shaken once by hand. Any adhering material was initially weighed with the metal. The metal was then scraped, washed, and baked to remove contaminants. The metal was weighed a second time, and the difference in weight considered to be attached contamination. Light ferrous, the marketed material, is defined as "can and container-related steel." For this material, attached contaminants amounted to 30.1% of the total weight. For aluminum cans, it was 26.1%. These data are significant and illustrate one of the lessons learned, i.e., that attached contamination can distort composition values for MSW. Simply weighing components such as ferrous metal and aluminum, sorted by inspection as they are taken from the waste, will not provide accurate estimates for predicting recovery potential.

Trommel

As noted earlier, Recovery 1 has the largest municipal solid waste trommel in operation. Its purpose is twofold: (1) to screen out and bypass around the primary size reduction shredder that material which is already less than 4 inches, thereby saving energy and maintenance; and (2) to concentrate organic-rich and materials-rich streams for additional recovery processing. The trommel also breaks glass and other friable materials, allowing 99% of these materials to report to the underflow. If there were an energy market in New Orleans, the slagging potential and ash content of the fuel fraction would be considerably reduced by the presence of this processing step.

Formal testing of the trommel, which began in December 1977, focused on the bypass question. The amount of material bypassing the primary shredder was measured in the mass balance. As far as recovery was concerned, it focused on screening efficiency. Screening efficiency is defined as the proportion of the material of the size range of interest (in the trommel case, 4 inches) which passed through the screen, divided by the total amount of material in the size range in the feed.

Data on the trommel was collected at two operating conditions: the nominal design condition, 62.5 tph, at which formal tests were run, and 100 tph, at which operational data were taken. The overall split in the former case is 45% by weight to trommel oversize (i.e., that material that did not go through the holes), and 55% to trommel undersize (which did go through the holes). This is "as-received," with an average moisture level of 30%. In the 100 tph case, the as-received figures are approximately 50% oversize and 50% undersize.

Mass balances and screen efficiencies for the recovered materials are given in Table 2. The mass balance is on a percent weight basis - 100% of the material of interest is contained in the trommel feed and is divided into the undersize and oversize fractions. Additional information is available in the test report [5]. The data indicate that the screening efficiency drops as the throughput increases. For example, 100 pounds of ferrous in the feed results in 35 pounds to the oversize and

TABLE 2. MASS BALANCE AND SCREENING EFFICIENCIES FOR RECOVERED MATERIALS

	Oversize (%)	Undersize (%)	Screening Efficiency (%)
62.5 tph Feed Rate			
Light ferrous metal	31	69	79
Heavy ferrous metal	70	30	90
Total ferrous metal	43	57	82
Aluminum cans	9	91	91
Glass	1	99	99
Paper	70	30	68
100 tph Feed Rate			
Light ferrous metal	48	52	60
Heavy ferrous metal	88	12	35
Total ferrous metal	60	40	56
Aluminum cans	15	85	85
Glass	6	94	99
Paper	—	—	—

65 pounds to the undersize at 62.5 tph, and 55 pounds to oversize and 45 pounds to undersize at 100 tph. The reason for the difference is that the increased burden reduces the probability that an individual ferrous item smaller than 4 inches will address an opening so it can go through. The problem is most acute for the near-size items, i.e., those whose largest measurement is close to the opening diameter.

The separation of paper in the trommel is not highly efficient - 68%. This, however, is beneficial in the production of a paper-rich fraction for fiber recovery or for production of RDF, as the oversize fraction provides the feed material for these products. Table 2 shows 70% of all the paper in the infeed reporting to trommel oversize. The separation efficiency is higher for those materials which have a particle size much smaller than the screen opening. This is the case with glass, and provides the reason for near-perfect separation efficiency.

The trommel separates unprocessed waste and creates a fuel-rich oversize fraction that is 90 to 95% combustible. Testing to date shows that the shredded trommel oversize material has a calorific value of 7,120 Btu/lb (dry weight basis) [5].

A proximate analysis of shredded trommel oversize appears in Table 3. The moisture is somewhat lower than generally reported in MSW samples, but not startlingly so. The ash level, however, is significantly below general level [7]. This reflects the impact of trommel processing.

TABLE 3. PROXIMATE ANALYSIS OF RECOVERY 1 TROMMEL OVERSIZE MATERIAL

Calorific value*	7,120 Btu/lb
Moisture	25.8%
Ash*	9.8%
Sulphur*	0.1%

*Dry weight basis

Clearly, the trommel, in addition to providing energy and maintenance cost savings (only about half the waste is shredded), is also a materials recovery concentrating device, since the larger proportion of the ferrous metals and other target materials go through the holes when the unit is operated at design capacity. Ferrous concentrations in the raw waste have been given. Using the data from the trommel tests, the concentrations in the trommel undersize, which is the stream processed for aluminum and glass recovery, become: ferrous, 5.5%; aluminum, 0.177%; and glass, 26.3% (as-received basis). Both trommel oversize and undersize are processed for ferrous recovery. However, the concentration of glass and other non-combustible material in the undersize is critical for both energy and materials recovery.

Shredders

The function of the shredder is to reduce particle size of MSW and to liberate composite materials. In greater detail, the shredder functions are:

(1) To prepare the refuse for air classification, thereby preparing it for other separation unit processes. The air-classification step requires that the refuse be processed so that the pieces are relatively free and the particle sizes are reduced to avoid having oversize pieces of light material adhering to the heavier ones.

(2) To prepare the refuse for disposal. Essentially, this is a dual function. In the case of landfill disposal, to prepare the refuse so that daily cover is not required. This means that the food waste must be reduced in size and dispersed adequately to avoid rodent and disease vector problems. In the case of fuel preparation, the shredder reduces the particle size of the combustibles as required for the combustion process.

Shredders are commercially available in either horizontal or vertical hammermill models, or in vertical ring-hammermill models similar to those used for shredding MSW in a score of cities. The two shredders at Recovery 1 are designed for a throughput of 62.5 tph of MSW (packer truck refuse), and are capable of handling oversized bulky waste such as refrigerators, washers, and other household appliances. The output particle size specification requires that 99% of the material, by weight, be less than 5 inches in any direction. This is considered a nominal 4-inch grind. In addition, the shredder specification requires that the metal cans shall not be balled to the extent that detinning is economically unattractive, since this is the "ferrous" market.

Two shredders were selected for Recovery 1, both rated for an average capacity of 62.5 tph. The primary line utilizes a Heil 92B vertical hammermill, and the secondary (backup) line, a Gruendler 60-94. Both shredders are driven by direct-coupled Allis Chalmers 1,000 hp, 4,160-volt motors.

NCRR ran several tests on the particle size distribution from the Heil (primary) shredder. Two of these were in conjunction with the trommel tests, and the third about a year later. The data from these tests are shown in Figure 2. The results from these tests indicate that the shredder as operated did not meet the specification listed above. Note that the shape of the curve is different for the later test.

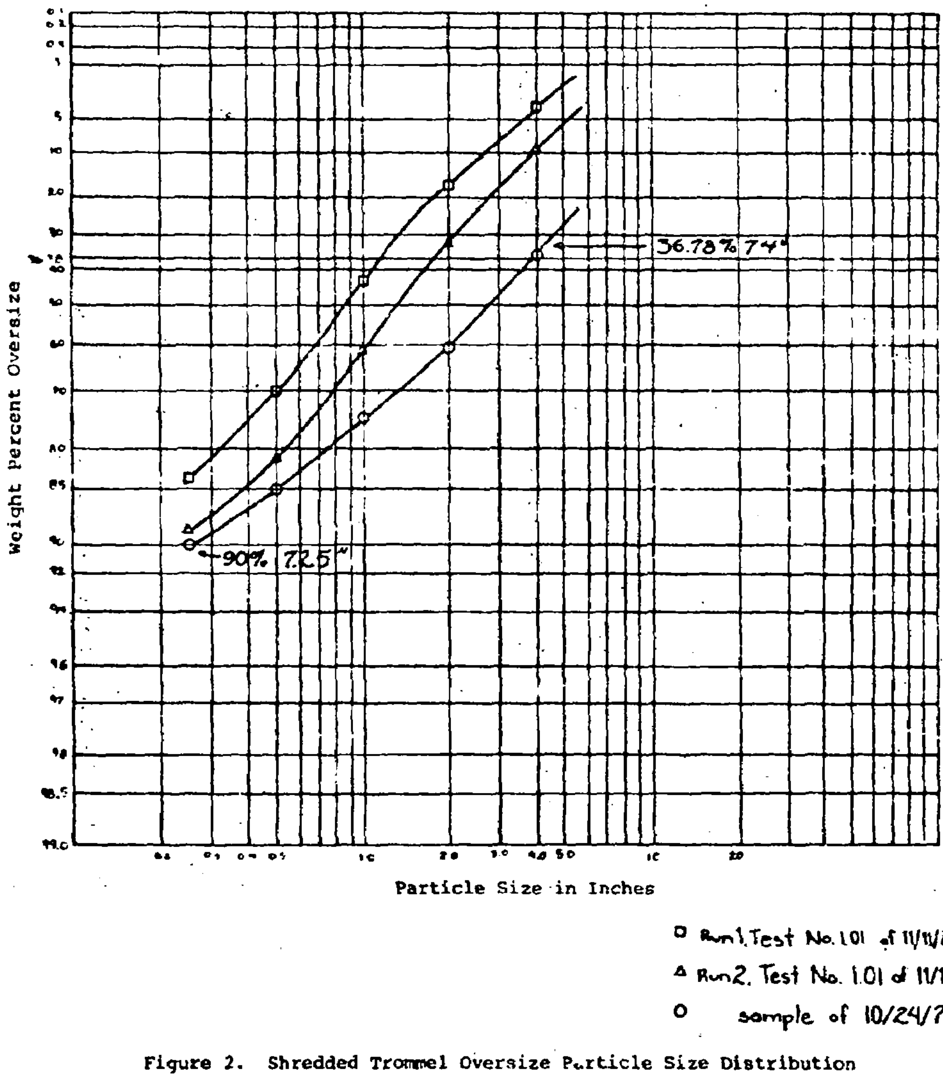


Figure 2. Shredded Trommel Oversize Particle Size Distribution

This probably indicates a different hammer condition (more or less wear) and/or patterns (location on the rotor).

Equipment Modifications

Three individual unit processes are discussed in this section: the trommel, the shredder, and the air classifier. The main thrust of these discussions is to highlight the modifications made and the effectiveness of each.

Trommel

This rotary screen (No. 4 in Figure 1) was made by Triple/S Dynamics, Dallas, Texas. The original specification called for a drive-train horsepower of 120 hp. However, the manufacturer felt that this was high, and a pre-delivery agreement was reached which provided for the drive to be one 40-hp motor with guaranteed performance. This motor drove a speed-reduction gearbox which was cross-shafted to a second gearbox. Each gearbox drove a single shaft, one on each side of the trommel barrel. Each of these shafts turned two trunnion wheels, which supported the barrel and drove two metal rims surrounding the trommel barrel.

The 40-hp motor was sufficient to run the trommel; however, insufficient horsepower was available to start an eccentric load of waste in the barrel. This was overcome by removing the cross-shafting that connected the two gearboxes, and driving each gearbox independently with a 40-hp motor. At the time the two motors were installed, direct reading ammeters were located in the control panel, which allows the console operator to note any significant difference in the output of the two motors.

The trommel barrel was declined 5° from the horizontal, which required a thrust roller to prevent the barrel from moving downward. The thrust roller, mounted on a 2-15/16-inch-diameter shaft, was positioned to ride against the side of the driven rim closest to the discharge. Physically, the roller was in the undersized material flow, located under the barrel at approximately seven o'clock. This thrust roller was relocated out of the flow to about the nine o'clock position to prevent undersized items from falling in between the thrust roller and the rim.

A dust cover completely encloses the trommel barrel. As originally supplied, it provided approximately 13 inches clearance between the rotating drum and the cover over the upper half of the drum. Long, thin objects (such as twisted small-diameter iron piping, automotive axles with flanged ends, wooden two by four's, etc.) would lodge in the holes and score the underside of the dust cover before eventually falling out. New covers were fitted which increased the clearance between the top of the drum and the cover by approximately 12 inches.

The trunnion drive shafts have been increased in size to gain strength. As delivered, the drive shafts were segmented and connected by flexible Dodge chain couplings. These repeatedly failed and were replaced by Falk flexible couplings. Also, the 2-15/16-inch-diameter solid shafts were replaced with 8-5/8-inch outside diameter tubing (0.156-inch wall, optimized), to increase torsional strength.

These two drive shafts are located so that the trunnion wheels contact the driven rims on each side at about 40° below the horizontal. This placed the exposed rotating shafts directly in the undersize stream. Long, flexible items (such as string, rope, typewriter ribbons, garden hoses, etc.) would become attached to the drive shaft. These items wound around the shafts, causing binding. To solve this problem, sheet metal covers were installed to shield the exposed shaft from the falling material.

Upon initial startup in the morning, moisture which had condensed on the trunnions and rim would cause slippage until the moisture was dissipated. This slippage wore flat spots on the driven rim which caused vibration or pounding. The pounding further deformed the rim. In addition, drum rim-to-trunnion misalignment aggravated the problem and caused the barrel to "walk" up and down the incline. The vibration became so severe as to prevent operation.

The driven rim was dressed by applying an abrasive stone to each rim while rotating the drum at a reduced speed of 3 rpm. Although some vibration persisted, it was of lower amplitude and did not prevent operation. Later, the rims were replaced.

Although mechanical difficulties have been faced with the trommel, many of these seem linked to one of three factors: (1) initial design faults, (2) inadequate maintenance, and (3) accelerated operation. However, it is a worthwhile unit process from the standpoint of materials concentration in the undersize material and reduction of wear-causing materials in the oversize. This was demonstrated by tests performed on the trommel and indicated by the separation efficiencies shown in Table 4. Note that the separation efficiencies are high for the noncombustible ash and wear-producing materials such as glass.

TABLE 4. TROMMEL SEPARATION EFFICIENCY

Component	Efficiency (%)
Combustibles	
Paper	67.7
Yard Waste	78.2
Plastics	74.4
Other organics	66.4
Non-Combustibles	
Ferrous metal	82.3
Aluminum	91.1
Other nonferrous	100.0
Glass	99.0
Stones and ceramics	100.0

While no quantitative data exist on the effect on shredder maintenance and operating costs resulting from removal of the non-combustible, abrasive fraction of the waste stream before shredding, observations have been made of such indicators as shredder motor amperage and frequency of hammer replacement or liner repair. These observations confirm that the trommel does reduce further processing costs while concentrating the recoverable materials.

Primary Shredder

The purpose of this vertical Heil unit is to reduce the particle size of the trommel oversize discharge. The specifications for this shredder require it to reduce 99% of the infeed to less than 5 inches in any dimension. Because of the trommel screening before the shredder, both the wear and the required horsepower are less than with unprocessed MSW.

The Heil is fitted with a ballistic reject capability and has a chute attached to the ballistic discharge port. As delivered, this chute had a fabric curtain covering the port. Material as light as paper passed into the chute. After several fabric thicknesses were tried, the curtain was replaced with 1-1/2-inch-thick steel plate hinged at the top.

Both the primary and the secondary shredder have, on occasion, ingested large, massive objects (examples include an office safe and a 4-inch-diameter, 4-foot-long solid steel shaft), causing damage to the shredder. The most extensive damage incurred consisted of breaking several swing arms and scoring the wear plates sufficiently to require replacement of some sections.

Because of its internal configuration, the Heil shredder generates a large air flow out of the discharge port. This causes severe housekeeping problems, even when the discharge conveyor was covered with a drop box. Final resolution was the installation of a positive-pressure cyclone with its blower, pulling air and shredded material from the discharge conveyor drop box and de-entraining the material onto the inclined shredded material conveyor leading to the trifurcated chute.

The means of lessening explosion effects used on both shredders was the installation of blow-off chutes extending from the top of the shredder through the roof. The chutes are covered by two overlapping doors that open outward under pressure generated by an explosion. They do not prevent fires or explosions. No explosion damage has been experienced with the one large and several small explosions in the four years of operation.

Secondary Shredder

The purpose of this horizontal Gruendler shredder is to reduce the particle size of the MSW when the primary system is not available. The mill has its own independent feed and discharge conveyor. However, it shares a common belt conveyor to the trifurcated chute with the primary unit. The MSW feed to this unit is not pre-processed by a trommel.

In addition to the backup function, this shredder was intended as a bulky waste or white goods shredder. However, grate configuration causes heavy sheet metal objects such as steel barrels to be hammered against the grates, blinding the openings. Also, difficulty has been experienced in shredding densely packed objects such as baled rags and rolled carpets. Several explosions have occurred in the Gruendler which were attributed to small arms ammunition. These were relieved by the relief doors.

One modification to the Gruendler consisted of removing the ineffective ballistic roller deflector immediately below the infeed.

Air Classifier

The purpose of this device (No. 12 in Figure 1) was to separate the lighter paper and plastic fraction from a heavier metals- and glass-rich fraction.

This device, trade-named Vibrolutriator, was modified several times. A heavy "U"-shaped rubber belt was installed internally to streamline the contoured inner air flow of the chamber. In Figure 3, this extended from the forward (left) wall of the infeed chute to the back wall of the exit duct for the light fraction and air.

The basic problem with the Vibrolutriator was its inability to produce an aluminum- and glass-rich fraction with a sufficiently high concentration. The Vibrolutriator was purchased to meet a performance specification which was expressed in terms of its success in recovering specifically shaped aluminum cans with a specified maximum percentage of the infeed reporting as heavy fraction. The standard of performance was divided into two specifications, one for each of the potential feedstocks which would be fed to the equipment:

(1) Trommel Undersize as Feed at 30 tph

82% aluminum can recovery, with maximum 50% of infeed reporting as heavy fraction.

(2) Shredded MSW as Feed at 30 tph

80% aluminum can recovery, with minimum 25% of infeed reporting as heavy fraction.

Two feedstocks were specified to have the capability to air classify material if either the primary line or the secondary line was operating.

Under test plans developed by NCRR, the manufacturer (Triple/S Dynamics) conducted tests - with NCRR assistance - during June and August 1978. Some of the tests satisfied the criteria of aluminum can recovery with less than the maximum heavy fraction. The results showed that when the can recovery requirement was met, it was at the expense of the heavy fraction requirement. Aluminum can recovery was directly and almost linearly related to the heavy fraction. Capture of 82% of the aluminum cans in the feed required approximately 82% of the infeed to report as heavy fraction. It should be noted that the 18% (by weight) of the material which was removed as light fraction was paper, yard waste, and other materials. These adversely impacted screen performance downstream and had to be removed.

No further effort was made to improve the air classifier until mid-February 1980, when major changes were made. Figure 3 depicts the modifications to the classifier. The original configuration is shown in solid lines, and the modified sections are shown in dashed lines. The changes include: (1) the addition of a shelf the full width of the classifier, (2) removal of the protruding nose between inlet and exit, and (3) enlargement of the heavy fraction discharge. The shelf blocked the air ports from the fluidizing blower, which is no longer operated. These changes were made by NCRR, based upon the experience with several air classifiers tested at the Equipment Test and Evaluation Facility in Washington, D. C., and from observations of other air classifier operations at various sites. A portion of these data are reported in an NCRR Test Report [8]. Operation of this modified air classifier has shown it to be capable of lifting more and heavier materials. A bypass gate allows air to be routed directly to the fan, thereby providing variation in air flow in the separation chamber and drawing less air in the heavy fraction discharge at lower

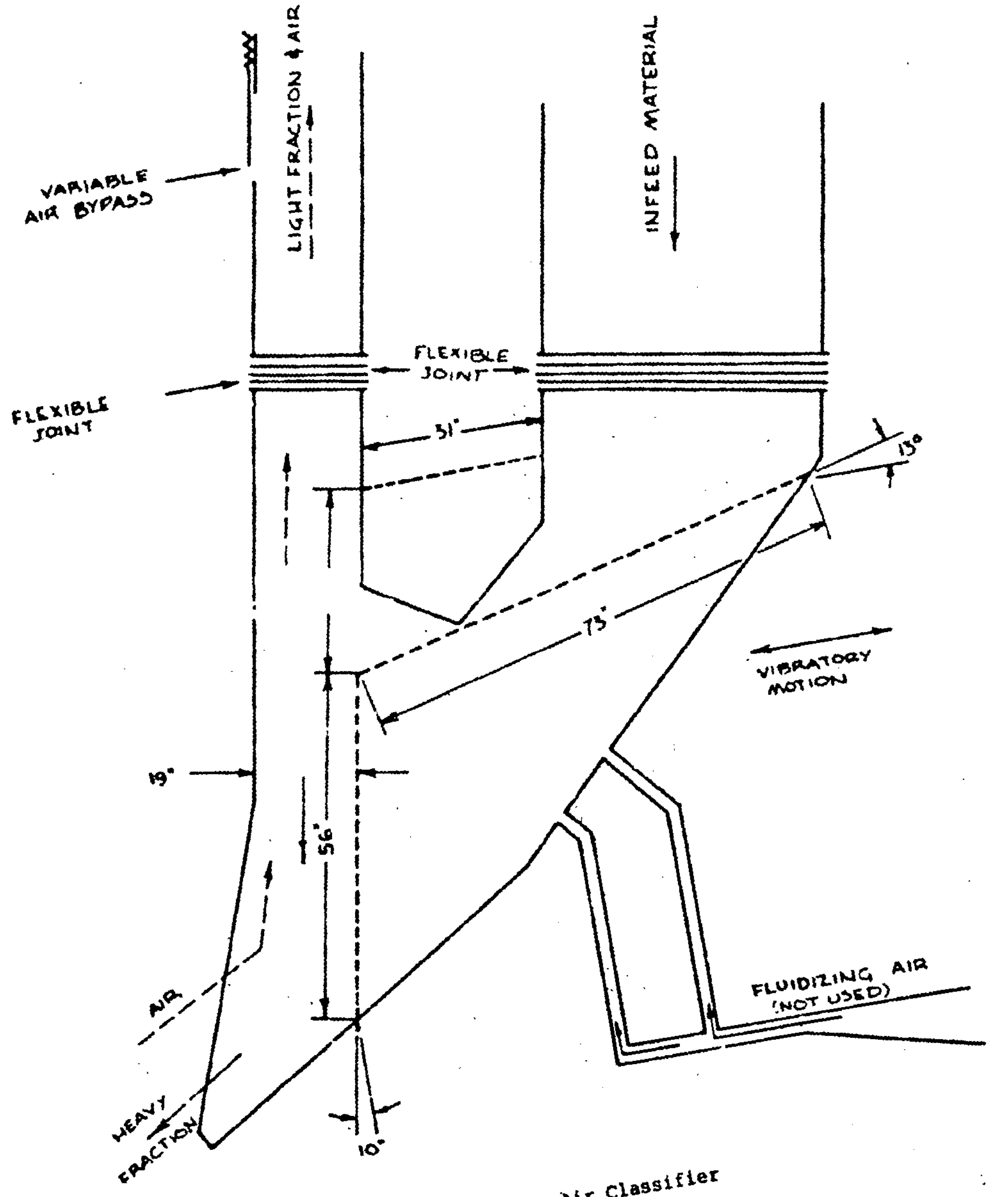


Figure 3. Air Classifier

air flow settings. Tests are planned to tune the classifier by varying this air bypass area.

Air Classifier

This equipment (No. 13 in Figure 1), with its attendant cyclone and conveying system, was never installed. The purpose for its inclusion in the design was to remove metal, glass, and other inert material from the shredded trommel oversize. Tests have shown that the shredded trommel oversize contains few recoverable materials. The exception is the ferrous metal, which is removed in the current configuration (i.e... magnet before the trifurcated chute). To air classify the stream to recover the small amount of aluminum was not considered cost effective. Also, no market for the RDF, which can be made by further size reduction of the light fraction from the second air classifier, has been developed. Therefore, the decision was made to defer the purchase and installation of this air classifier.

FERROUS RECOVERY SYSTEM

ferrous recovery system as initially designed and constructed consisted of two overhead rotating drum magnets removing magnetic metal from both shredded and trommel undersize materials. Further cleanup consisted of a Triple/S ferrous concentrator, which performed a three-way separation: (1) light organics, (2) heavy ferrous, and (3) light ferrous.

The system was then modified to include a hydraulically powered compactor in an attempt to increase the density in order to make the minimum railcar product weight of 60,000 lbs. A compactor designed for canstock scrap was purchased from Proler International; this increased the product density, but it was still insufficient.

Even with the initial modification to the ferrous system, the ferrous product was not acceptable to Proler International. After two years of adjusting the initial system, a decision was made to make a major revision. This revision is currently in operation. It produces a ferrous product which not only meets the specification for but is the cleanest ferrous scrap produced from MSW by a commercial-scale resource recovery facility.

Ferrous Metal Mass Balance

The ferrous recovery system as built constitutes the initial flow system, shown in Figure 4. The rectangles represent each unit process, and the figures along the flow path indicate the mass of ferrous metal based upon an MSW feed rate of 62.5 tph. The ferrous metal concentration in the MSW is 3.7%. This value is based upon the year-long sampling discussed earlier.

The primary product of this system, light ferrous sheet metal, was sold to Proler International for detinning. The product was unsatisfactory for two reasons. First, the contamination level averaged 15%; the specification called for 4% contamination. Also, even with the compactor mentioned earlier, the bulk density of the light ferrous shipped averaged about 16 lbs per cubic foot, less than the 21.5 lbs per cubic foot required.

In addition to these two problems, there is a 39% loss of ferrous metal in the system, as shown in the mass balance, Figure 4. The largest loss of ferrous metal occurred at the magnetic drum separators. The efficiency of the two magnetic drums differs markedly. The trommeled undersize magnet (No. 8 in Figure 4) has an efficiency of 93%, while the shredded material magnet (No. 7 in Figure 4) is only 27% efficient. This results in a loss of over 6 tons of recovered magnetics per day. Most of the loss (3.6 tons) is heavy ferrous, for which there is no market. However, the loss of 2.4 tons of potential light ferrous product is significant. The reasons for the inefficiency are twofold: (1) the field strength of the unit is too low for the application, and (2) the bulk density of the shredded trommel oversize is lower than anticipated, causing a higher conveyor burden. The unit should be replaced with a stronger one.

These problems led to a complete revision of the system. The modifications consisted, in brief, of eliminating the ferrous concentrator and the compactor and adding an air knife, a light ferrous metal shredder, and a secondary magnetic separator. Figure 5 shows the revised system flow and mass balance. This system is currently in operation. A detailed description of the modifications and testing was published by the ASME [9].

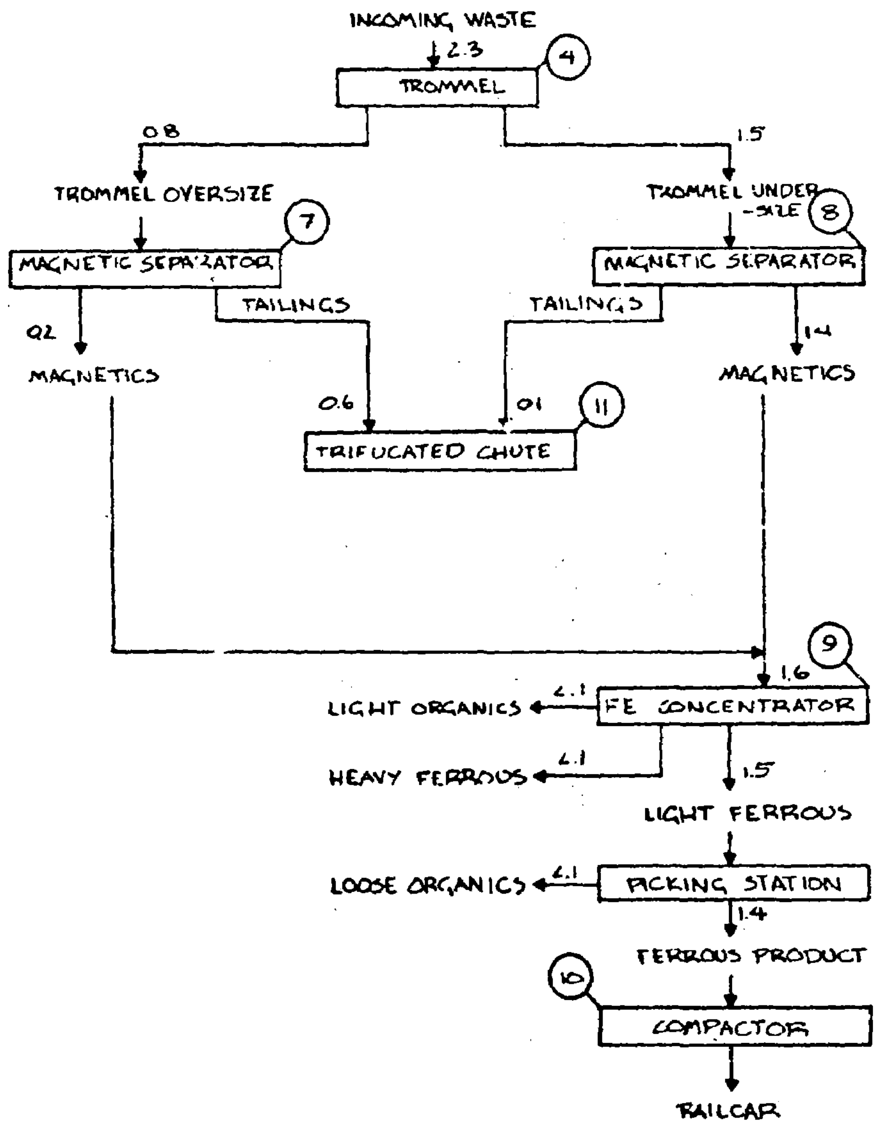


Figure 4. Ferrous Recovery Flow and Mass Balance (Original Configuration)

Note that there is a reduction in the amount of ferrous metal which reports as product with the revised system. This reduction of 50% can be seen by comparing Figures 4 and 5. The change is caused by the air knife, and is the result of two factors: (1) less heavy ferrous misreports to the light ferrous product, and (2) more cans report to the heavy ferrous product due to entrapped contaminants or to their aerodynamic shape. However, the revenue is higher, due to the higher value of the product.

Equipment Modifications

The ferrous recovery system was the subject of numerous small modifications and a major redesign. In the following paragraphs, the individual equipment items, in both initial and revised configurations, are discussed.

Magnetic Drum Separator

The purpose of this drum-type electromagnetic separator (No. 7 in Figure 4) is to remove the magnetic material from the shredded material - both trommel oversize and Gruendler product. The unit is mounted above the head pulley of the shredded material conveyor and turns against the material flow. The drum has eight cleats to move the magnetic material in the direction of drum rotation. This configuration of the cleats and the location of the drum, relative to the conveyor head pulley, has been changed several times.

The burden depth on the conveyor feeding this magnet varies as a function of which processing line, primary or secondary, is in operation. Figure 6 shows the relative positions of components. If the secondary (Gruendler) shredder line is operating, the burden depth tends to be lower, thereby calling for a magnet location with less gap. Conversely, when the primary line is in operation, the feed conveyor contains shredded trommel oversize material with a very low bulk density and higher burden. Further, there are variations in the burden - peaks and valleys - when either shredder is operating.

Observations showed magnetic material would often roll on the drum traveling over the lower cleats. This material would not be carried out of the magnetic field for further recovery. This rolling phenomenon accelerated the formation of clusters of wire and fabric, "wire balls," which caused blockages. These blockages could occur at the magnet; or if the "wire ball" was discharged from the magnet with the other magnetic material, the blockage occurred in the downstream equipment.

Optimum height for this magnet was different, depending on which processing line was in operation. The magnet and its frame was then hinged on one end and made adjustable up and down by two hydraulic actuators. Limits of the actuator travel allowed for a gap range of 14.8 to 21.9 inches. This corresponds to an angle, Ø, of 26° to 30°, as shown in Figure 6. The difficulties with jams or wire balls seem to have been eliminated. To further reduce the possibility of these tangled clusters of wire and textiles, a timer was installed in the magnet power circuit which interrupts the current, shutting down the field for a period of 3 seconds at intervals of 2-1/2 minutes.

No test data exist for magnet efficiency under the final condition of variable gap. Tests were conducted under a configuration which differed considerably from the as-designed conditions [10]. The parameters for the as-designed and as-tested conditions are shown in Table 5.

As-designed efficiency was guaranteed to be 95%. As-tested recovery efficiency was approximately 30%. Since that test, the variable gap hydraulic system was installed. The smaller gap has been estimated to result in an efficiency of 50%.

Magnetic Drum Separator

This unit (No. 8 in Figure 4) is similar to the No. 7, and was to remove magnetic material from trommel undersize material before air classification.

Because the trommel acts to concentrate the ferrous metal in the undersize, this magnet is exposed to 59% of the magnetics in the MSW. It recovers 90% of the magnetics in its feed stream. Design recovery rate was 95%, but called for a gap of 11.5 inches; it was not possible to install it closer than 14.9 inches. This resulted in a 23% reduction in gauss strength at the surface of the conveyor belt feeding the magnet. No difficulties have been noted with this magnet. A summary of its

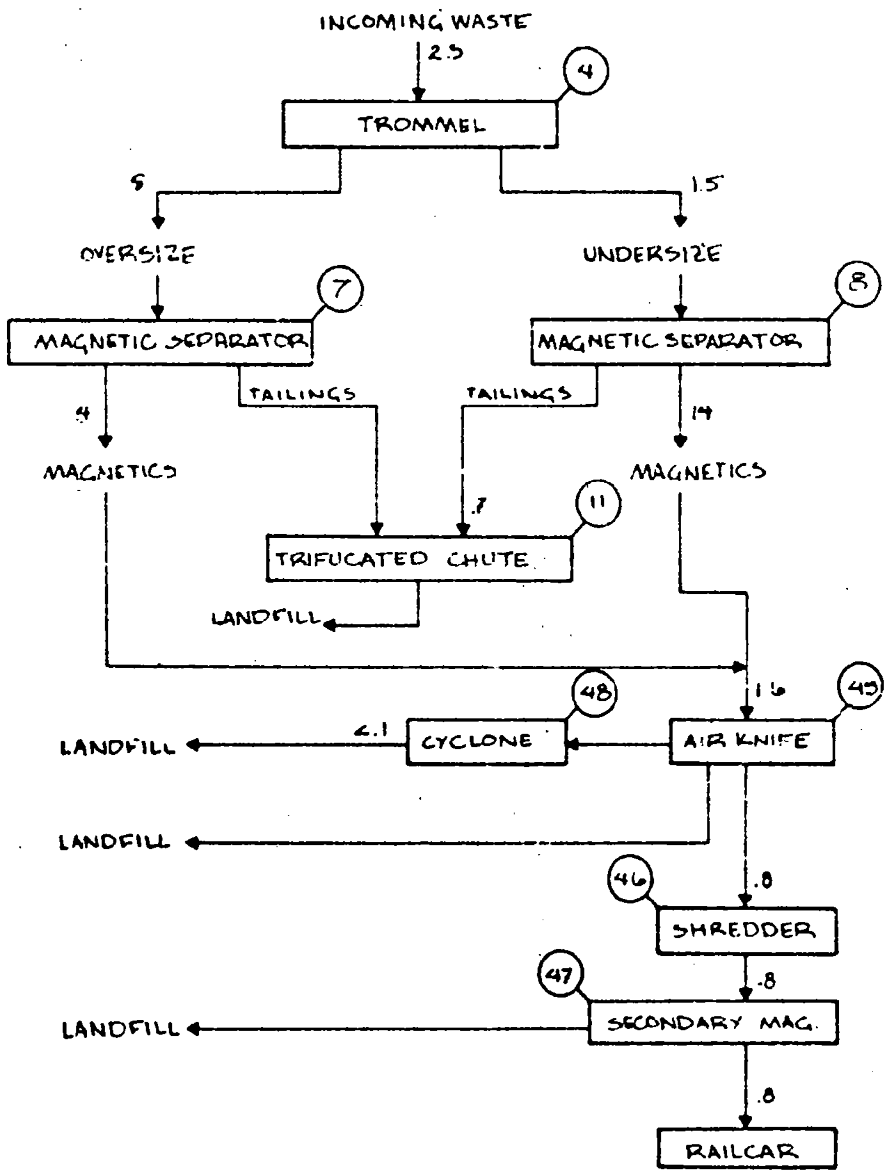


Figure 5. Ferrous Recovery Flow and Mass Balance (Upgraded Configuration)

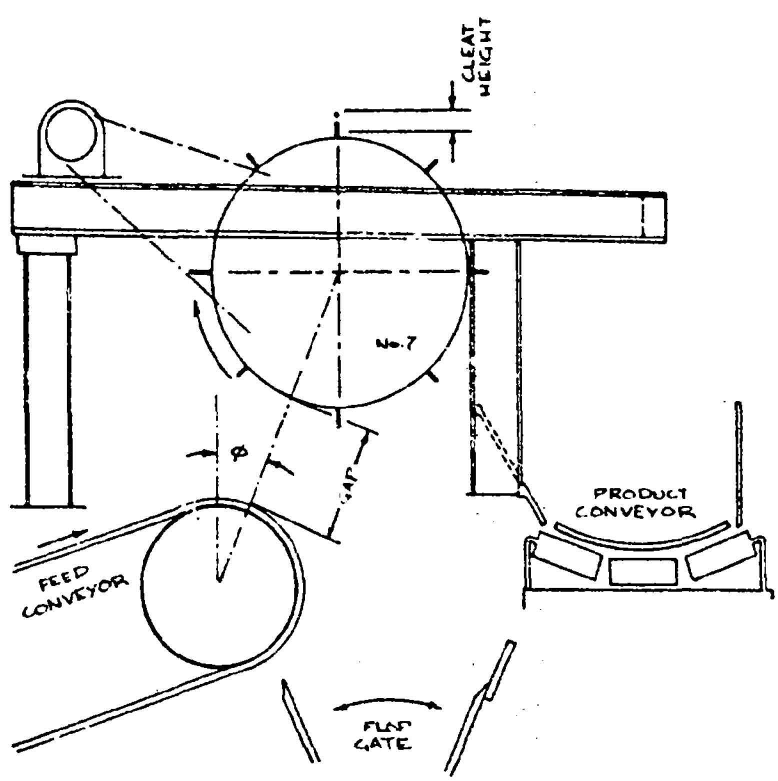


Figure 6. Primary Magnet System Locations

TABLE 5. MAGNETIC DRUM SEPARATOR (NO. 7)

	As-Designed	As-Tested
Feed mass flow rate	75 tph (max)*	23.5 tph
Nominal particle size of feed	99% <5 inches	94% <5 inches
Bulk density of feed	3.5 lb/ft^3	2.5 lb ft^3
Magnetics content of feed (wet wt)	7 to 10%	6.6%
Inclination (above horizontal of feed conveyor)	17.9°	18.5°
Feed conveyor belt speed	300 to 350 fpm	450 fpm
Air gap (between belt and drum surfaces)	14.5 inches	21.4 inches
Angle (between a line joining shafts of the head pulley and MDS, and the vertical)	30°	22.4°
Offset (between feed conveyor and MDS centerlines)	0 inches	2 inches
Maximum magnetic strength (at feed conveyor belt surface, est.)	460 gauss at 21.1 amps	140 gauss at 18.5 amps
Percent recovery of magnetics (wet wt)	95%	~28%
Percent loose contaminants in product (wet wt)	5%	0.3%

*Designed for secondary line operation.

as-designed and as-tested parameters is shown in Table 6. The results of the tests have been published [11].

Ferrous Metals Concentrator

This device (No. 9 in Figure 4) was designed to separate material removed by magnetic separators Nos. 7 and 8 into three discrete streams: light ferrous metal, heavy ferrous metal, and a light organic fraction.

The separation is accomplished by concurrently exposing the feedstock to vibration and turbulent air flow. Tests made on this device showed varying degrees of success. For instance, of the light ferrous metal that entered the concentrator, less than 1% misreported to the heavy ferrous fraction, and less than 1% was carried away with the light organics. Further, the machine removed 54% of the loose contaminants. However, of the heavy ferrous entering the concentrator, only 23% reported correctly. The majority of the heavy ferrous metal, 77%, reported as light ferrous product.

The large amount of loose contaminant and heavy ferrous which reported to the light ferrous product stream represented contamination above the level allowed by the buyer. A partial solution was the addition of a picking station to remove large, highly visible loose contaminants. However, this was only an interim solution, as the resulting product still failed to meet the specification of 4% for organic contamination. Also, the large amount of heavy ferrous reporting to the light ferrous product was only partially solved by the picker, who removed about 50% of misreporting heavy ferrous.

The internal dimensions and shape of the concentrator were too small to pass some objects re[illegible]ed by the primary magnets. These usually consisted of wire clusters and long, thin objects such as exhaust pipes and small-diameter iron piping. Consequently, numerous blockages and jams occurred. These, coupled with the insufficient product cleanup, led to the elimination of the concentrator and the manual picker during the major system revision.

In the revised configuration, the device is bypassed. The functions which the ferrous concentrator performed are now accomplished by the air knife (No. 45 in Figure 5)

TABLE 6. MAGNETIC DRUM SEPARATOR (NO. 8)

	As-Designed	As-Tested
Feed mass flow rate	40 tph (max)	40.8 tph
Nominal particle size of feed	99% <5 inches	98% <4 inches
Bulk density of feed	10 lb/ft^3	16.5 lb/ft^3
Magnetics content of feed (wet wt)	7 to 10%	4.5%
Inclination (above horizontal of feed conveyor)	17.9°	17.6°
Feed conveyor belt speed	300 to 350 fpm	360 fpm
Air gap (between belt and drum surfaces)	11.5 inches	14.9 inches
Angle (between a line joining shafts of the head pulley and MDS, and the vertical)	27°	26.5°
Offset (between feed conveyor and MDS centerlines)	0 inches	5-7/8 inches
Maximum magnetic strength (at feed conveyor belt surface, est.)	575 gauss at 14 amps	440 gauss at 15.3 amps
MDS rotational speed	28 rpm	28.3 rpm
Percent recovery of magnetics (wet wt)	95%	90.3%
Percent loose contaminants in product (wet wt)	3 to 5%	2.0%

Air Knife

The purpose of this device (No. 45 in Figure 5) is to perform two separations of the magnetic material: (1) separation of light ferrous from heavy ferrous, and (2) removal of light organic material.

The air knife consists of a separation chamber with one material and two air inlets. The air inlets are thin, near-horizontal nozzles. The bottom of the separation chamber forms two chutes, one for light ferrous metal and one for heavy ferrous. The air discharge is at the top corner, away from the air nozz. The configuration is shown in Figure In addition to the separation chamber, the system consists of a negative pressure cyclone and a blower in a circuit which recycles most of the air. The blower drives the air knife nozzles.

Some difficulty has been experienced with the air knife. Initially, air velocities were insufficient to prevent excessive light ferrous metal from reporting as heavy ferrous. The drive motor sheave was changed to a larger diameter to increase the air velocity. However, this resulted in the separation chamber operating under a positive pressure, giving poor separation of loose organics. The excess pressure was partially relieved by slightly opening the cleanout door on the air knife fan (see Figure 7 for cleanout door location).

The knife continued to yield a large amount of light ferrous with the heavy ferrous fraction. It was thought that this was caused by a rolling air flow inside the air knife box that carried light ferrous around past the light ferrous chute. In an attempt to break up this circulation, various baffles were installed. The knife was built with two movable baffles, but neither was satisfactory, and both were subsequently either modified or removed Figure 7 shows the location and size of air flow baffles installed on site to improve the air knife performance. Success of these modifications was mixed.

As Figure 7 shows, the light ferrous shredder (No. 46 in Figure 5) is immediately below the light ferrous chute. Rotor action occasionally causes material to be thrown back out the shredder infeed. This material often reports to the heavy ferrous chute. However, not all light ferrous found in the heavy ferrous fraction followed this path. Tests showed that 30 to 40% of the light ferrous was lost to the heavy ferrous chute, an unacceptable value. The manufacturer has been contacted, and efforts to correct the problem are being made.

Light Ferrous Shredder

This unit (No. 46 in Figure 5) was originally manufactured by the Gruendler Crusher and Pulverizer Company as an impactor, and was initially installed in the aluminum recovery system. It was found to be unnecessary and was removed from the aluminum system.

The intent of the shredding of the light ferrous product was not specifically size reduction, but to rip open or "butterfly" the can. Also, to impact the can sufficiently to dislodge any attached or entrapped contamination. This would allow cleanup by subsequent separation by the secondary magnet separator (No. 47 in Figure 5).

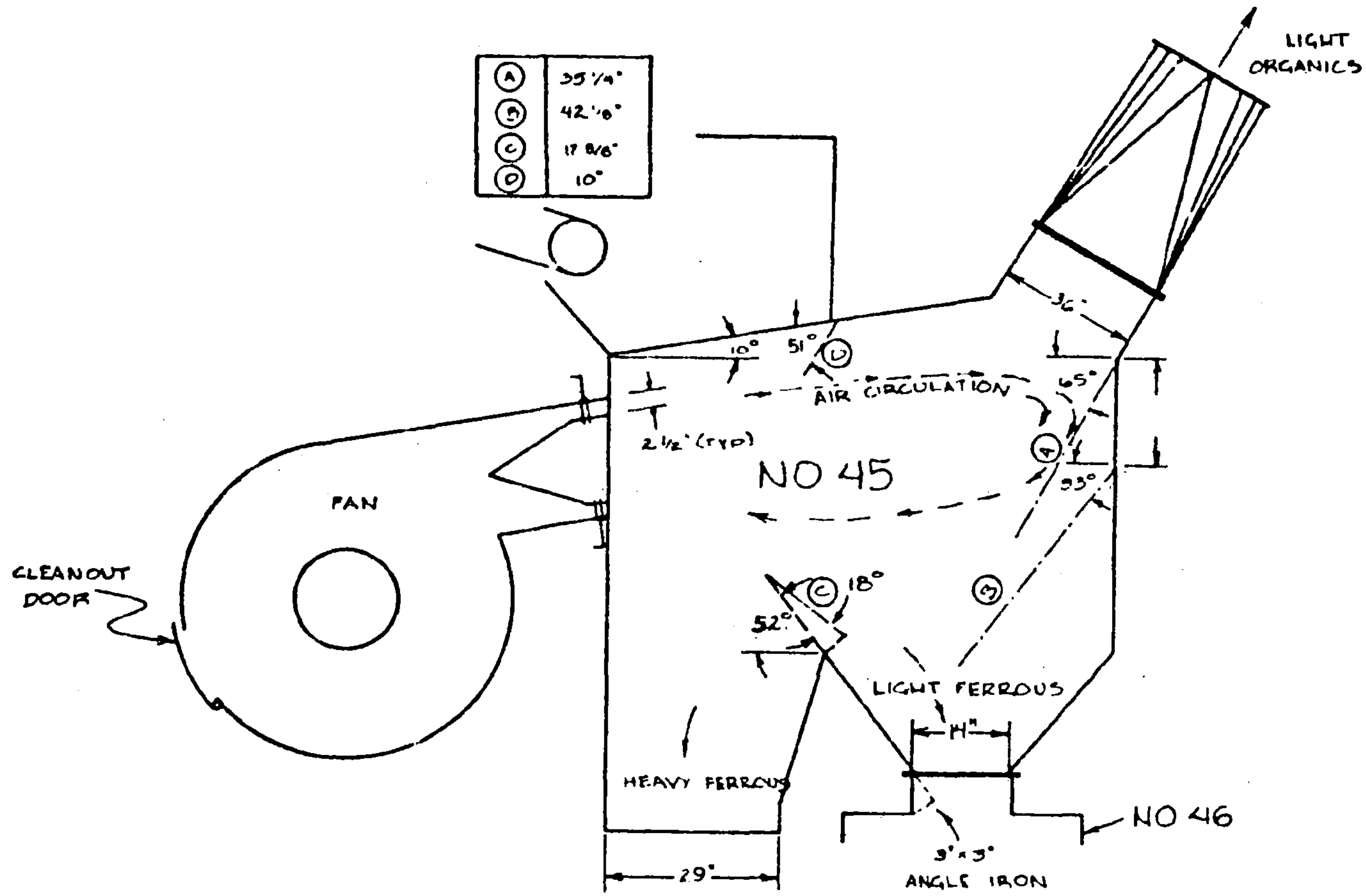
After consultations with Gruendler, the impactor was modified to accommodate four rows of four bull-headed hammers each, and an eight-compartment (approximately 8 by 4-inch openings) grate for can shredding. The unit was re-sheaved to obtain a rotor speed of 920 rpm. This produced a hammer tip speed of approximately 6,000 ft/minute.

As modified, the shredder was rated at 3 tph, with surges to 5 tph allowed. The shredder experienced jams caused by objects too large to be shredded.

The primary problem is that large objects are coming through the primary shredder. One oversized item removed from the ferrous shredder was an auto muffler, 24 by 12 by 6 inches. The problem is compounded when a large object reports to the light ferrous chute in the air knife. In addition, the ferrous shredder is slightly underpowered, restricting its ability to shred large items.

Secondary Magnet

This belt-type magnet separator (No. 47 in Figure 5) removes the magnetic metal in the light ferrous product, leaving behind



'igure 7. .Air Knife Internal Configuration the organic contamination after shredding. The unit was purchased under a warranty to recover 95% of the feed material, sized between 1 and 4 inches, with the unit suspended 8 inches above a stainless steel vibrating pan conveyor. Tests on the magnet showed it recovered ferrous metal with an efficiency of 98.5%, with a contamination of 4%.

The purchase order for the magnet called for a 30-inch-wide rubber belt with stainless steel cladding 24 inches wide. This cladding prevents pieces of wire from embedding into the rubber, wearing holes in the unclad portion and allowing metal to work its way between the cladding and the rubber belt.

Storage Bin

A number of problems in obtaining and scheduling railcars developed soon after the startup of the ferrous recovery system. The most severe was the delay in obtaining cars from the railroad on any schedule after a request was made. The ferrous system had to be shut down during these periods, resulting in loss of product. In addition, when production was slow, the resulting low filling rate would incur demurrage charges for the railcars after one day on the site.

These problems were ameliorated by the construction of a storage bin, made from an old railcar with extended sides. One end of the storage bin is open to allow entrance for a front-end loader to remove ferrous product and load it into a railcar. The dimensions of the storage bin are 50 feet long, 9 feet wide, and 8 feet high.

ALUMINUM RECOVERY SYSTEM

The aluminum recovery system processes a glass and aluminum concentrate - the air classifier heavy fraction. This contains contaminant materials which need to be removed. The initial processing step is a large, double-deck screen which functions as part of both the aluminum recovery system and the glass recovery system.

The function of this screen is to split the air classifier heavy fraction into two major streams: (1) a glass-rich fraction, and (2) an aluminum-rich fraction. The aluminum metal targeted for recovery consists mainly of canstock and occurs in the middling (4 by 2-inch) fraction. The 2-inch material is routed to the glass recovery system. The oversize fraction (larger than 4 inches) is rejected to landfill.

The non-canstock aluminum contained in the incoming MSW consists of mixed alloys. These come from various castings (auto parts, extrusions), lawn furniture, and stampings (cookware), and comprise almost 0.3% of the MSW. Most of these items are larger than a nominal 4-inch size, therefore they report to the trommel oversize for shredding. The non-canstock aluminum would be recovered for processing if air classifier No. 13 had been installed. However, as discussed in the Recovery Feed Preparation section, this was not considered cost effective.

Further size separation and aluminum recovery by the eddy current separator (Al-Mag) follows. Cleanup prior to pneumatic transport into a highway trailer completes the aluminum recovery process.

Aluminum Mass Balance

The process flow and the mass balance for the aluminum recovery system are shown in Figure 8. This diagram depicts the flow as it is currently operated. The equipment items which have been removed during the shakedown are also shown, represented by dashed lines.

The mass balance for aluminum is represented by the figures adjacent to each flow path. The mass is expressed in pounds per hour of aluminum canstock and represent the operation of the plant at the design throughput, which specified an input of MSW at 62.5 tph. This was the basis of formal testing. As mentioned elsewhere in this paper, the plant regularly is operated at above 100 tph.

The incoming MSW contains 0.3% aluminum canstock, as discussed in the Recovery Feed Preparation section. At the design throughput of 62.5 tph, this represents 375 pounds of aluminum canstock. At the design throughput, the trommel is 93% efficient in its separation of aluminum. This results in 350 tph of aluminum canstock being present in the air classifier feed.

When the trommel is operated at 100 tph or more, its efficiency of aluminum

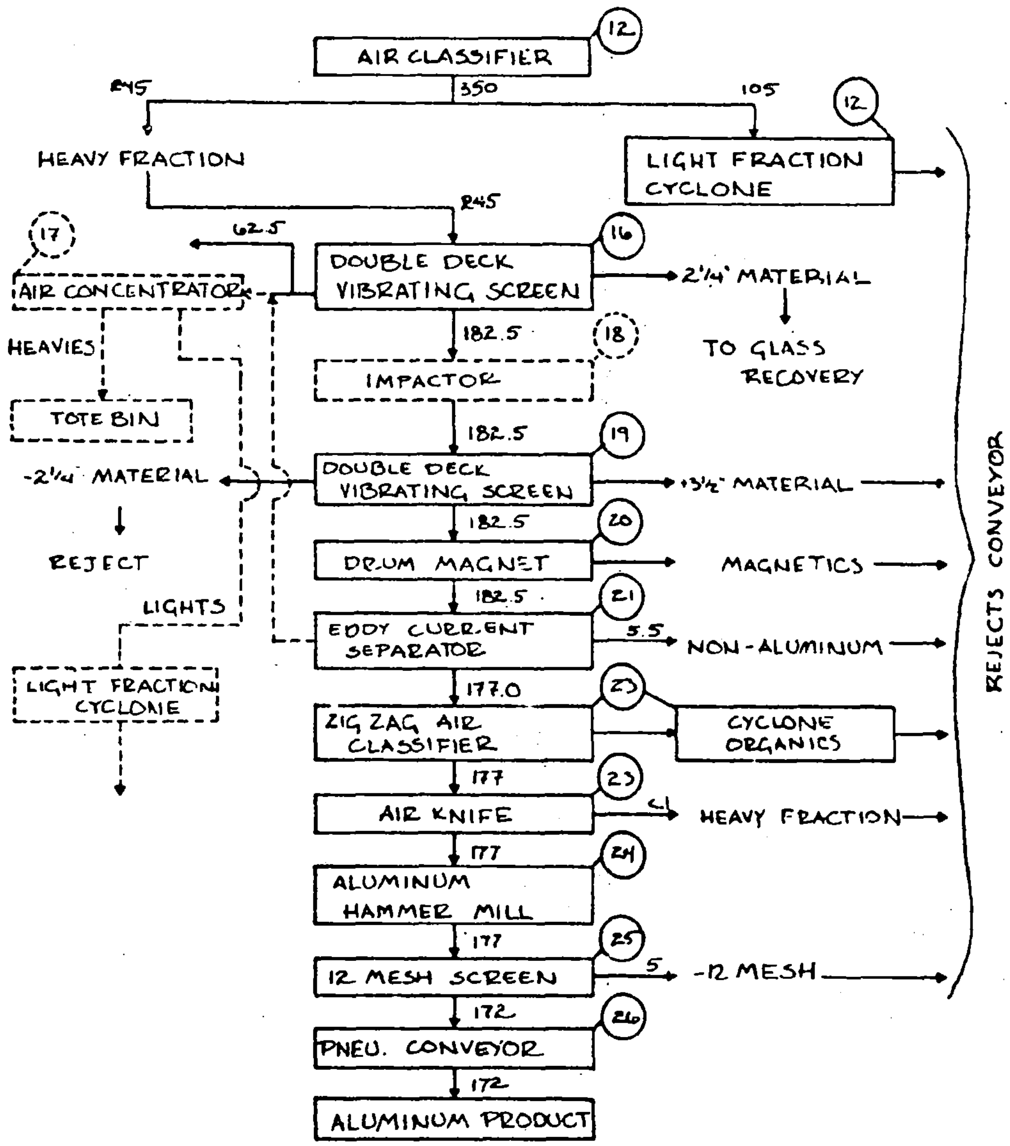


Figure 8. Aluminum Recovery Flow and Mass Balance

canstock separation drops to about 73%. This results in 50 to 70 tph of air classifier feed. In order to prevent the air classifier from plugging, the necessary air flow and velocity are so high that most of the aluminum canstock reports to the light fraction. An alternative is to divert about half of the air classifier feed material to landfill, with the resulting loss of aluminum.

At the design throughput, the aluminum recovery system currently recovers 49% of the aluminum canstock it receives. The air classifier is the source of the largest loss, having a recovery efficiency of only 70%. The second major loss point is the vibrating screen (No. 16 in Figure 8). Here the problem has been to develop an effective top deck - one which removes oversize flexible materials such as paper diapers - which does not cause some of the aluminum to report to the oversize. In the flow shown in Figure 8, some 25% of the aluminum feed to the screen misreports to the oversize and is rejected. From this point on, the process is quite efficient, with a total of only 10% of the remaining aluminum canstock being lost in six separation processes.

The overall recovery rate of aluminum canstock is 172 pounds per hour, resulting in an overall efficiency of 46% when the facility is operated at the design throughput. Shipments totaling 29 tons have been purchased by Reynolds Metals at their primary grade.

These flow data are the result of several individual tests. The details are given in the Test Report Series [2].

Equipment Modifications

In the following paragraphs, each of the equipment items in the process flow (Figure 8) is discussed. The initial configuration and subsequent modifications are covered.

Only the processing equipment is discussed. However, many problems were experienced with the materials handling operations in this system. Subsequently, modifications were made. Basically, the conveyors, elevators, and chutes were undersized. This stemmed from three causes: (1) over-estimation of the bulk density during the design, (2) inadequate allowance for surges (a 100% surge is not unusual), and (3) operating mode of the entire facility.

Overload of equipment causes jams and blockages in the short run and failures in the long run. These have both affected the reliability and availability of the aluminum recovery system. A variety of changes have been made to solve these problems, including enlarged chutes without sharp bends, increased speed of conveyors, full skirting on conveyors, larger buckets on bucket elevators, and finally, replacement of conveyors by larger units.

4 by 2-Inch Vibrating Screen

The purpose of this device (No. 16 in Figure 8) was to produce three fractions from the air classifier heavy material: (1) an oversize stream, (2) a 2 by 4-inch aluminum-rich middling stream, and (3) a minus-2-inch glass-rich undersize stream.

The screen was initially configured with the top deck made of 1/4-inch round rods with rectangular openings 4 by 8 inches. The lower deck was of heavy-duty 5/8-inch-diameter woven wire with rectangular openings, 2 by 8 inches. On both decks, the 8-inch dimension was longitudinal to the screen. The top deck of this screen was to remove large non-recoverable materials. The bottom deck was to separate the glass concentrate, generally smaller than 2 inches, from the aluminum concentrate, generally larger than 2 inches. The feed material to the screen contained about 0.4% aluminum as tested. Also, 1.6% of the material was larger than 4 inches, and 89% was smaller than 2 inches on a dry basis.

Problems were immediately encountered with both decks. The openings were too large on the top deck, and little screening of oversize material occurred. The rectangular 2 by 8-inch openings on the bottom deck allowed aluminum cans to wedge into the openings. Material immediately began to build up on the wedged cans, blinding the screen. In addition to can wedging, the large opening allowed slender objects such as sticks to pass through into the glass recovery circuit. Cleaning of the material blinding the bottom deck was difficult. Beginning in March 1978, a series of different decks were tried. In

July 1979, a punch-plate top deck with 5-inch-diameter holes on 5-3/8-inch staggered centers was installed. Aluminum loss was reduced, but at the cost of an increase in large, flexible contaminants. Little effect was seen in the minus-2-inch material transferred to the glass recovery plant.

In an attempt to reject large, flexible materials and those in plate form, 6-inch-high grizzlies of 1/4-inch steel plate were installed on the top deck. This was generally ineffective, although some material traveled down the grizzlies to be rejected.

Several modifications were made to the top deck, including adding a static partial flat plate deck with vibrating grizzly bars above the top deck. In conjunction with this top deck modification, a new distributor was fashioned which provided better distribution of the material on both top and bottom decks.

In early October 1980, both decks of this screen were replaced. The top deck was replaced by a punched plate with 4-1/2-inch-diameter openings on 4-7/8-inch staggered centers. The bottom deck was replaced by a punched plate with 2-1/4-inch-diameter openings on 2-5/8-inch staggered centers. It has been determined that this screen does not have sufficient capacity for this application, particularly the bottom deck.

Air Concentrator

The purpose of this zig-zag type air classifier (No. 17 in Figure 8) was to remove any nonferrous metals from the oversize material from screen No. 16 and the eddy current reject stream. However, composition analysis showed almost no heavy, oversize metal in that fraction. In addition, the device was subject to plugging. The unit was converted into a chute.

Impactor

This machine (No. 18 in Figure 8) was designed to crush any friable material in the 4 by 2-inch screen (No. 16) fraction. This was to be removed by screening for further processing in the glass recovery system. This also reduced the amount of material in the 4 by 2-inch aluminum-rich stream, which aided the recovery of aluminum by the eddy current separator.

Analysis showed the impactor was crushing large friable objects satisfactorily; however, the unit would jam when surges occurred. Further, little glass was found in the 4 by 2-inch stream. Therefore, the process was streamlined by removing the impactor and discarding the glass that was contained in the undersize material that was produced by screen No. 19.

Double-Deck Vibrating Screen

The original purpose of this screen (No. 19 in Figure 8) was to remove friable material crushed by the impactor and any residual minus-2-inch particles in the aluminum-rich stream. However, it is currently a supplement to screen No. 16, which is too small.

The screen, as purchased, was fitted with single-screen wire cloth. Rectangular openings were 2 inches wide by 6 inches long. Aluminum cans flattened on one end tended to wedge into the openings, obstructing material flow and blinding the screen. A 2-inch-square opening of woven wire was tried, but soon blinded with paper and textiles. Next, a 2-inch-diameter hole punched plate was installed, but this also blinded. In addition, the driven speed of the eccentric shaft was increased from 600 to 900 rpm. Amplitude remained at 0.32 inch. No noticeable improvement in screening was observed.

Experience indicated that a grizzly or bar deck was needed to prevent blinding. The punched plate deck was removed and replaced with grizzly bars 2-1/2 inches high, 1/8 inch thick, set on a 1-3/4-inch spacing.

Based upon the insights gained in several previous changes, the screen was torn down and rebuilt. The rebuilt screen utilizes two decks. The splash plate was increased in length from 12 to 24 inches, and two chevron-shaped flow distributors were welded in place. Also, the screen was raised.

The top deck is made of grizzly bars 24 inches long and 2 inches high with 2-1/2-inch spacing. The purpose of the grizzlies is to catch flexible material, such as rags. If the bars are longer than

24 inches, the action of the screen causes the rags to drop off the bars onto the second deck. The lower end of the grizzlies extends over a flat plate which completes the top deck. The second deck consists of a punched plate with 2-1/4-inch-diameter openings. This configuration, shown in Figure 9, is currently in use. These improvements work well, as the grizzlies remove a significant amount of flexible material and the screen does not blind, although periodic cleaning is still required. The 2-1/4-inch punched plate is 93% efficient in removing the undersize material from the 2 by 4-inch fraction.

Drum Magnet

This secondary drum magnet unit (No. 20 in Figure 8) removes residual ferrous metal (not removed by magnets Nos. 7 and 8) from the 2 by 4-inch fraction prior to the eddy current separator. Magnetic items become trapped in the eddy current separators for a time and cause blockages.

The principal difficulty of this unit has been its inability to pass long, thin, nonferrous objects, such as sticks. Items as short as 4 inches have caused jams. Two changes were effected to alleviate the

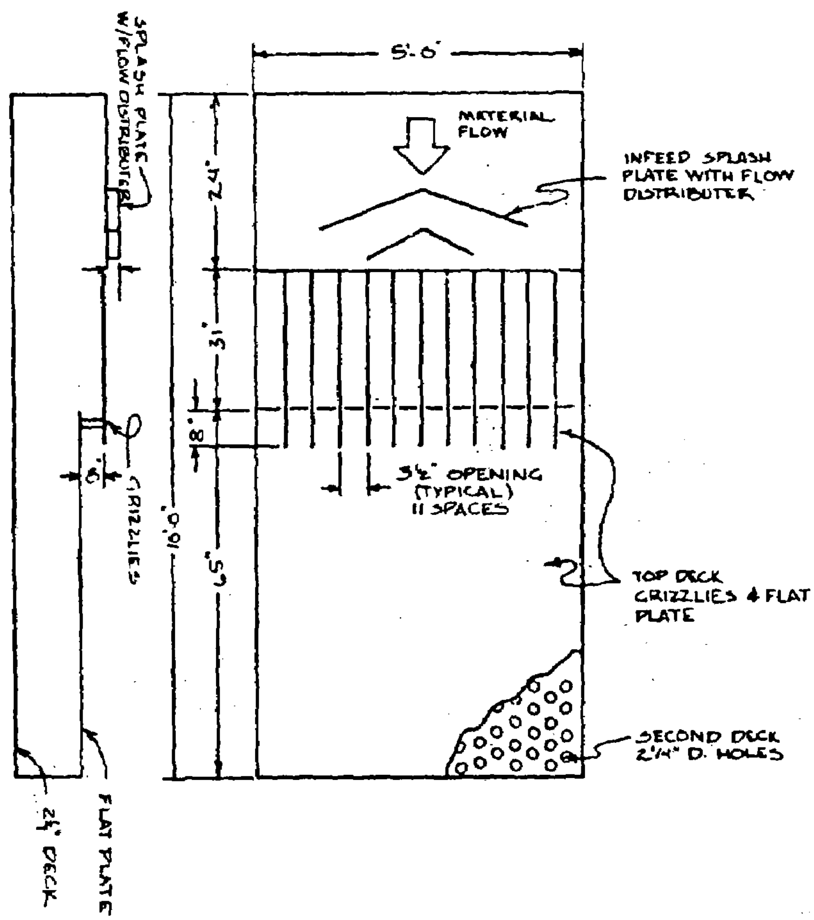


Figure 9. Equipment No. 19 Double-Deck Vibrating Screen plan and Side View

problem. The infeed side of the housing was enlarged. Also, the drum's original 3/4-inch-wide by 1/4-inch-high knockoff bar was augmented by adding two bars 1/8-inch thick by 1-inch high. This prevents ferrous metal from sliding on the smooth drum and not discharging.

Eddy Current Separator

The purpose of the eddy current separator, or Al-Mag (No. 21 in Figure 8), is to remove aluminum from the 4 by 2-inch fraction, which appears in this feed material at a concentration of 5%.

Problems with the Al-Mag centered on the water coolant system. Each of the eight banks of electromagnets contains four iron-core copper-wire-wound magnets that have copper tubing carrying coolant water wound in the core. Once-through city water is used. Overheating was experienced. The inlet water pressure was measured and was at the lower limit allowed by the separator's manufacturer. Pumps were installed to boost the water pressure to 60 psi. This was not enough to prevent the magnets from heating up from low coolant flow. Magnet temperature causes an increase in the coolant water temperature. The coolant water routing is a series arrangement such that the last bank of magnets receives water heated from passage through the other magnets. The heat increase was sufficient to cause the calcium carbonates to precipitate out of the water and adhere to the walls of the copper coolant tubes. This caused a restriction which, in turn, caused the coolant flow to decrease. The reduction in coolant flow caused even more heat to be transferred to the water, which accelerated the mineral deposition.

The water coolant lines outside the Al-Mag were modified to introduce a flushing liquid and recirculate it until a clean coil condition was obtained. The liquid selected is made by A. O. Smith, brand-named "Unlime." It is circulated in all coils as the liquid flowraters are monitored to determine liquid flow rate increase as the coils are cleared of the mineral scale buildup.

Table 7 shows the recovery efficiency of the Al-Mag at various belt speeds for a constant volume of feed material. Prepared seed cans were used. Deformed cans had one end crushed. Note that the efficiency is dependent upon can shape. The efficiency was approximately 8% lower for native (non-seed) aluminum of similar shapes. Approximately 11% loose organic contamination is contained in the Al-Mag product.

TABLE 7. AL-MAG EFFICIENCY

(In Percent)

Belt Speed (fpm)	Can Type: Flattened	Deformed	Whole	Total
300	97.7	98.4	100	98.4
400	92.9	98.4	100	98.0
500	90.7	95.0	86.6	94.5

The eddy current separator has shown it is capable of satisfactory separating efficiencies. However, it requires more attention than other materials recovery equipment.

Air Classifier/Air Knife

The purpose of this two-stage device (No. 23 in Figure 8) is to remove contaminants from the aluminum product of the Al-Mag. The contaminants in this 2 by 4-inch fraction are in two forms: (1) light materials (paper and plastic film), and (2) heavy items (such as grapefruit and nonferrous metal castings). These comprise 14% of this material, sufficient to lower the price received for the aluminum. Tests indicate that 90 to 100% of the light contaminants are removed and virtually all of the heavy contaminants.

This aluminum cleanup system consists of a zig-zag air classifier, its attendant cyclone and airlock, and an air knife with blower, as shown in Figure 10. Taken separately, no difficulties have been encountered with the zig-zag air classifier. The cyclone that de-entrains the organics from the zig-zag has been modified. This was built to operate under negative pressure with the butterfly damper and fan on the downstream side. Light, filmy organics occasionally passed through the cyclone and snagged on the butterfly damper gate. This was corrected by removing the gate from inside the butterfly damper, and making a

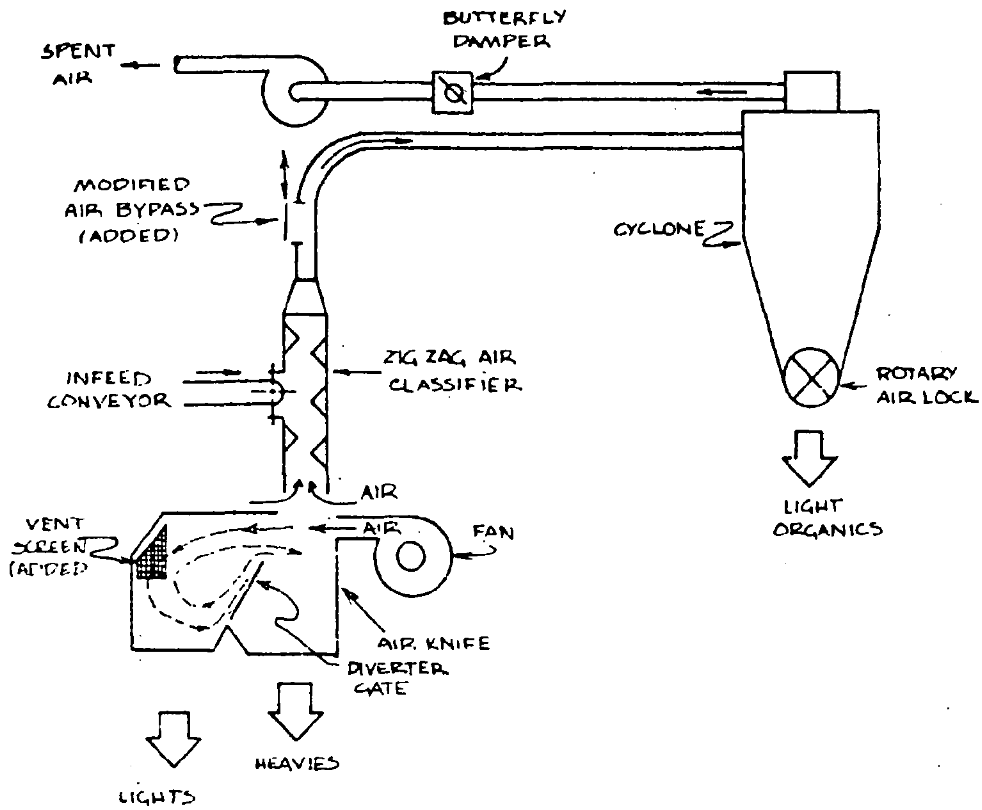


Figure 10. Aluminum Cleanup System

bleed gate and port on the air pipe above the zig-zag air classifier to modulate the air flow. The air classifier is fitted with a viewing window, allowing air tuning by observing the separation.

The system was delivered with a 7-1/2 hp motor driving the cyclone blower. It was retrofitted with a 10 hp motor to obtain sufficient air flow. Testing on the zig-zag showed 97.2% of the aluminum cans correctly dropped into the air knife, while 91% of the organic light material was removed by the classifier and blown to the cyclone for disposal.

The air knife separates light and heavy material reporting as heavy from the air classifier immediately above its infeed. During shakedown, it was determined that the 8-1/2 hp side channel compressor did not produce enough air to consistently blow aluminum cans across the knife to the lights side. It was replaced by a 10 hp blower. However, light aluminum continued to report to the heavy chute. Viewing window observations in the air knife showed that light aluminum was being initially deflected to the light material side of the air knife, but then rebounding back into the heavy material side. This was greatly reduced by installing two screened openings to allow the air to exhaust rather than deflect back into the air knife box.

Aluminum Hammermill

The purpose of this hammermill (No. 24 in Figure 8) is to reduce the aluminum to less than 1-inch particle size. This raises the bulk density to 15 pounds per cubic foot. The increased density allows for economical shipping. The shredding also liberates moisture and some non-aluminum. No problems have been encountered with the mill operation.

12-Mesh Vibrating Screen

The purpose of this screen (No. 25 in Figure 8) is to remove minus-12-mesh material from the aluminum product. The purchase specification for this product allows only 3% minus-12-mesh material. The material removed is 5% of the feed to the screen; of this, 30% is aluminum. The screen has performed satisfactorily.

GLASS RECOVERY SYSTEM

As originally designed, glass recovery was to be done by screening, crushing, electrostatic removal of conductors, and optical sorting, all dry processes. This was described in the Feasibility Study published by NCRR in 1972 [12]. A commitment to purchase glass recovery system equipment had to be made in 1974. At that time, NCRR's tests indicated that none of the optical sorters available could meet the Glass Packaging Institute's specifications, which are incorporated into the market agreements at Recovery 1. This resulted in the decision to implement froth flotation. Tests of this technology at the U. S. Bureau of Mines' pilot facility in College Park, Maryland, indicated that the specifications could be met. However, it was recognized that the lack of color-sorted products was a limiting factor on product markets. Markets were secured for the mixed color cullet from Recovery 1.

Glass Mass Balance

The froth flotation process flow was designed by the NCRR staff, with technical assistance from Bureau of Mines personnel. This initial flow appears in the chart in Figure 11.

The shakedown effort made many changes in the process. Some of these were small, but some entailed removal of equipment items. The modification and tuning effort is still in progress. The process flow as it exists at this time is shown in

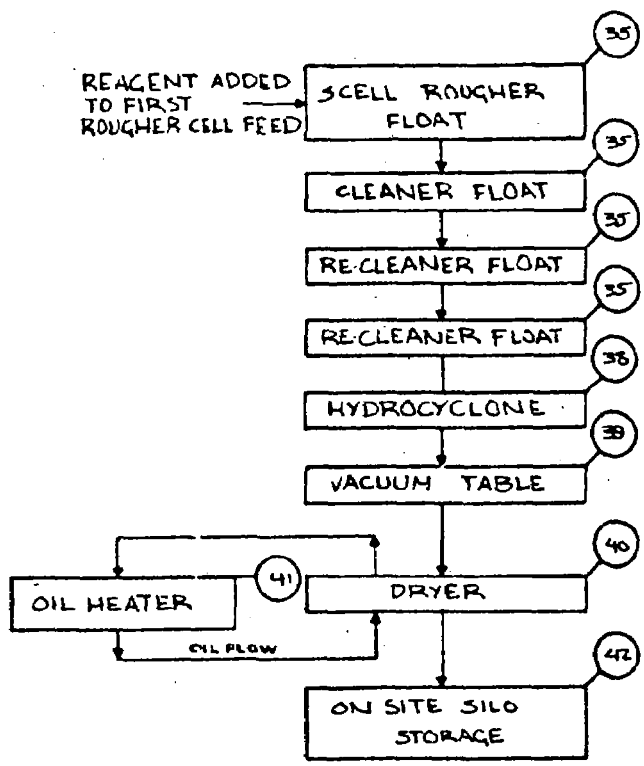


Figure 11. Initial Froth Flotation Process Flow (Cont'd)

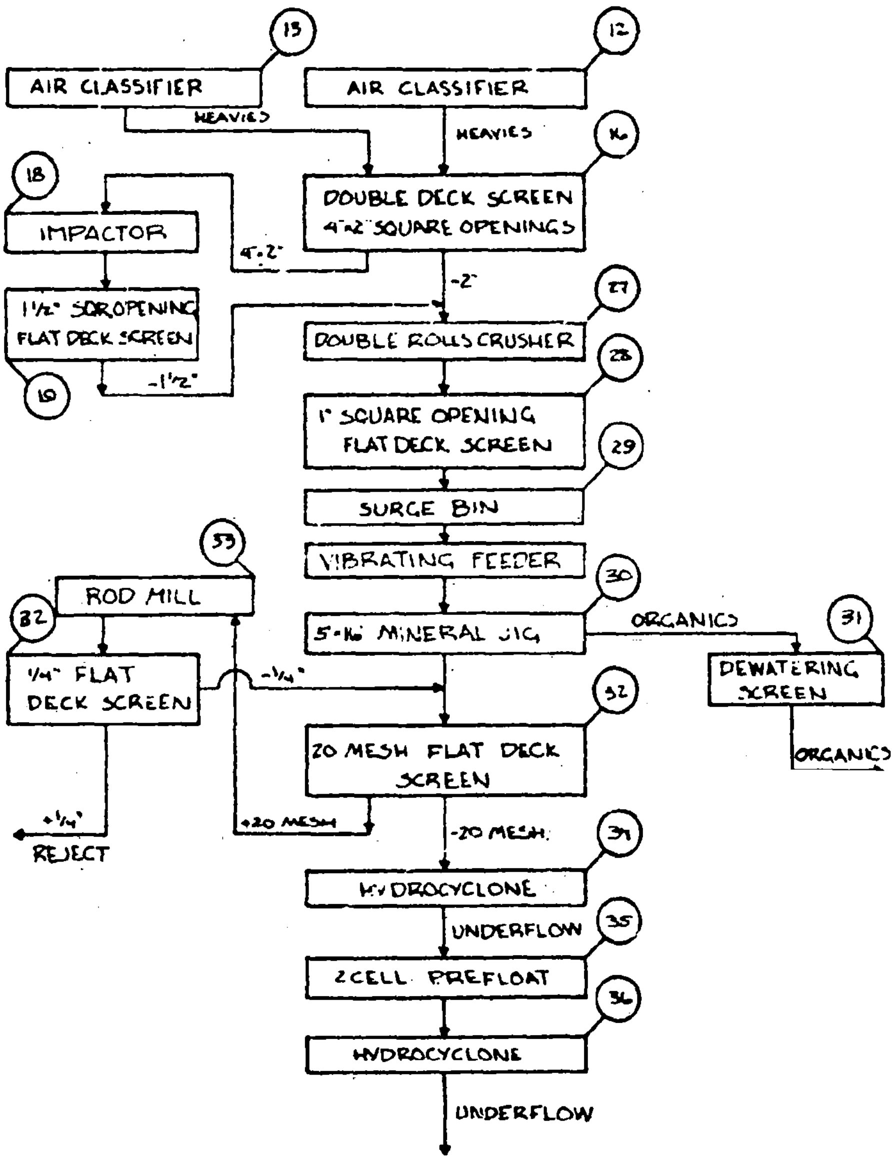


Figure 11. Initial Froth Flotation Process Flow

(Continued)

Figure 12. Also shown in the flow is the mass balance for glass in the system. These data are based upon samples taken during operation in September 1980. No formal testing of the glass system has been conducted.

The mass balance for the glass is calculated at 100 tpd input of MSW, as this was the operating rate during the testing period. At this rate, the loss of glass in the trommel is estimated at 6%. This is much higher than the 1% loss found during the trommel testing at 62.5 tph, as discussed in the Recovery Feed Preparation section. Also, there is a loss of the minus-1/4-inch glass (about 10%) in the air classifier. The figure for the quantity of minus-1/4-inch glass is based upon the trommel testing. A larger loss, about 20%, occurs on the vibrating screen (No. 16). The changes to the screen discussed below are expected to reduce this; however, some of this loss may be shifted to vibrating screen No. 28.

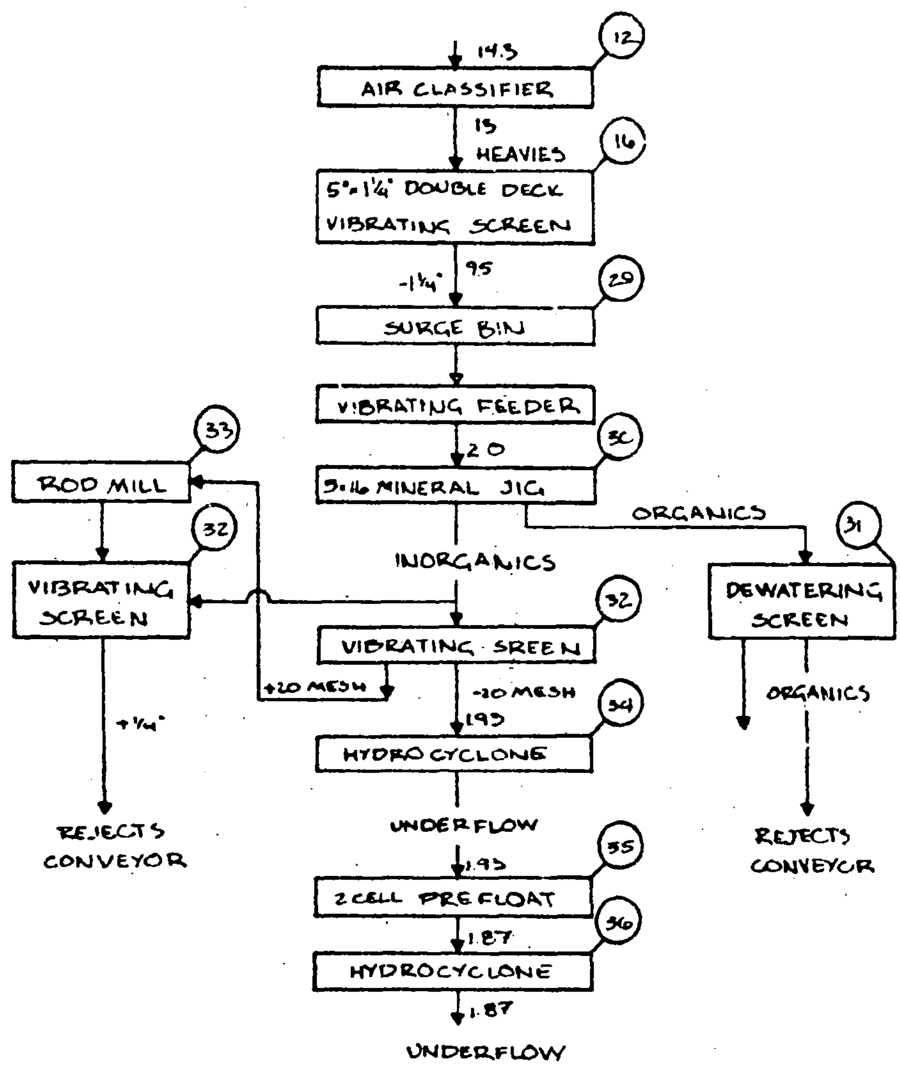


Figure 12. Current Froth Flotation Glass Recovery Flow and Mass Balance (Continued)

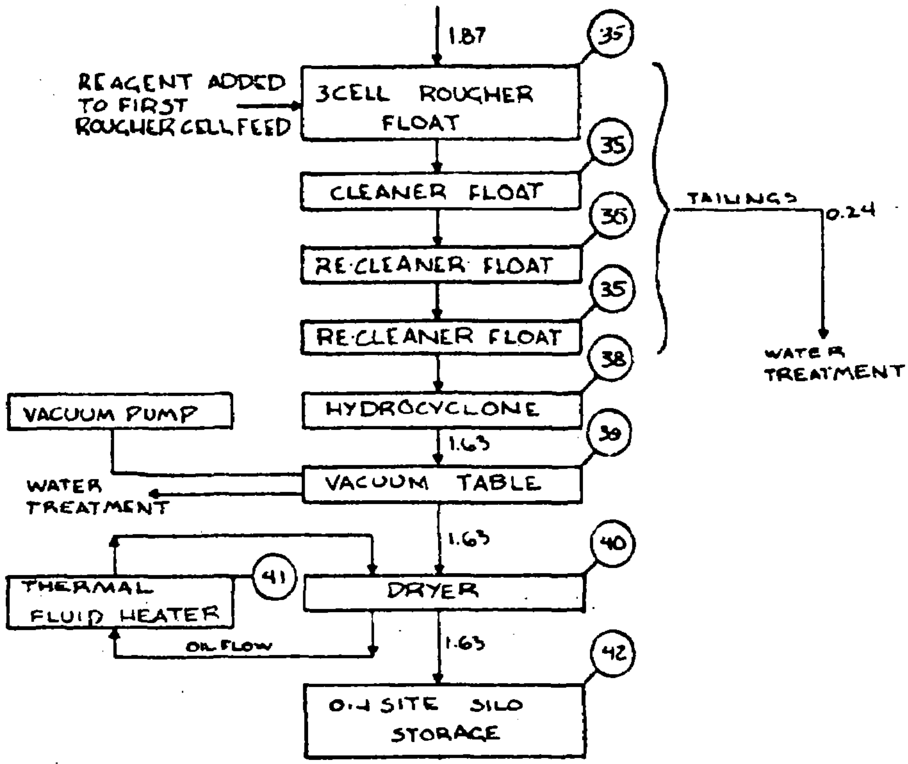


Figure 12. Current Froth Flotation Glass Recovery Flow and Mass Balance (Cont'd)

As can be seen in Figure 12, there is a marked flow rate change (4 to 1) at the surge bin. This highlights the very important function of this item in the glass system operation. The hydraulic portion of the system must be run at a continuous process. However, the front end of the glass system operates only when waste is being shredded. The shredding operation, part of the recovery feed preparation, is on a start-stop basis. The stops are caused by lack of a landfill loadout trailer, coffee and lunch breaks, shift changes, and equipment outages.

The wet portion of the glass system is currently operated at about 40% of design capacity. There are no specific known bottlenecks which prevent increasing the flow. However, insufficient feed material is presented during the 8 to 10-hour glass system operation to make increasing the flow worthwhile. The recovery in this portion of the system is 80%. There are no current plans to try to raise this yield.

The current goal is the production of a sufficient quantity of recovered glass to allow a large-scale melt test to be run in a glass plant. Approximately 350 tons of product have been delivered to the Owens-Illinois plant in New Orleans. Tests indicate that this meets the Glass Packaging Institute specification.

Equipment Modifications

The glass recovery system is essentially the last module in the recovery equipment train. Because of difficulties with upstream processing equipment, work on the glass system was delayed for a number of months. During attempts to operate the system in 1977 and early 1978, it proved impossible to achieve uninterrupted operation of sufficient duration to perform the tests necessary for evaluation. Effort was concentrated on the ferrous and aluminum systems. In mid-1979, effort was again directed to the glass recovery system. Since that time, the focus has been on sequentially operating, modifying, and evaluating the aluminum and glass systems.

The glass recovery technology employed involves wet processing. Initial hydraulic balancing problems caused water to overflow the tanks and equipment, which contributed significantly to the difficulties encountered. Overflow is now under reasonable control. This is the result of both equipment improvements, which have led to better operation, and to the installation of overflow control sumps and piping. This not only improved housekeeping, but the modifications made to control overflow allow the operator more time to correct the problem without having to shut down the entire glass plant. Operating days with as much as 10 hours of continuous operation have been achieved. This has allowed for test and evaluation and the beginning of an optimization process.

Each piece of equipment shown in the initial process flow (Figure 11) is discussed briefly below. The emphasis of each is the modification made. Equipment items which were eliminated are also discussed.

Two equipment items, the impactor (No. 18) and the screen (No. 19) are shown in the flow diagram in Figure 8. These are discussed in the Aluminum Recovery System section. The impactor, which was installed to break large glass in that flow path, was removed when analysis showed very little glass in that stream. Also, the underflow from the screen (No. 19) was rerouted to the residue discharge.

4 by 2-Inch Vibrating Screen

This screen was discussed in some detail in the Aluminum Recovery System section.

Double Roll Crusher

This crusher (No. 27 in Figure 11) was intended to reduce the size of all friable material in the minus-2-inch undersize fraction from the 4 by 2-inch screen (No. 16).

Numerous jams occurred in the crusher. These were caused by stones and metal items lodging between the toothed rolls. Jams could be prevented by increasing the distance between the two spring-loaded rolls; however, less size reduction resulted when this was done. A review was made of the particle-size distribution of glass reporting as trommel undersize. It was determined that approximately 80% was minus-1-inch before crushing. Based upon this data, the crusher was removed.

One-Inch Vibrating Screen

This screen (No. 28 in Figure 11) sizes the material for the minerals jig. The undersize, minus-1-inch, is discharged into a surge bin for feeding to the jig. Studies have shown one inch to be the practical upper limit on the size of the jig feed. Initial calculations based on an infeed rate of 12.3 tph indicated that a screen area of 40 square feet was required. The supplier, Vibranetics, submitted that a screen with 16 square feet area would suffice. This proved grossly inadequate. Several remedies were tried. The original 1-inch (nominal) opening size screen cloth was, in fact, only a 0.875-inch opening. This was changed to a cloth with a 1-inch clear opening, but no improvement was observed. Two symptoms were noted: (1) insufficient area, and (2) excessive blinding. Washing with high-pressure hot water provided short-term relief. Constant washing with ambient-temperature water was better than no washing, but this increased the moisture content of the undersize material being stored in the surge bin, which increased the difficulty of flow control into the jig. Also, washing separated the fine dirt from the oversize material, resulting in a mud buildup on the bottom of the screen.

As a method of alleviating the blinding problem, a cloth with 2 by 1-inch rectangular openings was tried. But this allowed particles which exceeded the jig top size to pass. A 1-inch-diameter hole perforated plate was installed, but the open area was less than the 1-inch-square mesh. As a result, it could not process material rapidly enough to keep pace with the jig.

A temporary solution was to remove the screen completely and make the 1-inch size separation on screen No. 16 (see Figure 11), as mentioned previously. This change was made, and sufficient throughput capacity was obtained. However, sticks and other long (3 inches or more) items entered the jig and caused plugging in the jig discharge pumps. Also, a negative effect was the introduction of an increased amount of 1 by 2-inch material into the middling fraction. This additional material had a detrimental effect on eddy current separator performance. A perforated screen with 1 by 3-inch ovals was tried; this solved the stick problem, but it also lacked the necessary capacity.

The supplier, Vibranetics, offered to exchange the small screen for a 5 by 12-foot unit (more than three times as large in area). However, this could not be easily accommodated into the existing configuration, due to the size and weight. A price regarded as fair by NCRR was negotiated. However, it was determined that a light-duty screen could be purchased for less cost. Also, the light-duty screen would not have the space and structural requirement as the one proposed by Vibranetics. A 4 by 10-foot screen was installed with a punched plate with 1-inch diameter openings. A slotted punch plate with 3/4 by 3-inch oval openings has been ordered for the unit.

Surge Bin

This bin (No. 29 in Figure 11) was constructed on site by the erection contractor. Its purpose is to absorb surges so that uniform feed to the jig can be maintained. The bin is rectangular, with a converging bottom. The top 7 feet has a 6 by 7-foot cross section. The bottom 7 feet converge on three sides to a rectangular size of 2 by 1 feet. The nature of the material and the converging bottom caused bin discharge problems from the initial testing. Several remedies were tried.

High-density, low-surface-friction polyethylene was used to line the steepest converging side. No apparent improvement was seen. Water injection on three sides was tried with limited success.

Direct spray onto the upper surface has been the most successful. The disadvantage of this method is the lack of control on rate of discharge of the wet material from the bin bottom.

A modification was also made to the discharge of the bin. A manually adjustable hinged opening was fitted which allows the discharge from the bin to be modulated. Also, because the size of the bin discharge opening can be quickly doubled, incipient plugging can be avoided by opening the gate. This provides additional modulation to the variable speed which discharges the bin. The disadvantage of the gate is that it requires the attention of an operator.

Minerals Jig

The purpose of the minerals jig (No. 30 in Figure 11) is to remove organic materials from the glass-rich fraction. A secondary purpose is to remove the small dense objects, mainly nonferrous metals, from the jig product.

This jig was originally fitted with BETZ water spray nozzles to fluidize the incoming material in the vertical chute at the feed end of the machine. These nozzles did not prove to be practical, and were removed.

The bed of the jig was initially operated with 1/4-inch-square mesh cloth over 1/4-inch-wide by 3/4-inch-long slotted holes in steel plate. At the recommendation of the manufacturer, this upper screen cloth was removed. The jig was then operated with punch plate steel and ball ragging, 1/2-inch diameter in the first half of the bed and 5/8-inch diameter in the second. Frequent plugging of the hutch drains occurred from large objects passing the slotted holes. Therefore, a new 1/4-inch-square mesh stainless steel screen cloth was installed. This prevented large objects from passing into the hutch, but did not totally solve the hutch drain problem.

Early jig operation was done with gate-type valves fitted to each of the hutch drains which were difficult to clean. The gate also contributed to plugging. These valves were replaced by short sections of soft foam rubber hose fitted with circular hose clamps. This allows for a variable orifice with a circular cross-section. Also, the transition in size is smooth, so the outlets are no longer so prone to plugging. Periodic disassembly and cleaning is required. (Concentric valves are available commercially, but are expensive.)

The jig was initially set with a 7° angle of declination. This caused the fluidizing of material to occur about halfway down the 16-foot-long bed. To fluidize the material closer to the feed end, the jig angle of declination was decreased to 5°.

This aided the jigging process, but still did not allow bottom water to pulse up through the bed of the first hutch. Therefore, the first third of the bed was covered with a steel plate and horizontal spray nozzles installed at the feed end to sluice the material into the working sections of the bed. This reduced the capacity, but proved workable at the reduced feedrate.

In summary, the jig has proven to be the most sensitive and difficult machine to operate. Difficulties were encountered with balancing top and bottom water and maintaining proper bed height at varied infeed rates. Operating procedures derived from the minerals beneficiation industry's use of the jig do not always apply to jigging glass from organic waste. Variability of the waste requires adjustments in the jig control settings to assure satisfactory material separation.

Organics Dewatering Screen

This vibrating screen (No. 31 in Figure 11) was to receive the organic residue discharge fro the jig and dewater it. The residue was to be discharged to landfill and the water recycled.

The screen was initially fitted with a 60-mesh stainless steel woven wire cloth which proved too tight a weave. The result was no dewatering, with most of the water passing over the screen and being discharged with the organics.

To alleviate this problem, a 30-mesh wire cloth was tried, with little improvement. Finally, 16-mesh wire cloth (0.018-inch-diameter wire) was installed and is satisfactory. The penalty extracted by the more open screen is the addition of minus-16-mesh grit and fines to the recycled water. This increases the frequency of the cleanout of the recycled water tank. The oversize material is dewatered sufficiently to be conveyed by conventional smooth belt conveyors. Periodic washing of the screen with high-pressure hot water is required to prevent blinding by fatty materials which close the screen openings.

1/4-Inch by 20-Mesh Vibrating Screen

The purpose of this screen (No. 32 in Figure 11) was twofold: (1) to size the glass fraction for the froth flotation cells at less than 20 mesh, and (2) to remove any non-friable material larger than 1/4 inch from the crushing circuit.

This double-deck screen was delivered with a top deck of 1/4-inch square opening wire screen cloth supported by 1/4-inch rods longitudinal, and a bottom deck of carbon steel with slotted openings 15-mesh by 5-mesh (nominal 20-mesh).

Two problems were encountered with this arrangement. The carbon steel material rusted and began allowing oversize (plus-20-mesh) material to report to the undersize (minus-20-mesh), thence to the froth flotation cells. Also, oversize material penetrated the seams in and around the screens.

The rusting problem was solved by replacing the original cloth with 304 stainless steel screen cloth. The first attempt to solve the unsupported joint problem was with two sections of screen cloth 3 feet wide by 10 feet long, with hooks on both sides. A longitudinal seam appeared feasible because there was a flat bar supported down the screen centerline which could be used to retain the hooks. This arrangement solved the support problem, but placed excess tension on the hooks, which resulted in the cloth tearing away from the tension hooks on the sides.

After several attempted solutions, discussions with the screen manufacturer, CE-Tyler, resulted in replacing the bottom deck with a two-piece stainless steel (316 SS) 20-mesh screen (two 6-foot by 5-foot panels with 0.017-inch-diameter wire). Backing cloth panels were installed (8-mesh, 0.025-inch-diameter wire) to provide tensile strength and prevent the lighter-gauge wire cloth above it from tearing. These were installed using the rubber wedges that provide seals along the edge where the two panels abut and at either end. A problem was encountered with the impingement of the glass on the top screen. The result was wear and breaking of the screen wires. Several changes to the feed distributor in the unit were made. In addition a third 8-mesh screen cloth was installed over the 20-mesh deck in the upper half of the screen to serve as a velocity brake for the glass particles. This appears to be satisfactory.

Rod Mill

The purpose of the rod mill (No. 33 in Figure 11) is to crush the glass fraction prior to froth flotation. Sizing at 20 mesh is done by the vibrating screen (No. 32).

It was noted that the slurry inside the mill was seeping out on the feed end near the large bull gear. This slurry contained small particles of very abrasive glass that were being picked up by the revolving bull and pinion gear and abrading the faces of the gears. The leak was stopped and the gaps between liners sealed by applying a coating of Nordback, an epoxy manufactured by Rexnord. The first layer was of steel powder-impregnated epoxy, followed by a layer of ceramic bead-impregnated epoxy for abrasive resistance. No further leaks have occurred.

Several rod charges have been used since shakedown started. The size of the charge - number of rods - and the amount of water for a given amount of feed determine the particle size of the discharge. Currently, the mill charge is 37 rods totaling 4,073 pounds. This is approximately 20% of mill volume. The charge varies as the rods wear. The particle size distribution of the mill product is analyzed to determine the need for rod replacements.

Hydrocyclone

The purpose of this 10-inch hydrocyclone (No. 34 in Figure 11) is to remove the solids which are finer than 150 mesh from the undersize material (minus 20 mesh) from Screen No. 32.

The initial configuration had a 3-1/2-inch vortex finder and a 2-inch adjustable apex. The underflow was observed and attempts were made to optimize its operation by adjusting the inlet pressure. The performance was not satisfactory; therefore, the 6-inch-long spool section immediately above the apex was removed. This improved the performance. However, the most critical parameter affecting cyclone operation was found to be pulp density, or percent solids of the slurry fed to the hydrocyclone. Low pulp density resulted in more solids reporting to the overflow, where the potential for their loss is greater. This must be controlled upstream of the hydrocyclone by modifying the jig feed rate. Minor adjustments may be made by adding water to the rod mill circuit.

Froth Flotation Circuit

The configuration of the flotation cells is an eight-cell unit (Model 18 Special Type A), consisting of two prefloat cells, three rougher cells, and three cleaner cells. The individual functions in the circuit are discussed below.

Prefloat Cells (No. 35* in Figure 11). The purpose of these two cells is to provide an opportunity for non-glass, greasy, waxy, and other organic material to float in untreated water. The initial operation resulted in the second cell in the two-cell series flow path sanding up, and not discharging the tailings for further glass processing. To a lesser extent, the first prefloat cell was slow in discharging its tailings (sink fraction) to the second cell. Both sand relief port bushings (first cell to second cell and second cell to discharge) were removed, providing a 3-inch-diameter passage for the tailings.

Hydrocyclone. This 6-inch hydrocyclone (No. 36 in Figure 11) is fitted with an adjustable, air-actuated apex for underflow particle-size control. As with hydrocyclone No. 34, the only operational difficulty is controlling the pulp density of the feed.

Flotation Cells (No. 35* in Figure 11). These six flotation cells are configured into three roughers set in a combination of series and parallel, and three cleaners in series. Aside from adjustments to weir heights to balance cell-to-cell water levels, no changes or problems in the equipment have been encountered.

Problems have been experienced with the flotation of the larger glass particles. Tests show that 30 to 35% of the glass in the 20 by 40-mesh size range does not float and is lost to the tailings.

*The equipment number "35" is applied to the entire eight-cell unit. The different functions of the individual cells are discussed separately.

Increased reagent concentration increases the yield, but does not recover all of the fraction. Also, it increases the cost. The system now recovers 87% of the glass entering the first rougher cell (initial flotation cell). A slightly smaller particle-size distribution might improve the yield, but has not been tried.

Hydrocyclone (No. 38 in Figure 11). The purpose of this 6-inch hydrocyclone is to feed the vacuum filter and partially dewater the slurry deposited on the vacuum table.

This unit is located immediately ahead of the vacuum table (No. 39). Initially, all of the underflow (apex discharge) was put directly on the vacuum table, with the overflow water piped to the recycle water system. To balance the cyclone, a tee was fitted to the overflow and valved so that one leg of the overflow was routed back into the sump serving the pump which supplies the cyclone slurry. The second leg was routed to the waste water tank.

Vacuum Filter (No. 39 in Figure 11). The purpose of the vacuum filter is to partially dry the glass product. Problems experienced with this filter have been in the area of appropriate-size filter cloth weaves and filter media.

Magnified examination of the original top filter cloth (400 SCFM rating) revealed the individual polypropylene threads had swollen, thereby reducing the open area. All 20 panels were stripped from the table and new polypropylene cloth rated at 250 SCFM caulked onto the table above the existing backing cloth. Moisture removal down to 5% is now possible, and no other problems of dewatering were found.

The vacuum pump draws air through the vacuum table to remove the free moisture. It is constructed with carbon steel impeller vanes that tend to rust and seize to the vane housing if not frequently rotated. In extreme cases, the pump must be disassembled and cleaned to free the vanes. During shakedown, several periods of two to three weeks with no activity were encountered. After the initial period of inactivity, the impeller froze, but was freed by rocking the impeller shaft. A standard operating procedure was adopted to start and run the vacuum pump for several minutes once a week when an outage prevents normal plant operation.

Dryer (No. 40 in Figure 11). The purpose of the Holoflite dryer is to reduce the moisture level of the glass product from 5 to 10% of the feed to less than 1%.

This device is essentially a twin-screw conveyor which works by passing a hot (600°F) thermal fluid through both the jacketed trough and the hollow screw flites. When the Holoflite dryer was purchased used, both flites and jackets sustained a hydrostatic pressure test. In addition, the rotary valves were rebuilt by the equipment supplier prior to purchase.

Insufficient moisture removal to satisfy the product specification was a problem from the beginning. Tests showed the trough jacket was receiving sufficient heat transfer oil to reach operating temperature. However, the flites were not. This was traced to improper valve operation. The rebuilt valves had been used in a different configuration and had been improperly modified for this application. New valves were purchased and installed, and no further heat imbalance was seen.

Although the dryer passed hydrostatic pressure tests, it developed two leaks in the trough where rust had caused several pitted areas of thin metal. The consequence of these leaks was contamination of the glass product with heat transfer oil. The contaminated glass was rejected, and metal plate patches were welded over the weakened areas.

The thermal fluid for the dryer is heated to 600°F by an oil-fired heater. This experienced some initial control problems which have since been corrected.

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SUMMARIES OF COMBUSTIONS OF REFUSE-DERIVED FUELS AND DENSIFIED FUELS

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ABSTRACT

The Solid and Hazardous Waste Research Division has supported investigations of the use of refuse-derived fuels (RDF) for power generation. Two projects used fluff RDF in municipal power generating boilers. The St. Louis-Union Electric refuse fuel project was the first demonstration plant in the United States to process raw municipal waste for use as a supplementary fuel in a utility boiler. A second such project was at Ames, Iowa. Two other projects investigated the use of densified RDF (d-RDF) as a substitute for lump coal in smaller spreader stoker boilers. Approximately 2,500 tons of d-RDF were combusted with and without coal at plants located in Hagerstown, Maryland, and Erie, Pennsylvania. Although other RDF combustion projects have been supported, these four are summarized in this paper.

INTRODUCTION

Recent concerns about the cost and availability of energy have sparked great interest in the possibility of recovering energy from refuse. Such energy recovery would not only offset steeply rising fuel costs, it would also help solve the Nation's solid waste disposal problem. The U.S. Environmental Protection Agency (EPA) assigned the Municipal Environmental Research Laboratory (MERL) in Cincinnati, Ohio, major responsibility for research and development in the field of recovery and use of municipal solid waste. This paper describes four major EPA projects that are aimed at the recovery of energy from solid waste. These projects combust refuse either directly for steam recovery or in combination with fossil fuels for power generation. The latter involve the processing of the refuse to remove the combustibles for use in a modified power generation boiler, usually in combination with coal. The processed refuse is usually referred to as refuse-derived fuel (RDF).

The RDF concept in the United States was originally considered for major power generating facilities that burned pulverized coal. However, the use of RDF need not be limited to large users and may in fact be more valuable to small power generating facilities. Small industrial and institutional boiler owners may find RDF an attractive and cheaper alternative to fossil fuels, for which they receive no quantity discounts, as do the large users. In addition, small users may have increased flexibility in negotiating contracts for RDF (especially with regard to length of commitment). Many small power generators are economically marginal because their boiler facilities are older, coal-burning models that require costly air pollution equipment. The use of RDF may help such facilities absorb the cost for such controls.

RDF prepared for large utility boilers is typically composed of the light fraction of shredded refuse that has been air-classified, screened, or otherwise processed to remove the noncombustibles. In this fluffy form, it can be pneumatically fed into the suspension utility boiler. For the smaller, stoker-fed boilers, however, a densified form of RDF is probably more desirable.

This densified refuse-derived fuel (d-RDF) may approximate the physical characteristics of the stoker coal fed to the boiler. RDF in this form offers increased flexibility in transport, handling, and storage, and it can be mixed directly with the coal and fed to the boiler with few if any modifications.

EPA realized that for fuel recovery from refuse to be widely implemented, a credible experimental program was needed to establish the environmental acceptability and economic and technical soundness of such fuels. Of major importance to users would be the effects on boiler physical facilities and operations, and on the environment. A number of demonstration projects were thus undertaken by EPA to provide the necessary experimental data and operational experience to interest potential users in implementing the concept.

Among these projects were the four combustion studies that are the subject of this paper. They include two demonstrations of the preparation and firing of RDF (one at St. Louis, Missouri, and the other at Ames, Iowa) and two demonstrations of the firing of d-RDF pellets in spreader stoker-fired boilers (one at a Hagerstown, Maryland, institutional heating boiler, and one at a larger industrial boiler in Erie, Pennsylvania). The combustion studies are summarized as follows:

St. Louis/Union Electric Refuse Fuel Demonstration System

This project was the first demonstration plant in the United States to process raw municipal waste for use as a supplementary fuel in a utility boiler. It was designed as a simple, minimal investment experiment to test the combined firing of coal and RDF. Two separate facilities make up the system--a processing plant operated by the City of St. Louis, and an RDF receiving, handling, and firing operation at the Union Electric Company's Meramec plant near St. Louis. At the processing plant, raw solid waste is milled to a nominal 38.1-mm (1-1/2-in.) particle size and air-classified into light and heavy fractions. The light fraction (which accounts for approximately 80% to 85% of the incoming municipal refuse) is temporarily stored and then hauled 29 km (18 miles) by transport truck to the Meramec Plant. At the power plant, RDF is unloaded from the transport trucks into a receiving bin from which it is conveyed pneumatically to a surge bin. A pneumatic feeder system conveys the RDF from the surge bin through four separate pipelines directly to the boiler.

Ames, Iowa, Solid Waste Recovery System

The Ames project was the first continuous, full-scale solid waste recovery system for the processing and burning of municipal solid waste as a supplementary fuel for power generation. Two facilities make up the system: One is a 136-Mg/day (150-ton/day) waste processing plant where the RDF is received by means of a pneumatic transport system stored in a 454-Mg (500-ton) Atlas bin, and fired into two small steam-electric boilers. The 50-ton/hr processing plant incorporates two stages of shredding, ferrous and nonferrous metal recovery, and an air density separator.

Firing of Coal:d-RDF Blends in Spreader Stoker-Fired Boilers at Hagerstown, Maryland

Experimental combustion tests of d-RDF pellets were conducted at the State of Maryland Correctional Institution for Men. The d-RDF pellets used in these tests were prepared by the National Center for Resource Recovery (NCRR). The boiler plant consists of a battery of three 150-psig Erie City boilers. Their design steam ratings are 78,500, 60,000, and 25,000 lb/hr. Each unit is equipped with Hoffman Combustion Engineering Firerite spreader stokers to distribute the lump fuel in the furnace. The large coal pieces that do not burn in suspension are combusted on the surface of Hoffman vibrating grates, and ash is discharged to the front. The boilers have tube-and tile furnaces.

Firing of Coal:d-RDF Blends in an Industrial Spreader Stoker Boiler in Erie, Pennsylvania

Long-term demonstration tests were conducted at the General Electric Power Plant in Erie, Pennsylvania, to determine more accurately the general performance of d-RDF in a boiler representative of those used throughout industry. Pellets of d-RDF were supplied by Teledyne National and NCRR. The demonstration consisted of four tests during which fuel handling, boiler performance, and stack emissions were monitored. The test boiler was a 150,000 lb/hr steam generator consisting of a Babcock and Wilcox two-drum Sterling Boiler with a Detroit Rotograte Spreader Stoker.

Other Related EPA Project

Several other projects were undertaken to establish the economic impact of burning d-RDF. Briefly, they include:

- A research grant to the National Center for Resource Recovery (NCRR) to study production requirements for d-RDF;
- A research grant to the University of California to supplement the NCRR grant in examining the theoretical basis for producing and using d-RDF;
- A contract with Teledyne National to produce 2000 tons of d-RDF and provide additional information on production processes.

ST. LOUIS/UNION ELECTRIC REFUSE FUEL DEMONSTRATION SYSTEM

In April 1972, the City of St. Louis began to operate a 300-ton/day municipal solid waste (MSW) processing facility designed to produce RDF and to recover ferrous metals. The RDF has been burned and tested by the Union Electric Company as a supplement to pulverized coal in steam-electric boilers. During the tests, the RDF made up 0% to 27% of the heat input to the boilers.

This project was partially funded by an EPA grant to the City of St. Louis. Technical, economic, and environmental evaluations of the project were conducted by Midwest Research Institute under contract to EPA. Performance assessments were made both at the processing plant that produced the RDF and at the power plant where it was burned as a coal supplement.

Processing Plant Evaluations

Process Description--

Residential and commercial waste is first shredded in a horizontal hammermill to a 1-1/2-in. particle size. A cyclone particulate collection system over the hammermill feed throat collects large pieces of paper that blow back out of the mill. The shredded material is then air classified by a vertical chute classifier, where the lighter materials such as paper and plastic films are separated in a turbulent air stream from heavier materials such as metals, glass, rubber, wood, textiles, and thick, dense plastics. The light materials is de-entrained from the air-stream in a cyclone and is conveyed to a storage bin before it is trucked to the power plant. The heavy fraction is processed to recover ferrous metals for use as a scrap charge in a steel mill. The remaining residue is landfilled.

Plant Operations--

Processing rate--The overall processing rate average for the 53-week test period was 168 Mg/8-hr day (185.5 tons/8 hr. day) at 31.0 Mg/hr. (34.2 tons/hr.) The plant was operated at maximum capacity of 272 Mg/8 hr. day (300 tons/8-hr. day) during the first 2 weeks of the testing, demonstrating that the plant could sustain this rate for at least a short period. The maximum 1-day average processing rate was 45.8 Mg/hr. (50 tons/hr.).

Down time--Two major equipment breakdowns occurred at the processing plant, along with several plant shutdowns resulting from equipment maintenance outages at the Union Electric power plant and from repair of an electrical substation serving the processing plant. Planned shutdowns for normal maintenance also occurred.

Material balance--Plant material balance by weight showed that plant output averaged 7.6% less than input. Scale error and moisture and particulate loss from the air classifier and dust collection system were identified to account for 1.6% loss, leaving a 6% error. Moisture loss from the hammermill is thought to be the major cause of this loss.

Product Analysis--RDF has approximately 42% of the heating value and 2.7 times the ash content of Illinois Orient 6 coal, but the refuse fuel has only some 12% of the sulfur and 35% of the nitrogen content of the coal. Ferrous metal recovered is a marketable byproduct used as part of the scrap charge at a nearby steel mill. On the average by weight, the RDF represents 80.6% of the processed raw refuse, and the recovered ferrous metal accounts for 4.5%. The plant reject material, which is landfilled, has very low energy content.

Operating costs--

Operating costs increase rapidly when the plant is operated below its design capacity. Total monthly operating costs for the refuse processing plant plus the receiving facility ranged from $4.45 to $57.99/Mg ($4.04 to $52.6/ton). Total average operating costs for the 53-week period were $8.26/Mg ($7.49/ton).

Environmental Assessments--

Air--Future plants using an air classification system of the type used at the St. Louis demonstration plant will need an air emission control device to control particulate emissions from the large deentrainment cyclone. Particulates in the air exhaust to the atmosphere from this cyclone averaged 0.57 g/Nm^3 (0.25 grains/ft^3). Also, this exhaust air contained total counts of bacteria and viruses that were much higher than those found in suburban ambient air.

Water--A small quantity of washdown water from the paved area around the plant is the only water emissions, and it poses no pollution problem.

Noise--A sound survey of the plant revealed several locations with noise levels above 90 dBA, the maximum allowable for continuous 8-hr. exposure. But since no worker is present at these locations for 8-hr. or more, no noise exposure problem exists.

Leachate--Analysis was made of laboratory-produced leachate from plant products that might be landfilled (RDF and magnetic belt rejects). Results indicated that groundwater contamination could result if the dilution rate were not high enough.

Power Plant Evaluations

Process Description--

The processed RDF is unloaded at the power plant from the transport trucks into a receiving bin, from which it is conveyed pneumatically to a surge bin. A pneumatic feeder system conveys the RDF from the surge bin through four separate pipelines directly to the boiler. Unit 1, a corner-fired pulverized coal suspension boiler with a nominal generating rate of 125 Mw, was the boiler used for this test program.

Plant Operations--

Operations at the Meramec power plant using RDF as a coal supplement extended over several months and demonstrated that burning 5% to 20% RDF as a supplementary fuel in a coal-fired boiler is a viable concept. Shutdowns occurred for routine modification and maintenance, and many short-term shutdowns or reduction in RDF firing rate resulted from problems with the pneumatic conveying lines and blockages of the discharge chutes from the Atlas storage bin (surge bin). No major equipment problems were encountered, however, and the burning of RDF had no discernible effect on boiler erosion/corrosion.

Leaks in the pneumatic conveying lines to the boiler were a frequent problem. The erosion of these lines was caused by the abrasive materials in the RDF, which were initially present at high levels because no air classifier was used to remove metals and glass. But even after an air classifier was added, some metal and glass fragments remained in the RDF, and erosion of the carbon steel pneumatic pipelines continued to be a problem.

Performance of the electrostatic precipitator decreased with increasing boiler load. Above 120 Mw. the burning of coal plus RDF did decrease ESP efficiency. Note, however, that the boiler was operating in excess of design capacity above 120 to 125 Mw.

Costs--

Cost estimates for firing of RDF do not include any expense for purchase of RDF from the city or any credit for the coal saved by using the RDF. Costs for the receiving building, which was owned by the City of St. Louis, were included as part of the operating cost for the power plant. All other equipment was owned and operated by Union Electric.

Capital cost of the facilities at the Meramec plant was $945,640. Of this cost, $578,097 represents Union Electric's initial investment, and $367,543 represents the City's cost for the receiving building and associated equipment.

Over an 8-month period (October 1974 to May 1975), operating and maintenance costs averaged $9.39/Mg ($8.25/ton) of RDF. These costs ranged from $5.67/Mg to $17.70/Mg ($5.14 to $16.05/ton) and did not include amortization of equipment. These costs are probably not representative for such plants, however, because the system usually operated below design capacity and maintenance costs were high because of the need for frequent repair and replacement of pneumatic conveying lines. Future well designed plants should be able to operate more economically than the Meramec plant.

Environmental Assessments--

Potential emissions associated with combined firing of coal and RDF include (1) boiler bottom ash and fly ash from the ESP, (2) boiler sluice water and ash pond effluent, and (3) air emissions (both particulate and gaseous) from the boiler stack. To assess the potential environmental impacts of these emissions, comparisons were made of test results when firing Orient 6 coal only and Orient 6 coal mixed with 5% to 10% RDF.

Bottom and fly ash--A sevenfold increase in boiler bottom ash occurred with the burning of coal plus RDF. This increase was accompanied by higher concentrations of Cu, Pb, Na, Zn, and Cr, and decrease Al, Fe, Li, and S. Landfilling of bottom ash from combined firing could create water pollution problems, but it was not possible to assess them relative to those of the coal-only bottom ash.

Fly ash from combined firing had a higher heating value than the coal fly ash (2,361 compared with 1,551 kJ/kg). The RDF fly ash also had higher concentrations of Sb, As, Ba, Cr, Cu, Pb, Hg, Zn, Br, and Cl, whereas the coal-only fly ash had a greater iron content. These differences are not sufficient to pose greater disposal problems with the RDF fly ash, but they might create leaching problems during landfilling. The relative impacts are difficult to assess, however.

Boiler sluice water and ash pond effluent--Levels of trace constituents in boiler sluice water are approximately equal for the two types of fuels, but the coal plus RDF produces higher concentrations of total dissolved solids (TDS).

Ash pond effluents from coal-only firing meet proposed Missouri guidelines with respect to biological oxygen demand (BOD), dissolved oxygen (DO), and suspended solids (SS), but effluents from coal plus RDF do not. The latter are lower in sulfates but higher in ammonia, B, Ca, chemical oxygen demand(COD), Fe, Mn, and total organic solids. Measurements of 48 other parameters showed no significant differences.

Conventional gaseous emissions--Except for chloride emissions, (which increased by some 30%), combined firing of coal plus RDF did not produce major changes in the emission of gaseous pollutants compared with the firing of coal-only. Average carbon monoxide emissions were slightly higher for the RDF fuel (89 compared with 82 ppm). No apparent change occurred in NO_2 emissions, and the levels measured complied with current Federal and State regulations. Hydrocarbon levels did not appear to be higher with the RDF fuel; SO_2 emissions would tend to be lower with the burning of RDF, which has a lower sulfur content than coal; but the decrease would not be sufficient to meet Federal regulations. A shift to lower sulfur coal or use of an SO_2 control system would be required. Emissions of particulates from the ESP at loadings above 100 Mw could not meet Federal requirements, regardless of the fuel mix. Potentially hazardous particulate emissions (Be, Cd, Cu, Pb, Hg, Ti, Zn, and F) did increase when coal and RDF were fired. Cl, Br, Pb, may exceed acceptable limits even when coal alone is burned, and RDF only compounds the problem.

AMES, IOWA SOLID WASTE RECOVERY SYSTEM

The city of Ames, Iowa has been commercially operating a system for materials and energy recovery from municipal solid waste since November 1975. Constructed and operated solely with municipal funds, it was one of the first municipal resource recovery systems and represented a giant step in this field. As part of their resource recovery research and development program EPA implemented a 3-year detailed evaluation of the system.

Processing Plant Evaluations

Process Description--Both industrial and private vehicles deliver refuse to the tipping floor where it is reduced to a nominal (6-in.) size by the first stage shredder. After passing the magnetic separator for ferrous removal, the shredded refuse is further reduced to a nominal size (1 1/2 in.). The shredded material is then air classified into a combustible fraction (RDF) and the heavy rejects, which are further divided into ferrous and nonferrous material.

Characterization of Refuse-Derived Fuel--

The Ames RDF appears to be of higher quality than that produced at St. Louis, even though the processing systems are quite similiar. The reason is probably that the Ames waste contained a large amount of commercial waste with a high percentage of paper, whereas the St. Louis RDF was produced strictly from residential refuse with a high proportion of food waste and moisture.

The Ames RDF heat value averaged 5,700 BTU/lb, the average moisture content was 22 percent, and the ash content averaged 17 percent.

Processing Plant Performance--

The plant operated regularly except for a shredder bearing failure and two fires at the processing plant. Average production rate was 50 tons/hr. The air classifier was a major maintenance area. The second stage shredder was discovered to use nearly twice the electric power required for the first stage shredder. A major disappointment was the aluminum recovery system, which produced only minor amounts of marketable aluminum scrap during 1976.

Costs--

The net cost of operating the refuse processing plant (net cost of refuse disposal) for 1976 was $18.90/Mg of raw refuse received. This total represents the cost after credits are given for the RDF, dump fees, and recovered metals. Improvements in net cost can be achieved by reducing operating expenses and increasing the volume of raw refuse received.

Power Plant Evaluations

Process Description--

Originally, RDF was to be used as a supplementary fuel with an Iowa-Wyoming coal mixture in a suspension-fired steam generator. The supplementary burning of the RDF in the stoker boilers was to occur during shutdown of the pulverized coal unit. However, attempts to fire RDF in the suspension system revealed that continuous burning was prevented by high dropout of unburned wood, cardboard, and large paper. Thus RDF is now burned in the stoker-fired boilers at an average rate of (4.5 to 5 tons/hr), or 50% input on the basis of heat energy input.

Boiler Description--

The two stoker-fired boilers used at the Ames power plant were installed in the 1950's and use cyclone collectors (multicyclones) for particulates removal from the exhaust gas to the atmosphere. Both are traveling grate spreader stokers. RDF is fed into the boiler by a pneumatic conveying system.

Environmental Emissions--

Particulate emissions showed no clear trends regarding the function of RDF heat input, either before the particulate collector or in the stack particulate emissions to the atmosphere. NO_x and SO_x emissions both tended to decrease with increased percentages of RDF. Chloride emissions increased with the percentage of RDF for all boiler loads. The substantially higher levels of chloride emissions for coal plus RDF appear to be a function of the chlorine in the RDF. Formaldehyde, cyanide, and phosphate emissions were quite variable, with no clear trends based on the percent of RDF burned. No significant hydrocarbon emissions in the C_1 to C_5

range, were found, and many of the heavy organic compounds in the stack emissions were below the laboratory detection level. Most of the organics found were in the stack gases and not in particulate form.

Boiler Performance--

RDF combined with coal was successfully fired in the stoker boilers with some difficulty but with no major problems. The maximum RDF firing rate was 50% of the heat input to the boiler. The burning of RDF had no significant direct effect on the measured boiler thermal efficiency. The average heat input leaving as combustibles in the ash was about 5% for both coal and RDF. Secondary air (excess air) supplied was increased by the RDF pneumatic feeders and the additional overfire air required to burn RDF. The increase in excess air required to burn RDF reduced the boiler thermal efficiency. The general consensus among the boiler operators was that more combustion air through the grate was necessary when firing RDF to prevent slagging and to maintain a proper fire bed.

Ultimate fouling occurred in the super-heater section of one boiler. Calculation of the fuel fouling index correlates with this behavior. The most significant influence is the higher sodium content of RDF, which has a detrimental effect on the fouling index. Soot blowers would reduce this fouling, as might an alternate method of RDF injection.

At most boiler loads, bottom ash tended to increase somewhat and fly ash tended to decrease with increasing percent RDF.

Ash fusion temperatures of RDF are typically 60° to 110° C lower than for coal, but no specific correlation of boiler performance to ash fusion temperatures has been determined.

Boiler Corrosion Studies--

Examinations by metallography, microbe, and chemical analysis were conducted of waterwall tubes, superheater tubes and their scales, and deposits. Results show that during exposure to firing of a mixture of 50% coal and 50% solid waste for a period of 1,018 hr., the corrosion of the waterwall tubes was virtually zero. Corrosion of superheater tubes, if any, did not exceed approximately 0.025 mm. The scale on the superheater tube contained up to 12% to 18% sulfur. Whether this amount which is present along with other elements constitutes a potential for catastrophic corrosion is not known.

Chlorine in both waterwall and superheater tube scales is present in amounts below the limit of detection of the analytical method used (600 ppm), and it is thought to constitute a significant factor in tube corrosion.

FIRING OF COAL:d-RDF BLENDS IN SPREADER STOKER-FIRED BOILERS AT HAGERSTOWN, MARYLAND

Introduction

After experience was gained with the cofiring of RDF and coal, little information was available on the production and burning of d-RDF. EPA therefore implemented parallel programs to (1) determine to economics of preparing d-RDF, and (2) assess the technical and environmental implications of using d-RDF as a coal substitute. The first part of the program involved the three projects described earlier: Grants to NCRR and the University of California to study the production and use of d-RDF, and a contract with Teledyne National to produce 2000 tons of d-RDF and provide information on production. The second part of the program involved a contract with Systems Technology Corporation (SYSTECH) to conduct a comprehensive technical and environmental test program for coal:d-RDF cofiring. The first phase of The SYSTECH program was a feasibility study with demonstration tests carried out at the Maryland Correctional Institute for Men (MCI), at Hagerstown, Maryland. The second phase was a longer-term demonstration test in an industrial sized boiler at the General Electric plant in Erie, Pennsylvania.

The MCI plant of Hagerstown had three small institutional heating boilers that produced 3.1, 7.6, and 9.9 kg/sec. (25,000, 60,000, and 75,000 lb/hr) of 1034 kPa (150 psi) saturated steam.

The test was designed to combust 258.5 Mg (285 tons) of d-RDF during 236 hours of firing various blend ratios of coal:d-RDF. These tests were conducted in a series of burns with coal:d-RDF volume ratios of 1:1, 1:2, and 0:1, and with test durations ranging from 20 min. to 132 hr. The cofiring tests were preceded and followed by a coal only test with duplicate conditions. Because of plant steam demand, the tests were designed to ensure that d-RDF could be safely burned without jeopardizing the boiler's ability to meet the steam demand.

d-RDF characterization

The (1/2-to 3/4-in.) pellets had an average bulk density of 425 kg/m^3 (26.5 lb/ft^3) and ranged from 400 to 466 kg/m^3 (25 to 29 lb/ft^3). The material density for intact pellets ranged from 1.22 to 1.34 x 10^3 kg/m^3 (76 to 84 lb/ft^3), and that for deteriorated pellets averaged 0.98 x 10^3 kg/m^3 (61 lb/ft^3). The as received properties were 12.10 to 15.12 MJ/kg (5200 to 6500 BTU/lb), 20% to 29% ash, 9% to 10% fixed carbon, 12% to 13% moisture, 50% to 57% volatiles, and 1142°to 1152°C (2088° to 2105°F) hemispheric reducing fusion temperatures. NCRR, who produced and supplied the pellets, projected that further processing of the shredded refuse to remove glass and other inerts could produce a pellet with a heat content of 19.1 MJ/kg (8200 BTU/lb) and an ash content of 10% to 12%.

Material Handling

Throughout the field testing, 259 Mg (285 tons) of d-RDF was received, stored, and conveyed to the boilers without major difficulty or malfunction of the fuel handling system. Difficulties were limited to dusting and pellet hang up in the feed hoppers.

Pellet Storage--

During successive periods, the pellets were stored in (20-yd^3) open containers, in a warehouse (uncovered), and on an outdoor concrete slab (tarpaulin-covered).

Pellets stored in the open containers tended to steam when received during the winter, and eventually they froze in a solid mass. But minimal rodding broke up the frozen pellets, and subsequent handling further restored the individual pellet integrity without significant degradation to the pellet.

Storage in an unheated warehouse was the most effective method for maintaining pellet integrity over extended storage periods (2 months). Mild odors and some fungus growth occurred, but temperature increases resulting from composting were negligible since pile depth was limited to 1.8 m (6-ft). Pile temperature stabilized at 60° C (140°F).

The tarpaulin-covered pellets stored in a 1.8-m (6-ft) piles on an open concrete slab accumulated moisture under the cover and caused pellets at the top to deteriorate and cake. Swelling and roughed edges also occurred in some pellets because of water infiltration.

Pellet Feeding--

Coal and d-RDF were volumetrically blended in various ratios by separately feeding coal and pellets from two hoppers to a common bucket elevator, which subsequently conveyed the mixture to a weigh lorry. This feed system worked well generally, but as the fines increased from excessive handling, the pellets would not flow from feed hoppers without rodding. The considerable dusting caused by these fines throughout the plant was subsequently controlled by installing a steam jet at the conveyor transfer point.

Boiler Performance

Feeder Performance--

The (1/2- by 3/4-in.) pellets generally handled and fed well, with the larger pellets traveling to the rear of the grate and the fines falling close to the spreader. During the initial combustion tests with 100 percent pellets, the spreader had to be adjusted to decrease the pellet trajectory by approximately 0.3 m (12 in.). In addition, because of volumetric feeding capacity limitations, the maximum load that the boiler could carry was 24,500 kg/hr (54,000 lb/hr), or 70% of rating.

Combustion of d-RDF--

The combustion of the various blends of coal and d-RDF was generally as good as that of coal only. But the length, intensity, and volume of the fireball grew as the proportion of of the d-RDF was increased. Flame temperature (1.5 m) above the center of the grate also increased from 1200°C (2192°F) for 100% coal firing to 1240°C (2264°F) for 100% d-RDF.

When the 1:1 blend and 100% d-RDF were test fired, the fireball was kept well away from the rear wall of the furnace by adjusting the overfire air. Once these jets were adjusted for minimum smoke and maximum efficiency for coal-only burning, they continued to meet the mixing and wall protection requirements when either blends or 100% pellets were burned. As viewed from the side of the furnace when firing both pellets and blends, the bed was well burned out by the time it approached the front ash pit. The flame pattern above the grate indicated that the fuel bed was maintaining proper porosity with minimum clinkering or agglomeration. This operation was achieved when burning a double-screened coal with a high ash fusion temperature (1370°C, or 2498°F). A 10% to 12% carbon dioxide content in the flue gas at the boiler outlet was readily obtained with little attempt to optimize the system.

Fouling--

After the tests, a light coating of ash was observed on the tubes, and a third of the rear wall of the boiler was covered with slag. The slagging was subsequently eliminated when a spreader was adjusted to prevent pellet impingement on the rear wall. Subsequent inspections of the boiler after being on line for 8 days revealed that the slag had sloughed off.

Clinkering--

The use of coal with a low ash fusion temperature (1204°C, or 2200°F) caused frequent clinkering on the grate during initial tests. The clinkering stopped when the coal was replaced with one having a higher fusion temperature (1373°C, or 2500°F). However, no clinkering was experienced with the firing of 100% pellets, which had a low ash fusion temperature of 1151°C (2103°F). This observation is valid within the constraints of the test conditions (a 4-hr test burn at 30% of rated boiler design capacity and 100% to 130% excess air).

Corrosion--

Eight clamp-on corrosion test specimens were installed on the supply tubes of the rear screen wall 1.5 m (5 ft.) above the fuel bed. After 478 hr. of exposure to firings of various blends and of coal-only, normal wastage (less than 5 mils per year) was evident on all specimens except one. This test specimen, which had extremely high metal wastage, was mounted in the area where the heavy slagging occurred because of the maladjusted spreader.

Boiler Operation--

Air Flow Controllers--During periods of load shedding, the fuel bed was more susceptible to clinkering when coal:d-RDF blends were fired. The clinkering was eliminated by biasing the underfire air control to supply approximately 70 percent excess air to the fuel bed. On the basis of these results, boilers that are tight (minimum air leaks) should be capable of satisfactorily burning coal:d-RDF blends with 50 percent excess air.

Oscillating Grate Dwell-Shake--Throughout the test, the duration and amplitude of the grate shake pulse was adjusted to advance the fire line at the rear of the boiler approximately 15.2 cm (6 in.) per excitation. In all advances, the pulse frequency was the principal controlling variable. At 40% load, the frequency of the pulse decreased from 11 min. for 100% coal to 3 min. for 100% pellets. When a blend was fired, the pulse duration tended to increase because the bulk density of the blend ash was less than that of the coal ash.

Ash Handling--

Bottom Ash--The sieve analysis of bottom ash samples taken during blend firings indicated that conventional pneumatic ash handling systems should be able to handle the bottom ash from blend firings as well as that from the firing of coal-only. On a few occasions, fire occurred in the bottom ash hopper during blend firing. Rodding of the clinkers in the ash hopper revealed that the ash had a taffy-like consistency. Under similar conditions, when coal only was fired, the bottom ash was much easier to break up by rodding.

The bottom ash removal system malfunctioned only during 100% pellet firing. The bottom ash was so fine that it would not de-entrain properly in the cyclone. The particles, which had been wetted by the steam in the vacuum ejector, passed through the cyclone and eventually plugged the ejector.

Dust Collector Ash--As a greater proportion of d-RDF was substituted for coal, the fly ash particles became finer. The size of the particles in the dust collector ranged from 200 μm for 100% coal firing to 90 μm (sizes at the 50th percentile) for 100% pellet firing. Also, the carbon content of the fly ash decreased significantly with increasing d-RDF substitution.

Mass and Energy Balance--

Mass Balance--The mass balance indicated that an unusually large amount of the fuel ash had accumulated in the collectors. Subsequent analysis of the collector fly ash revealed that the high collector ash weights were due to the presence of 50% to 70% carbon in the collector ash. Also, since 90% of the particles existing from the boiler were greater than 50 μm in diameter, these large particles were removed by the cyclone. The carbon content of the stack fly ash (not captured by the cyclone) was 30% to 40%. Analysis of the stack fly ash as a function of blend revealed that its carbon content decreased as the d-RDF substitution increased.

Efficiencies--During the testing the boiler efficiencies were extremely low (55% to 60%) primarily because of the low boiler loads (less than 30% of rating), high excess air (80% to 115%), and extremely high losses of combustibles in the refuse (up to 25%). Results indicated that the coal-only and blend firing efficiencies had no discernable differences. However, this observation may be unique to the boiler installation at MCI, since the large amount of unburned combustibles removed by the collectors is certainly an anomally to expected boiler performance.

Environmental Performance

Data Normalization--Since the co-firing tests spanned a 6-month period, the properties of the coal and d-RDF burned in the successive tests varied considerably. To eliminate the effects of these variables, all the emissions data were corrected to 50 percent excess air and then normalized to a reference coal and d-RDF composition. All the co-firing emissions data were then statistically compared with a coal-only baselines plot of emissions concentration versus boiler load. If the co-firing emissions data fell outside the 90% confidence limits for the coal-only emissions data, they were considered to be significantly different.

Particulate Emissions--

Mass Concentration--The particulate mass concentration in the 1:1 and 1:2 blend firings was slightly less than in the coal-only firing, but the reductions were not significant at the 90% confidence level. The mass flux at a 40% boiler load for 1:1 and 1:2 blend firings averaged 0.45 g/scm corrected to 12% CO_2. The coal fired during these tests was a nominal size of (1 1/4 x 1/4 in.), with a maximum of 30% passing through a nominal (1/4-in.) screen.

Particulate Size--As more d-RDF was substituted for coal, the particulate diameter decreased. In the May test, the diameters for the coal-only firings were 3 μm, and those for the d-RDF-only firings were 0.8 μm (at the 50th percentile point).

Particulate Resistivity--Because of the unusually high carbon content in the fly ash during the coal-only firing, the resistivity was generally less than 10^8 ohm-cm. As d-RDF was substituted for coal, the carbon burnout in the fly ash improved, and the resistivity increased to 2×10^{10} ohm-cm for the 1:1 blend firing.

Opacity--As d-RDF was substituted for coal, the overall opacity of the plume reduced significantly. At 40% boiler load, the opacity for coal-only firing was 16% (based on a 1.22-m-(4 ft) diameter stack). At the same boiler load and excess air, the opacity was only 10% for d-RDF-only firing.

Gaseous Emissions--

SO_2--Since the d-RDF had a sulfur content of 0.4%, the SO_2 emissions decreased with increasing d-RDF substitution. The decrease was particularly significant for the 1:2 coal:d-RDF blend and the 100% d-RDF firings. At 40% boiler load and the same excess air levels, the SO_2 dropped from 1300 ppm for coal-only firing to 250 ppm for d-RDF-only firing. This reduction in SO_2 follows exactly the reduction in sulfur content of the fuel.

NO_x--No significant changes occurred in NO_x as d-RDF was substituted for coal. At 40% boiler load and the same excess air levels, the NO_x concentrations ranged from 200 to 350 ppm with either fuel.

Chlorine--As d-RDF was substituted for coal, the chlorine in the emissions increased from 60 ppm for coal-only firing to 650 ppm for d-RDF-only firing. There appeared to be no appreciable change in chlorine concentrations as the load changed from 70 to 50% of design capacity.

Fluorine--Fluorine concentrations also increased with increasing d-RDF substitution, but the concentrations were very low (e.g., 8 ppm for coal-only firing and 12 ppm for d-RDF-only firing at a 40% boiler load and constant excess air conditions).

Hydrocarbons--No significant changes occurred in hydrocarbon emissions when substituting d-RDF for coal. At a 40% boiler load, the toal hydrocarbons ranged from 10 to 25 ppm. As the boiler load increased, the hydrocarbon concentrations decreased significantly. This reduction is probably attributable to the improved combustion conditions at higher boiler loads.

Trace Organic and Inorganic Emissions--

Organic Emissions--The overall emissions of polycyclic compounds for coal-only and blend firings were well below the threshold limits proposed by the National Academy of Science.[3] Typical measured values were 543 ng/m^3 for anthracene/phenanthrene, 100 ng/m^3 for methyl anthracene, and 137 ng/m^3 for fluoranthene (all at 1:1 blend firing).

Inorganic Emissions--Fly ash analysis for trace metals revealed that relative to coal-only firing, the blend firing enriched some metal but reduced others. For examples, when a blend of 1:2 coal: d-RDF was fired, compared the amount of lead in the stack particulates was 8217 µg/m^3, with 230 µg/m^3 for coal-only firing. Though d-RDF was the main contributor of Br, Mn, Pb, and Sb, coal was the primary source of As, Ni, and V.

Several elements, particularly As, Ga, Na, and Sb, tended to concentrate in small particles. In addition, as the d-RDF substitution increased, both the solubility of the fly ash and the quantity of small particulates in the respiratory range increased. Consequently, each of these effects pose potential hazards from (1) respiration of heavy metals associated with aerosols, and (2) leaching of high levels of heavy metals in landfills.

Conclusions

While the test was limited to firing at reduced boiler loads, the preliminary results from these field tests indicate that coal and d-RDF can be co-fired at volumetric coal:d-RDF ratios up to 1:2 with only minor adjustments to the boiler and fuel handling systems. Subsequent testing should address the long-term effects of corrosion and erosion on boiler tubes.

FIRING OF COAL:d-RDF BLENDS IN AN INDUSTRIAL SPREADER STOKER BOILER IN ERIE, PENNSYLVANIA

Introduction

Earlier field tests (Hagerstown and others) involving the co-firing of coal and d-RDF blends were typically of short duration and were performed under less then desirable boiler operating conditions and specifications. The objectives of demonstration tests conducted under EPA contract to SYSTECH at the General Electric plant at Erie, Pennsylvania, were to provide longer-term cofiring tests in a boiler representative of those used throughout industry. Sufficient testing was to be done to determine (1) whether or not d-RDF has any detrimental effects on the boiler system or its performance, and (2) whether it can be burned within existing environmental constraints.

The test program was designed to determine the technical and environmental effects of cofiring d-RDF and coal in an industrial power plant. To determine these effects, a (150,000 lb/hr) steam generator equipped with a chain grate spreader stoker was instrumented to monitor efficiency and emissions. The demonstration consisted of four distinct tests: (1) an initial coal baseline test, (2) cofiring of coal and d-RDF using pellets from NCRR, (3) cofiring of coal and d-RDF using pellets from Teledyne National, and (4) a final coal baseline test. Portions of the last two tests were conducted without fly ash reinjection. Throughout each test, fuel handling, boiler performance, and the stack emissions were monitored and evaluated.

Fuel Characteristics

Five different coals were used during the blend firing and coal baseline tests. Their sulfur contents ranged from 1.7% to 6.8%, and ash contents ranged from 9.5% to 18.2% (dry weight basis). Two different d-RDF's were tested. Both were formed as (1/2-in) diameter cylindrical pellets. The pellet produced by NCRR contained over 30% ash and had a heating value of 6,755 BTU/lb on a dry weight basis. The pellet produced by Teledyne National contained 14 percent ash and had a dry weight heating value of 8,123 BTU/lb. Moisture contents of the d-RDF ranged from 14% to 34%, and bulk densities ranged between 30 and 35 lb/ft^3.

To ensure an adequate supply of pelletized d-RDF, EPA contracted with Teledyne National and NCRR to produce and ship pellets by truck to Erie. Ultimately, 1702 tons of pellets (1256 tons by Teledyne and 446 tons from NCRR) were produced and shipped to Erie. Because of difficulties encountered in the production of the pellets, this quantity was approximately 800 to 1000 tons less than anticipated.

Boiler Performance

At a 1:2 coal:d-RDF volumetric blend ratio, a 2% to 3% reduction in boiler efficiency was experienced because of the increased flue gas moisture formed during d-RDF combustion. When firing was done at full load with coal:d-RDF blends, the combustion volume. Puffs of flame were observed in the screen tube section. This increased flame activity is directly associated with the higher volatile content of d-RDF as compared with coal. No significant increases in hydrocarbons or carbon monoxide were detected in the flue gas, however. Uniform flame distribution across the fuel bed was easily achievable when firing both types of d-RDF. Though NCRR pellets had a tendency to clinker, the lower-ash Teledyne pellets did not show this tendency.

When d-RDF was burned, an increase of slag accumulation occurred on the lower furnace walls. Boiler operators observed, however, that this slag accumulation was easier to remove than coal slag. Small globules of slag were also observed on the screen tubes, but they did not accumulate. Short-term corrosion testing, performed by soaking metal specimens in heated slag samples, indicated that no corrosion problems should be caused by the slag. Fouling was not observed to be a problem during this test.

Since the test boiler was designed with approximately 20% excess capacity, no derating was experienced from the combustion of d-RDF. Calculations show that combustion of 100% d-RDF requires less forced draft fan capacity, 5% more induced draft fan capacity, and 3 1/2 times the volumetric fuel feed capacity of coal. Grate speed was increased by about 25% when combusting a 1:2 (coal: d-RDF) volumetric blend.

Material Handling

The d-RDF was stored up to 6 months at Erie, Pennsylvania in an open coal yard through winter and spring weather. The piles of d-RDF formed a protective crust (6 to 8-in) thick. While in storage, the pellets increased in moisture and fines content. Also, the aged pellets expanded and formed serrated edges that subsequently created handling problems. While being conveyed to the bunker, the d-RDF blended thoroughly with the coal. But the low bulk density, high elasticity, and fibrous shape of the deteriorating pellets required constant rodding for them to flow out of the conveyor feed hopper. In the bunker, the coal/d-RDF blend would "rat hole" and demonstrate angles of repose in excess of 90°. Bunker vibrators and air blasters did not eliminate the need to manually rod the fuel blend into the nonsegrating distribution chutes feeding out of the bunker.

Compared with coal, the d-RDF blends required more frequent ash removal because of the increased ash content and decreased heating value of the fuel. Except for the manual removal of the infrequent clinkers, no ash handling problems were noted with the pneumatic ash handling system.

Environmental

The combustion of d-RDF blends exhibited the same range of particulate emissions as the burning coal only. Though NCRR blends caused decreased particulate size, firing the Teledyne blends resulted in increased particulate size when compared with coal only. The ESP performance was unchanged by the substitution of d-RDF for coal. However, d-RDF raised the fly ash resistivity to 10^8 ohm-cm resistivity of the coal-only fly ash. Pb emissions increased by a factor of six. Cd, Zn, and Cr, emissions increased 50% to 100% when firing d-RDF.

The substitution of d-RDF for coal had no significant effect on NO_x, CO, or hydrocarbon emissions. But as expected, d-RDF caused a 30% to 50% decrease in SO_x emissions and a 250% increase in chloride emissions.

Fly ash reinjection from the multicyclones was found to have no effect on the mass rate or size distribution of particulates at the ESP inlet when d-RDF blends were fired. Fly ash reinjection was found to decrease particulate size when firing coal only.

Conclusions

Coal/d-RDF blends can be combusted in an existing spreader boiler at the same excess air levels as coal only. No derating of the boiler was caused by the d-RDF substitution, and the decrease in boiler efficiency was minimal. With a low-ash d-RDF, no operational problems (clinkering) were experienced. No adverse impacts were measured on the plant emissions as a result of firing d-RDF. Materials handling problems were experienced with the existing coal handling equipment, but such problems had not been observed in earlier tests. They may therefore be due only to the aged and weathered condition of the d-RDF.

Further study is warranted on the long-term corrosion and erosion effects of d-RDF combustion.

SELECTIVE ENHANCEMENT OF RDF FUELS

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ABSTRACT

Conversion of the organic fraction of municipal solid waste to a powdered fuel offers a number of advantages for improving both the quality and marketability of the product. Cellulose embrittlement processes have been developed to convert the organic fraction of MSW to a powder. This project concentrated on improving the embrittlement process developed in an earlier study and characterizing the properties of the powdered fuel obtained. Over 363 kg. (800 lb) of powdered fuel were processed for characterization studies. The processing procedures used for converting the RDF from the Americology plant in Milwaukee is described. In the initial phase of this project, the physical, chemical and thermal properties of the powdered fuel were evaluated. Particle size distribution, morphology and density were measured. Proximate, ultimate and ash analysis were determined and TGA, DTA and heat content were established. In the second phase of this project, the combustion characteristics of the powder alone and mixed with powdered coal and oil were extensively evaluated. This work was conducted in fulfillment of Grant No. R-806535010 by the University of Dayton Research Institute under the sponsorship of the U.S. Environmental Protection Agency.

INTRODUCTION

The primary purpose of this study was to develop effective processes to convert the organic fraction in MSW to a powder. The processes for converting the organic fraction in MSW to a powdered material offer a number of advantages for improving both the quality and marketability of refuse derived products. In the powdered form the refuse is a more effective fuel, can be used as a filler material in plastic and rubber products and can be used as a feedstock in several biomass conversion processes (acid hydrolysis, pyrolysis, etc.).

This study concentrated on improving the embrittlement process developed in an earlier study(1) and better characterizing the properties of the powder obtained from embrittling RDF from the Americology Plant in Milwaukee. Over 363 kg (800 lb) of RDF were processed and the combustion characteristics of RDF powder, powder/coal and powder/oil mixtures were extensively investigated.

POWDER PREPARATION

A major emphasis of this project was the production of large quantities of powder from RDF for combustion analysis. About 453.6 kg (1000 lb) of RDF were obtained from the Americology Resource Recovery Plant in Milwaukee, Wisconsin to be used as the feedstock for the embrittlement treatments. During the course of the project some 363 kg (800 lb) of RDF were processed in the UDRI Pilot Reactor Unit for the production of 252 kg (555 lb) of minus 149μ (100 mesh) powder for testing and evaluation.

Batches of 2.3 kg (5 lb) of the

RDF were embrittled in the reactor unit at a treatment temperature of 149°C (300°F) using a 72 percent hydrogen chloride, 28 percent nitrogen reactant gas mixture for treatment times of 3-5 min. The embrittled RDF was ball milled for two hours and then screened in a sieve stack for one hour. A tabulation of the powder preparation conditions is presented in Table 1. The reactor unit built by the University of Dayton Research Institute (UDRI) is shown in Figures 1 and 2.

POWDER CHARACTERIZATION

Samples of the powder produced were obtained throughout the program for chemical, physical, and thermal analysis. In addition, samples were sent to the Commercial Testing and Engineering Company and Battelle Columbus Laboratory for analysis of selected chemical and thermal properties.

Physical and Chemical Analysis

Particle size distribution, moisture content, morphology and density of the powder samples were measured using a RoTap with quartered powder samples and the results are shown in Table 2. The data presented include the moisture content measured for each size fraction. All of the data reported represent the average values calculated from five or more measurements.

Using a scanning electron microscope, the morphology of the minus 149μ and 74μ (100 and 200 mesh) powder were studied. Representative electron micrographs are shown in Figures 3 and 4.

The density of the loose powder, lightly compacted, and compressed was also measured. The loose density of the minus 149μ (-100 mesh) RDF powder was measured by filling a 50 ml graduated glass cylinder with powder to a defined volume and then weighing the cylinder contents. The cylinder was then gently tapped to remove air gaps, more powder was added to maintain the same volume and the new weight determined. The compressed density of the powder was determined by pressing 1.5 g (0.053 oz) of powder in a cylindrical die with a hydraulic press to 1.55 x 10^6 kg/m^2 (220 psig). Using this procedure, several 1.27 cm x 1.27 cm (0.5 in. x 0.5 in.) cylindrical pellets were made and the average density of the pellets were measured. The results of the density measurements are reported in Table 3. The data show that a 400 percent increase in density was obtained when loosely packed powder was compressed to a pellet.

Chemical properties of the powder were measured at both the UDRI and the Commercial Testing and Engineering Company, Chicago, Illinois. Proximate and ultimate analysis, mineral analysis, and fusion temperature

TABLE 1. POWDER PROCESSING CONDITIONS

Quantity of RDF processed	2.3 kg (5 lb)
Processing temperature	149°C (300°F)
Processing time	3 - 5 min
HCl flow rate	439 cm^3/sec (0.93 ft^3/min)
N_2 flow rate	170 cm^3/sec (0.36 ft^3/min)
HCl adsorbed by RDF	2% by wt
Ball mill time	2 hr
Screening time	1 hr

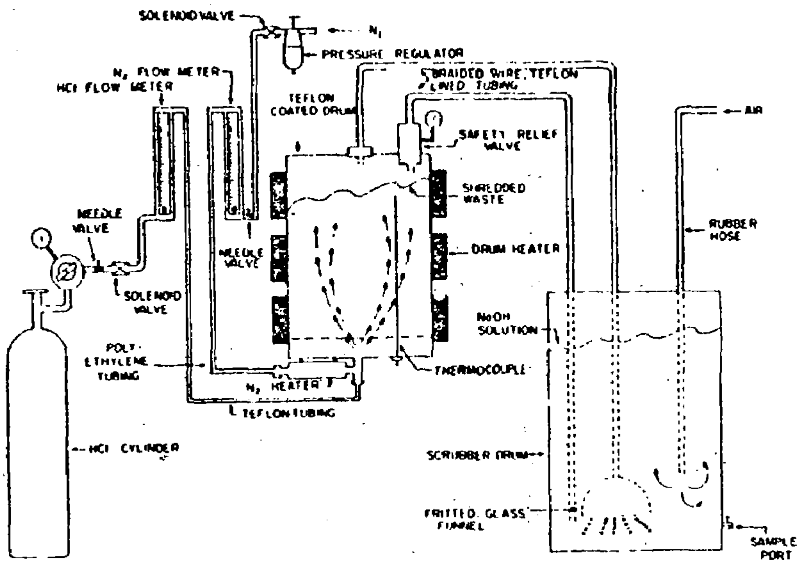

Figure 1. Process flow diagram for pilot reactor.

of the ash in the powder were measured by the Commercial Testing and Engineering Company and the results are presented in Tables 4 through 7. A number of ash analyses were also conducted by the UDRI on several different size fractions of powder using ASTM standard D271. The results obtained are presented in Table 8. As shown in Table 8 almost 40 percent of the minus 345μ (-45 mesh) powder from the ball mill is noncombustible. The higher ash content found in the minus 74μ (-200 mesh) fraction indicates that the finer fraction of the powder contains a greater fraction of inert materials believed to be predominantly glass particles.

Thermal Analysis

The heat content of the powder was measured at the UDRI and the Commercial Testing and Engineering Company. At the UDRI the heat content was measured using 1 gm (0.035 oz) samples in a Parr Adiabatic Bomb Calorimeter following ASTM D2015. The results obtained are presented in Table 9.

Thermogravimetric (TGA) and Differential Thermal Analysis (DTA) methods were used to further evaluate the thermal properties of the RDF powder. These studies were conducted by Battelle Columbus Laboratory. A summary of the data from the thermograms is presented in Table 10 along with comparative data for coal.

POWDER/OIL SLURRIES

Suspension of the RDF powder in a fuel oil offers a number of advantages for extending the commercial potential of the RDF powder. Powder/oil suspensions should be easier to transport and less subject to explosions. In addition, suspension of the powder in oil should facilitate introduction of the powder into conventional oil fired boiler and furnace units. During the course of this program two different techniques for preparing powder/oil slurries were investigated and selected properties of the slurries prepared were evaluated. The two methods were:

(a) gradual dispersal of minus 149µ (-100 mesh) powder in diesel oil by conventional blending procedures; and

(b) combined ball milling and mixing of the treated RDF with diesel oil.

Unfortunately, the slurries prepared by both methods did not display long term stability. Within 8 hours the powder was found to have completely settled out of the diesel oil. Dispersion agents were investigated for enhanced slurry stabilization. Slurries of 23 and 37 weight percent solids were prepared to evaluate settling characteristics, density, and viscosity.

Several 150 ml (40×10^{-3} gal)

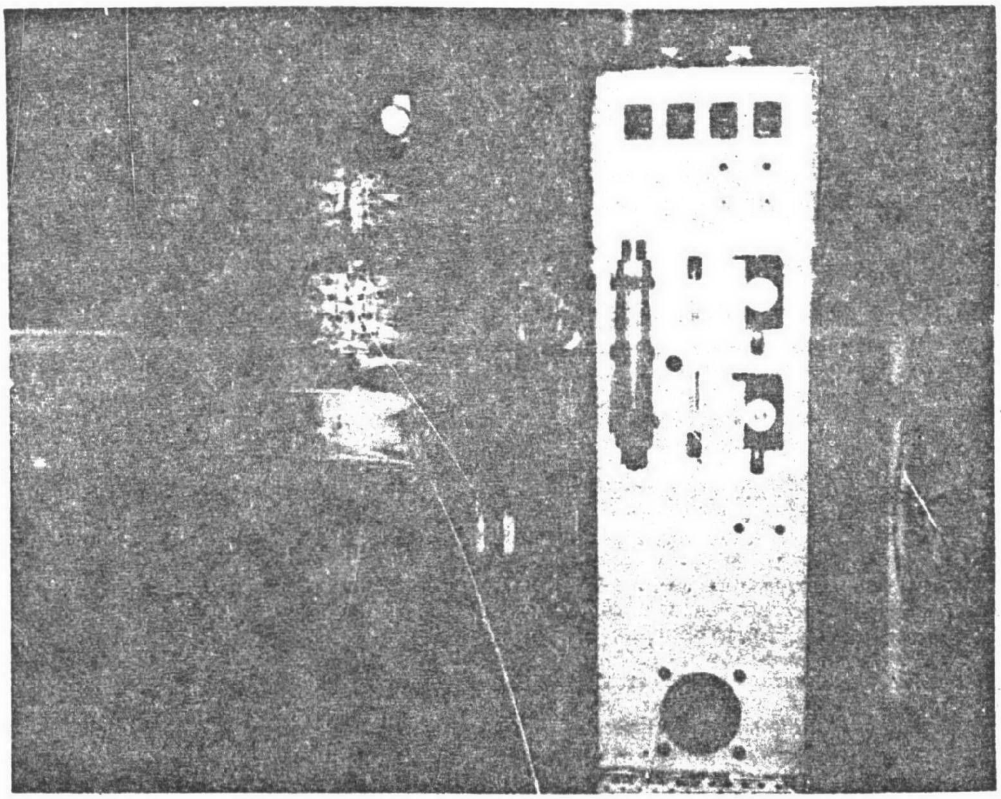

Figure 2. Pilot reactor.

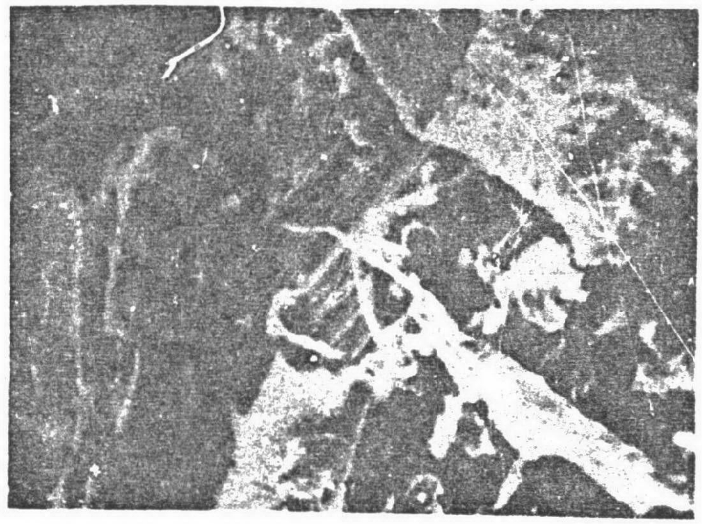

Figure 3. 149μ (100 mesh) material at 300X.

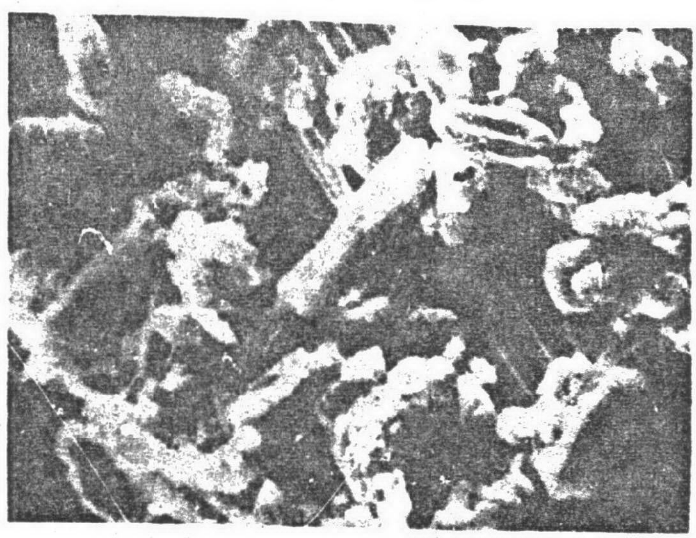

Figure 4. 74μ (200 mesh) material at 300X.

TABLE 2. PARTICLE SIZE DISTRIBUTION AND MOISTURE CONTENT OF POWDERED RDF

Particle Size μ (mesh)	Quantity %	Moisture %
+354 (+45)	18.1	5.86
-354 + 149 (-45+100)	12.5	6.54
-149 + 74 (-100+200)	31.1	5.91
-74 (-200)	38.3	5.03
	100	

TABLE 3. DENSITY OF MINUS 149μ (-100 Mesh) POWDER+

Condition	kg/m^3	(lb/ft^3)
Loosely packed	271	(16.9)
Compact	418	(26.1)
Compressed	1096	(68.4)

TABLE 4. PROXIMATE ANALYSIS+

Property	Powdered RDF (%)		Midwestern Coal (%)	
	As Recv'd	Dry Basis	As Recv'd	Dry Basis
Moisture	7.33	xxxxx	11.07	xxxxx
Ash	24.91	26.98	12.26	13.79
Volatile	51.83	55.93	34.96	39.31
Fixed Carbon	15.93	17.19	41.71	46.90
	100.00	100.00	100.00	100.00

TABLE 5. ULTIMATE ANALYSIS+

Property	Powdered RDF (%)		Midwestern Coal (%)	
	As Recv'd	Dry Basis	As Recv'd	Dry Basis
Moisture	7.33	xxxxx	11.07	xxxxx
Carbon	32.70	35.29	59.49	66.89
Hydrogen	4.30	4.64	4.15	4.67
Nitrogen	0.68	0.73	0.92	1.04
Chlorine	3.11	3.36	0.16	0.18
Sulfur	0.20	0.22	4.39	4.94
Ash	24.91	26.88	12.26	13.79
Oxygen	26.77	28.88	7.56	8.49
	100.00	100.00	100.00	100.00

+Data from Commercial Testing and Engineering Company

TABLE 6. FUSION TEMPERATURE OF ASH+

Property	Powdered RDF °C(°F)		Midwestern Coal °C(°F)	
	Reducing	Oxidizing	Reducing	Oxidizing
Initial Deformation	1065(1950)	1100(2010)	1093(2000)	1260(2300)
Softening Point	1218(2220)	1222(2230)	1182(2160)	1332(2430)
Hemispherical	1238(2260)	1250(2280)	1193(2180)	1343(2450)
Fluid, Temperature	1318(2400)	1360(2480)	1271(2320)	1432(2610)

TABLE 7. ASH ANALYSIS+

Mineral	Powdered RDF % Weight, Ignited	Midwestern Coal % Weight, Ignited
Silica, SiO_2	56.40	47.52
Alumina, Al_2O_3	9.55	17.87
Titania, TiO_2	1.10	0.78
Fernic, Oxide, Fe_2O_3	3.17	20.13
Lime, CaO	12.50	5.75
Magnesia, MgO	6.30	1.02
Potassium Oxide, K_2O	1.50	0.36
Sodium Oxide, Na_2O	6.88	1.77
Sulfur Trioxide, SO_3	1.92	--
Phos. Pent. P_2O_5	0.30	--
Undetermined	0.38	4.8
Silica Value	71.97	63.85
Base/Acid	0.45	0.44
T_{250}/Poises	1291°C (2355°F)	1299°C (2370°F)

TABLE 8. ASH DISTRIBUTION IN RDF POWDER*

Particle Size μ (mesh)	Quantity %	Ash %
+354 (+45)	18.1	-
-354 + 149 (-45 + 100)	12.5	35.1
-354 + 74 (-100 + 200)	31.1	37.5
-74 (-200)	38.3	43.6

+Commercial Testing and Engineering Company

*UDRI

TABLE 9. HEAT CONTENT OF RDF POWDER+

Particle Size μ (mesh)	Heat Content as Received Mj/kg (BTU/lb)	Heat Content Dry Mj/kg (BTU/lb)
-0.64cm (-1/4 in)	13,255 (5699)	13,428 (5773)
+354 - 0.64cm (+45 - 1/4 in)	14,883 (6399)	- -
+354 + 149 (-45 + 100)	13,632 (5861)	14,658 (6302)
-149 + 74 (-100 + 200)	13,132 (5646)	13,198 (5674)
-74 (-200)	13,060 (5615)	13,777 (5923)
Average -354μ (-45 Mesh)	13,274 (5707)	13,877 (5966)
Commercial Testing & Engineering Co. data	12,846 (5523)	13,863 (5960)

+measured at UDRI

slurry samples with 37 percent by weight powder were prepared. The slurries were prepared by gradually mixing 50 g (1.8 oz) of powder in 100 ml (26 x 10^{-3} gal) of diesel oil with a magnetic stirrer until uniform suspension was obtained. Slurries of minus 149μ (-100 mesh) and minus 74μ (-200 mesh) powder were prepared.

The blended slurries were placed in a hood and the sedimentation characteristics were observed. The sedimentation pattern for these slurries are analogous to zone settling where a zone is formed when rapidly settling coarser particles act as a group and collective settling occurs. When particle concentration reaches this point, a definite interface is formed between the settling particles and the fluid. For these initial evaluations the solid fluid interphase was recorded as a function of time and was used as the criterion to compare the stability of the different suspensions prepared. In an effort to obtain more stable suspensions, various dosages of the dispersing agent, Rheotol (manufactured by R. T. Vanderbilt) were added to the newly prepared slurry samples and the solid fluid interphase readings were recorded every four hours.

The results of these preliminary slurry stability tests are summarized in Table 11. From the results, it appears that powder/oil slurries of both minus 149μ (-100 mesh) and minus 74μ (-200 mesh) powder settled rapidly (4 hr) without any significant differences in the settling characteristics. However, addition of a dispersing agent, Rheotol (1 percent by volume) resulted in the stabilization of slurries with powder of both sizes. Greater stability was observed in the slurries prepared from the minus 74μ (-200 mesh) powder.

The apparent density and viscosity of powder/oil slurries were measured immediately after preparation and were compared with pure diesel oil. A Brookfield Viscometer (Model RVF 7) was used to measure the viscosities of the mixture and the pure diesel oil. Since the apparent viscosity of powder/oil mixture varies with shear rate, four determinations were made with number 1 spindle at 2, 4, 10, and 20 RPM. The average of the four determinations is reported in Table 12. The preliminary results in Table 12 show that the density and viscosity of the oil are increased significantly (as expected) when the powder is dispersed in the oil. It is interesting to note that the density of the freshly made 37% by weight powder/oil slurry is approximately the same as water and should have interesting transport and storage characteristics.

TABLE 10. THERMAL ANALYSIS OF POWDERED RDF[+]

	Thermogravimetric Analysis[a]	
Property	Powder RDF	Coal
Ash %	44.4[e]	10.3
Temperature Range[b] (°C)	130-380 (266°-716°F)	220-585 (428°-1085°F)
Maximum Rate of Weight Loss (mg/min)	37(81.6 x 10^{-6} lb/min)	17.5(38.6 x 10^{-6} lb/min)
Temperature at Maximum Rate of Weight Loss (°C)	290 (554°F)	320 (608°F)
	Differential Thermal Analysis[c]	
Starting Exotherm (°C)	222 (431°F)	233 (451°F)
Ignition Point (°C)	276 (529°F)	426 (799°F)
End of Ignition Exotherm (°C)	289 (552°F)	615 (1139°F)
Secondary Exotherms (°C)	379-433 (714°- 811°F)	-----
Endotherm (°C)	457 (855°F)	400-584 (752°- 1082°F)[d]

(a) TGA performed with Cahn Electrobalance at 15°C/min (59°F/min) and air flow of 800 ml/min (.0035 gal/sec)

(b) Temperature range over which most of wieght loss occurs

(c) DTA performed with Stone Model 202 at 15°C/min (59°F/min) and dynamic gas flow of 0.0057 m^3/hr (0.2 SCFH)

(d) Endotherm range in presence of N_2 gas. Three peaks in each range

(e) Residue measured after combustion in the test burner

[+]Battelle Columbus Laboratory

TABLE 11. PRELIMINARY EVALUATION OF OIL-POWDER SLURRY

Particle Size μ (mesh)	Quantity of Powder in Slurry Wt %	Quantity of Slurry/ ml ($X10^{-3}$ gal)	Quantity of Dispersing Agent/ml ($X10^{-3}$ gal)	Settling Time hr	Settling Depth/ ml ($X10^{-1}$ gal)
-149 (-100)	37	150 (40)	0	4	100 (26)
-149 (-100)	37	150 (40)	1.5 (.39)	4	25 (6.6)
-149 (-100)	37	150 (40)	1.5 (.39)	20	100 (26)
-74 (-200)	37	150 (40)	0 --	4	100 (26)
-74 (-200)	37	150 (40)	1.5 (.39)	4	15 (3.9)
-74 (-200)	37	150 (40)	1.5 (.39)	20	100 (26)

NOTE: Above screening was conducted in 250 ml (66 x 10^{-3} gal) beaker.

TABLE 12. DENSITY AND VISCOSITY OF OIL AND POWDER/OIL SLURRY [At 24°C (75°F) & 10,336 kg/m² (14.7 psia)]

	Diesel Oil	37% Powder/Oil Slurry
Density (ρ), g/cm³ (oz/in³)	0.84 (0.49)	1.01 (0.58)
Viscosity (μ), cp	10.62	32.00

NOTE: The Brookfield Viscometer Model #RVF7 with number 1 spindle was used for all viscosity measurements.

It should be noted that only preliminary slurry characterization studies have been conducted, and effective design of transportation and storage systems for the powder/oil slurry would require an extensive investigation of the flow and possible corrosion characteristics of the slurry.

INVESTIGATION OF THE BURNING CHARACTERISTICS OF THE POWDERED RDF COAL AND POWDER/OIL SLURRIES

In this part of the study the combustion characteristics of the RDF powder as a fuel was investigated. RDF powder, powdered coal,+ and two RDF-coal mixtures were fired in Battelle's small pulverized coal combustor units. The fuel feeder and combustion unit used in this study are shown in Figure 5. Fuel is fed to the combustor by lifting the small particles from the solid fuel surface with air jets and entraining them in a 0.64 cm (0.25 in.) O.D. tube, which leads to the burner head. With this arrangement, the combustor can burn pulverized coal at rates from 0.454 to 1.13 kg/hr (1 to 2.5 lb/hr) and can maintain maximum combustion temperatures approaching 1482°C (2700°F) for short periods of time and lower temperatures approaching [∿1371°C (∿2500°F)] for extended periods of time. The

+Illinois No. 6 Coal

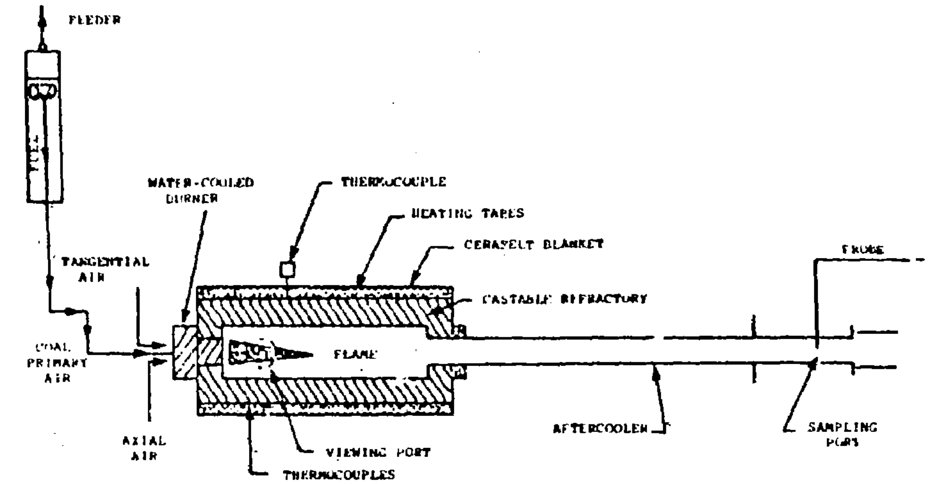

Figure 5. Combustion setup

dry pulverized coal is transported to the combustor from a feeder by primary air. This primary air comprises about 1/3 of the total air required. The remaining (secondary) air can be introduced axially and/or tangentially to the combustor to produce varying amounts of turbulence and to alter flame shape. Gas residence time in the combustor chamber ranges from about 0.7 to well over 1.0 sec depending on temperature conditions, fuel type, firing rate, and excess air level.

The fuels and fuel mixtures used in this study were as follows:

1. Illinois No. 6 coal⁺
2. RDF powder
3. 25 percent RDF; 75 percent coal (by weight)
4. 50 percent RDF; 50 percent coal (by weight)

The Illinois No. 6 coal was used as a reference coal. Six combustion runs were conducted with the various fuel combinations. A compilation of the combustion runs and the results obtained are presented in Table 13.

A slurry of RDF powder and distillate oil was fired in the Battelle 37 kw (50 hp) research boiler facility shown in Figure 6. This slurry was prepared without the use of a dispersant agent. The slurry burned satisfactorily although fuel pumping problems were experienced when the powder settled out of the distillate oil. The primary objective of these combustion tests was to demonstrate the feasibility of burning the RDF powder in an oil slurry.

In these experiments, RDF powder was co-fired with No. 2 fuel oil in a 37 kw (50 hp) fire-tube boiler with firing rates between 1.37 and 1.48 x 10^9 j/hr (1.3 and 1.4 x 10^6 BTU/hr). The slurry ignited easily and burned well. In order to feed the powder/oil mixture into the boiler without plugging the nozzle, a

⁺Illinois No. 6 Coal is a midwestern bituminous coal

TABLE 13. RESULTS OF THE COMBUSTOR EXPERIMENTS+

Run No.	Fuel Type	Feed Rate kg/hr (lb/hr)	Wall Temp.(a) Average °C(°F)	Approximate Residence Time in Furnace Sec.	PPM CO	PPM NO_x	PPM NO	% CO_2	% O_2	Wt % (in ash) [illegible]	Wt % (in ash) [illegible]
1	[illegible]	0.56 (1.2)	[illegible] (1735)	[illegible]	550	2900	550	13.0	6	11.2	0.3
2	[illegible] Powder	[illegible] (62)	[illegible] (1650)	[illegible]	100	[illegible]	150	14.4	9	8.1	0.3
2a	[illegible] water	[illegible] (72)	[illegible] (1600)	[illegible]	[illegible]	--	-	--	10.5	1.2	--
3	[illegible]	[illegible] (1)	[illegible] (1550)	[illegible]	550	2200	--	15.0	6	24.1	[illegible]
4	[illegible] water	[illegible]	[illegible] (1650)	[illegible]	[illegible]	2,000	--	[illegible]	[illegible]	11.9	[illegible]
5	[illegible] Powder	[illegible]	[illegible]	0.90	160	1500	--	[illegible]	5	4.0	0.2
6	[illegible]	1.36 (3)	[illegible]	[illegible]	[illegible]	1500	--	14.6	[illegible]	[illegible]	[illegible]

(a) [illegible] inside wall [illegible] wall temperature [illegible]

(b) [illegible] all other fuels [illegible]

(c) [illegible]

+Conducted at Battelle Columbus Laboratory

special, large bore oil nozzle was used in the boiler.+ The nozzle used is rated at approximately 136 kg/hr (300 lbs/hr). Four atomizing air jets [0.4 cm (0.0625 in) diameter] intersect the oil exit port at a 90° angle.

The nozzle that was used required in excess of 27 kg/hr (60 lbs/hr) atomizing air in order to ensure adequate fuel vaporization. Low air flows through the air jets 27 kg/hr (60 lbs/hr) give rise to high CO levels (650 PPM) and high smoke numbers (10+) even though adequate primary air is available for complete combustion.

Pumping and feeding of the powder/oil mixture proved to be the most difficult phase of the combustion studies. Conventional gear pumps would be likely to jam so a screw pump was used to feed the fuel mixture. This pump did not experience any pumping problems at the 15 percent powder concentration, but it did plug at powder concentrations above 15 percent. At the higher concentrations feed lines plugged and valves jammed.

Although there were no combustion problems experienced when firing the 30 percent powder/oil mixture, extended runs could not be sustained. The flame produced appeared to be a very bright yellow and was quite stable. This experiment lasted only 30 minutes because the fuel feed lines plugged and the tests could not be continued.

+RIPCO, South Charleston, West Virginia

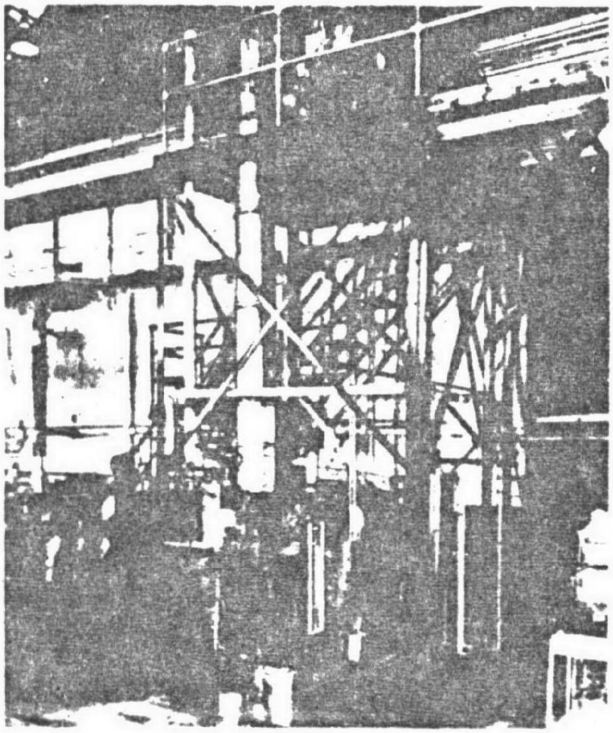

Figure 6. Battelle-Columbus Combustion Research Facility

Table 14 summarized the results of the combustion tests for the 15 percent by weight powder/oil mixture. Visual examination of the flame indicated good combustion with the generation of only a few "sparklers". Smoke numbers could not be determined with any degree of accuracy because of the presence of a yellowish tint to the soot. Apparently the combustion of the RDF powder somewhat "colored" the soot particles. This same phenomenon has been observed when firing residual oils containing trace metals. At excess air levels above 6 percent, CO levels were reasonably low. SO_2 and NO levels are consistent with predictions based on fuel analyses.

A particulate loading of 800 mg/Nm^3 was measured for the powder/oil mixture. This is relatively high compared to the levels normally recorded for residual oil (100 mg/Nm^3 and distillate oil 20 mg/Nm^3). Chemical analysis of the filter catch indicated that less than one percent of the particulate was unburned carbon. This result confirms the observation that the powder/oil slurry underwent complete combustion. These results also show that the high inorganic content of the RDF powder cause high particulate loading during combustion.

As noted earlier, the slurry with 30 percent powder burned well; however, sustained boiler operation could not be achieved because of fuel line and pump plugging problems. Table 15 summarizes the data for the 30-minute run.

Based on the limited tests conducted it appears that the RDF powder can be fired in slurry form.

TABLE 14. SUMMARY OF 15% RDF POWDER IN DISTILLATE OIL COMBUSTION EXPERIMENTS. [BOILER FEED RATE WAS 36 KG/HR (80 LB/HR)]

O_2% (dry)	CO_2% (dry)	CO PPM	NO PPM	SO_2 PPM	Particulate Loading Mg/Nm^3
8.4	9	20	125	55	--
6.0	10.4	55	120	60	--
5.3	10.7	211	125	65	--
6.5	10.2	25	112	60	800

TABLE 15. SUMMARY OF 30% RDF POWDER IN DISTILLATE OIL COMBUSTION EXPERIMENT

O_2% (dry)	CO_2% (dry)	CO PPM	NO PPM	SO_2 PPM
6.8	10.0	25	14[illegible]	70
5.8	11.0	235	140	75
6.2	10.5	85	140	65

However, the high inert content of the powder will cause significant particulate loading. In addition, a stabilizing agent is needed to maintain a homogeneous mixture of powder and oil to inhibit settling in the fuel handling system.

SUMMARY OF FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

During the course of this study, over 363 kg (800 lb) of RDF were processed by embrittlement treatment for conversion to a fine powder. The major objective of this project was the evaluation of the RDF powder as a fuel. The powder produced was characterized and its combustion performance with powdered coal and in an oil slurry were measured.

Powder Characterization

The powder obtained by the embrittlement of RDF consists primarily of short choppy fibers minus 150μ (-100 mesh) in size. Dispersed in the fibrous mix are irregular shaped inert materials (predominantly silicate glasses). The powder contained 5 to 7 1/2 percent moisture and 25 to 44 percent noncombustible material. The high quantity of noncombustibles (glass, metal and minerals) is a characteristic of the RDF prepared by Americology in Milwaukee and will vary considerably for different processes and for different areas of the country. From the proximate and ultimate analysis it was found that the powder contained about 52% volatiles, had a carbon content of 35%, and a chlorine content of 3%. The powder had a loose density of 271 kg/m^3 (16.9 lb/ft^3) and an average heat content of 13025 Mj/kg (5600 BTU/lb). If an RDF with lower inert content were used, a higher heat content would be obtained. The inert fraction of the powder was analyzed to be a calcium, magnesium, sodium, aluminum silicate low in iron. It had a fusion temperature above 1360°C (2480°F). Based on TG and DT analysis it is observed that the RDF powder is easily ignited (*ignition temperature*, 277°C (530°F)) and burns readily.

Compared to powdered coal the RDF powder has a lower ignition temperature, higher volatile content, much lower carbon content, about half the heat content, twice the ash content, one-tenth the sulfur, fifteen times the chlorine content and is four-tenths the density. As a fuel the RDF powder will ignite and burn more rapidly than coal, but it will generate less thermal energy. Combustion products will present about as much corrosion problems as coal (Cl versus S) but should present greater handling problems because of a lower density and high ash content.

Powder/Oil Slurries

Suspension of the RDF powder in a fuel oil offers a number of advantages for enhancing the use of the RDF powder as a fuel (easier transport and storage, greater safety, etc). The procedure for preparing powder/oil slurries and selected properties were evaluated.

The powdered RDF can be easily slurried in oil up to about 40 weight percent. The only problem encountered was the sedimentation of the powder within four hours. However, more stable suspensions (in excess of 20 hr) were obtained with small (1%) additions of a dispersion agent (Rhectol). As would be expected the density and viscosity of the powder/oil slurry is considerably higher than the pure fuel oil ($\rho \sim 1\ g/cm^3$, μ = 32.00 cp). The stabilized slurry does not appear to present transport and handling difficulties, however, long term experience with these fuel mixtures will be required.

RDF Powder and RDF Powder/Coal Mixtures

The RDF powder and RDF powder/coal mixtures were fired in a pulverized coal test combustor. The RDF powder and mixtures of 25 and 50 weight percent RDF powder with coal were studied. Although some handling problems were encountered with the RDF powder due to its lower density and heat content, the RDF powder/coal mixtures (particularly the 50/50 blend) handled very well and all the compositions tested burned well. In addition to its good handling characteristics the 50/50 blend proved to be the most effective fuel mix studied. The lower ignition temperature and higher quantity of volatiles in the RDF aided the combustion of the coal.

More complete combustion is also achieved in the coal when it is mixed with the RDF powder. The very low sulfur and alkali content of the RDF powder effectively reduced SO_2 in the combustion gas emissions. However, the high chlorine content in the RDF powder may cause corrosion problems and some environmental concerns. The use of a less corrosive embrittling agent (e.g., HNO_3, H_3PO_4, O_3, H_2O_2, etc), if effective, could reduce or eliminate this problem.

RDF Powder/Oil Slurries

The RDF powder/oil slurries with up to 30 weight percent RDF burned well in the test furnace. However, above 15 weight percent there were a number of problems encountered in transporting the slurry. Plugging of the pump and feed lines due to powder sedimentation was the primary problem encountered during the combustion tests. The use of a dispersion agent should alleviate this problem. The combustion of the powder/oil slurries *produced considerably* more ash than is obtained when the oil is burned alone. This causes considerable handling problems since the conventional oil burning units are not designed to process large quantities of ash. The ash content of the RDF powder is likely to be the limiting factor for determining the RDF powder to oil ratio for slurry preparation.

Conclusions

An effective procedure for converting RDF to a fine powder by embrittlement treatment has been developed. The RDF powder appears to be an effective fuel compatible with coal and some oil burning equipment. Although the RDF powder can be burned alone or in combination with coal and oil, its best performance was in a mix with pulverized coal. The most promising application for the RDF powder is in a 50/50 mix with pulverized coal. This fuel mixture burns well (better than either component) and results in lower SO_2 emissions.

The major difficulties with the use of the RDF powder as a fuel is the high inert content (ash) and the potential problems from the high chlorine content. The use of screening and other classification processing of the raw refuse should result in a significant reduction of the inert content and the use of different embrittlement reagents (HNO_3, H_3PO_4, etc.) should eliminate potential corrosion and environmental problems. However, selection of effective unit processing procedures to reduce inert content and selection of a less corrosive embrittlement agent will require additional research studies.

During the course of the work conducted on this project a number of observations have been made pertaining to the effectiveness of the technology, the potential applications of the technology and the areas needing further development. In this work a technology for converting refuse to a fine powder has been established based on the use of cellulose embrittlement techniques. However, the mechanisms of the process are not completely understood and need further elucidation. The identification of effective alternative embrittlement reagents, particularly reagents that would not leave residues which could be corrosive or detrimental in other ways is also needed.

The RDF powder proved to be an effective fuel when used in a 50/50 (by weight percent) mix with pulverized coal. The RDF powder provided considerable enhancement for combustion of the coal. However, more needs to be known about the handling (transport, storage, etc.) behavior of both the RDF powder and the powder in a 50/50 mix with pulverized coal. In addition, more needs to be known about the emissions from combustion of RDF/coal mixtures.

It would appear that a variety of biomass materials, particularly cellulose wastes from industrial and agricultural sources (stalks, husks, bark, wood and crop residue, straw, etc.) could also be converted to a powder for use as a fuel or as a feedstock for biomass conversions. However, more work is needed to develop effective processing procedures for powdering the variety of biomass materials which might be available for conversion to a powdered fuel.

Based on these observations the following recommendations for future work are proposed: (1) further elucidation of the embrittlement mechanisms; (2) identification of alternate embrittlement reagents; (3) further characterization of the RDF powder mixed with pulverized coal: and (4) extension of the embrittlement process to other biomass materials.

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ASSESSMENT OF EPA's CELLULOSIC WASTE CONVERSION PROGRAM

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ABSTRACT

Energy may be obtained from municipal refuse by a number of processes, including direct combustion, cofiring with coal, pyrolysis, catalytic reduction or hydrogasification, acid hydrolysis, and bioconversion. The U. S. Environmental Protection Agency (EPA) has supported research in these areas, but no single energy extraction process is a panacea. In the early stages of EPA's resource recovery program, considerable emphasis was placed on the use of microorganisms to convert cellulose into protein and chemicals. Research the last 5 years has focused on the development of cellulose-to-glucose acid hydrolysis technology for alcohol and chemicals production. This report summarizes research aimed at the recycling of cellulosic waste and discusses recent advances in acid hydrolysis technology.

INTRODUCTION

An estimate 122 million metric tons of solid waste are generated each year from homes and commercial establishments (1). A study completed in January 1979 (2) projected that gross solid waste discards would total 142 million metric tons in 1980. Converting the organic fraction (70% to 80%) of solid waste to fuel could provide energy equal to approximately 2% to 3% of the Nation's requirements. In the future, however, technology for using cellulose as a feedstock for chemicals, fuel, and food production may be of even greater importance than direct combustion processes.

Energy may be obtained from municipal refuse by a number of processes, including direct combustion, cofiring with coal, pyrolysis, catalytic reduction or hydrogasification, acid hydrolysis, and bioconversion. No single process is a panacea, however. For example, direct combustion to produce steam requires a nearby customer for this product. Cofiring with coal has few applications on the West Coast, where boilers are most often oil- or gas-fired. Furthermore, the substantial moisture content of municipal wastes reduces the efficiency of pyrolytic processes. Additional environmental hazards may also be produced by waste incineration (e.g., increased lead emissions in cofiring waste and coal).

Interest persists in biochemical waste conversion processes for these reasons and because the processes offer alternative products such as methane, ethyl alcohol, and chemical feedstocks.

For approximately 10 years, EPA has supported research on the development of processes for recycling large amounts of cellulose. Considerable research has been focused on the identification and development of promising cellulose conversion technology that could make an impact on the growing problem of municipal waste disposal. A review of some of these EPA-supported investigations follows.

Microbial Protein Production Studies

At Bay St. Louis, Mississippi, Callihan (3) designed, constructed, and operated a chemical-microbial pilot plant to produce microbial protein from cellulosic waste. This project was directed to determine the technical and economic optimization of the pilot plant (3).

More basic knowledge of the theory and technique of cellulose fermentation was sought. Areas of investigation included (a) means to improve substrate treatment to enhance fermentation rates, (b) increased cell productivity, and (c) improved cell harvesting techniques. The cellulolytic bacteria used in the study were mixed cultures of Alcaligenes faecalis and Cellulomonas. A microbial cell concentration of 12 g/liter and rates of cell synthesis of 1 g/liter pr hr were achieved in each batch and occasionally in continuous fermentation operations. A 55% protein product was produced with an amino acid profile that compared favorably with other protein sources.

In another study, Leatherwood (4) studied the use of anaerobic bacteria to ferment cellulosic wastes; strains of a cellulolytic organism isolated from bovine rumen were evaluated. Products identified included volatile fatty acids, soluble carbohydrates, and microbial cells as a potentially useful protein.

Undegraff (5) investigated the conversion of waste paper to a protein supplement for use as livestock feed. Only one of the fungi evaluated, Aspergillus fumigatus, was capable of attacking purified cellulose, ballmilled newspaper and newsprint.

Both the Leatherwood and Undegraff studies were discontinued because of the slow rates of cellulose-to-protein conversion by test microorganisms.

Pretreatment Processes

Physical and chemical processes designed to enhance the digestion of waste cellulose during fermentation processes were studied both in-house (6) and by other workers through EPA grants and contracts. The processes investigated are described briefly.

Sensitized Photodegradation

A 1967 patent of Schwartz and Rader (7) revealed that polysaccharides such as starch and cellulosic materials can be converted to saccharides of lower molecular weight by irradiating them with light rich in frequencies near 335 nm when the material is in the presence of a water soluble metal or a nitrogen-based salt of nitrous or hyponitric acid. On the basis of this information, Frohnsdorff and

TABLE 1. RESULTS OF A. FUMIGATUS GROWTH TESTS ON MATERIAL FROM WASHED AND DRIED FILTER CAKES

Sample Number	Amount of Solka-floc (g)	Amount of $NaNO_2$ (%;ml)	Irradiation[a] time (hr)	Additives	DP	Protein[b] (%)
U-182	10	0;100	19	1ml acid[c]	336	9.8
V-183	10	1;100	19	2ml acid	160	8.7
W-187	10	0;100	19	2ml acid	328	10.5
X-188	10	1;100	19	3ml acid	149	9.1
Y-198	10	1;100	19	O_2	284	11.9
Z-200	10	1;100	19	PO_2;2#ml acid	222	10.3
AA-2	10	1;100	19	N_2	393	9.9
AB-3	10	1;100	19	N_2;2#ml acid	296	8.8
AC-5	10	1;100	19[d]	—	808	11.3
AD-6	10	1;100	6[d]	—	884	11.1
AE-7	4	1;148	1	—	811	10.2
AF-7	4	1;148	0.5	—	840	10.5
AG-8	10	0;100	4[d]	—	945	11.4
AH-9	4	0;0			5	11.3

[a]Sixteen lamps; 2537 A.

[b]Following 48 hr incubation. Samples autoclaved before innoculation with fungi.

[c]In all cases the acid was IN H_2SO_4.

[d]Stirred only; no irradiation.

Fookson (8) investigated the technical and economic feasibility of using the sensitized photodegradation process to enhance the use of waste cellulose in recycling processes.

When 2.7%, 200 mesh cellulosic slurries were irradiated in a 1% sodium nitrate solution of 2537 Angstrom, the degree of polymerization (DP) was reduced from 1000 to 800 in less than 2 hr, and finally to 125 after 48 hr. The number of scissions calculated from the DP also increased linearly.

Table 1 presents the growth response of Aspergillus fumigatus on irradiated cellulose under various conditions. Based on protein yields, there appears to be no relationship between the DP and the digestion of cellulose by this fungus. These findings were contrary to expected results. Further tests with other Fungi confirmed the findings observed with A. fumigatus.

Microwave

Johnson (9) reported that slurries with starch contents as high as 75% could be hydrolyzed to sugars and other decomposition products with microwave energy at 180° to 200°C. To enhance the biodegradation, cellulose was treated with microwave energy as follows:

Twenty milliliters of a 1% cellulose suspension in water was placed in each of several Pyrex tubes with 3/4-in. O.D. and 1/8-in. walls. These tubes were frozen, sealed under vacuum, and then treated for various lengths of time in a 2450-megahertz microwave oven. During a period of 25- to 30-min, temperatures rose above 200°C and pressures above 400 psi were attained. As a measure of cellulose modification, the filtered, treated solution was tested for the presence of soluble sugars. A 1% cellulose suspension in 2% hydrochloric acid was also subjected to microwave treatment. After the liquid was analyzed for sugar concentration, the remaining cellulose was washed, dried, and subjected to enzymolysis. Sugar produced by cellulose action was taken as a measure of cellulose structure modification by microwave treatment. Under these experimental conditions, microwave energy did not improve enzymatic degradation of cellulose (Table 2).

Laser Treatment

Klein (10) demonstrated that lignosulfonate could be photomodified to improve biological availability of this material. Biological responses were measured by assays of substrate carbon before and after growth, by fungal dry weights, and by the presence of bacterial populations relative to substrate photolysis treatment time.

The energy source used for lignosulfonate modification was a medium-pressure, 500-watt, type A mercury vapor lamp, model #6?3A-36. The power source was a #20651-1 transformer (Hanovia Company, Newark, NJ).[2] A Hanovia double-wall immersion well (model #194??) contained the lamp and allowed the coolant water to circulate. A Pyrex reaction vessel was designed to fit externally to the immersion well.

A 1% W/V cellulose slurry (200-mesh Solka-floc) in tap water was irradiated for

TABLE 2. EFFECT OF MICROWAVE ENERGY ON THE SUSCEPTIBILITY OF CELLULOSE TO DEGRADATION BY ENZYMES[a]

	Glucose produced at various enzyme reaction times			
	1.5 hr	3.0 hr	4.5 hr	6.0 hr
Control (unheated cellulose)	55.5	53.5	57.0	63.0
Cellulose heated 25 min in water	47.0	47.5	49.5	63.5
Cellulose heated 30 min in water	44.5	47.0	53.5	57.0

[a]Cellulose (0.32 g) was suspended in 25-ml buffer (pH 4.0) and was incubated at 40°C. After incubation, the enzyme was inhibited by heating to 80°C for 10 min.

1, 2, 16, and 20 hr with an air flow of approximately 200 ml/per mixture.

When these laser-treated samples were tested for increased rates of biological growth response, all showed a marked improvement over the control.

Alkali

Cellulosic substrates were subjected to an alkali-oxidation treatment (11). The treatment sequence was designed to swell the cellulose structure, break up the lignin physical structure, and modify the cellulose into shorter molecular chains. One gram of each alkali-treated cellulose was tested to determine the biodegradation rate and compare it with that of untreated cellulose. All samples showed modestly improved rates of biodegradation over the control (6).

High-Temperature Hydrolysis

A high-temperature, stirred chemical reactor constructed of Type 316 stainless steel was used to study the effects of high-temperature hydrolysis on the biodegradation rates of cellulose. This treatment process was designed to remove some crystallinity and to provide some readily fermentable sugars so the initial growth of the molds would be accelerated. Theoretically, 10% fermentable sugars could be liberated under the conditions used. The 1% cellulose suspension in the reactor was removed and adjusted to pH 5. Biodegradation rates were then compared with that of untreated cellulose. The treated samples were less susceptible to biodegradation when compared with controls (6).

Electron Irradiation

In an experiment designed to determine whether irradiated cellulose was more susceptible to degradation than untreated cellulose, two polyethylene bags (one containing 10.0 of 40-mesh ground cellulose, and the other containing 10.0 of 100-mesh ground cellulose) were irradiated for 1 and 2 hr, rspectively. A dynamic electron source (Dynamatron, NASA Lewis Laboratory, Cleveland, Ohio), provided an exposure of 10^8 rad/hr. The irradiated samples were then used in biodegradation studies and compared with nonirradiated cellulose samples of the same mesh sizes (6).

Evaluation of Pretreatment Processes

The degradation of untreated pure and waste cellulosic substrates was compared with that of cellulosic substrates previously treated by alkali oxidation, high-temperature hydrolysis, electron radiation, and the nitrite photochemical process (8). The medium for these studies contained 1 each of NH_4Cl, K_2HPO_4, KH_2PO_4, $MgSO_4$, $CaCl_2$, and yeast extract, and 40 mg of thiamine combined with steril water to a final volume of 1 liter. This mineral salt medium was adjusted to pH 5, and 100-ml portions were placed in 500-ml shaker flasks, each containing 1 g of cellulose. The flasks were autoclaved at 121°C for 15 min. After cooling, the medium was inoculated with selected fungi, incubated at 35°C in an environmental room on a reciprocal shaker for 4 days, and observed for the disappearance of cellulose and the growth of the fungal mass. The inocula for these experiments were obtained from 48-hr fungal cultures grown in a mineral salt medium containing glucose, cellobiose, and cellulose in 0.1% concentrations. The dry weight of each inoculum was approximately 10% of the weight of the substrate (6). Samples were taken after 4 days of incubation and analyzed for their protein value based on the content of amino acids.

The amino acid contents of peanuts, soybean meal and cellulolytic fungi grown on cellulose are reported in Table 3. These data confirm that fungi can produce protein containing complements of essential amino acid from cellulosic waste. The improvement, identification, and development of new, more effective pretreatment processes will be required, however, if cellulose-protein conversion is to become a technical and economically feasible reality.

Hydrolysis of Cellulose

Acid Hydrolysis

Porteous (12) proposed a new technique for waste disposal that would use both agricultural and municipal wastes as raw materials. This proposal consisted of hydrolyzing the cellulosic wastes to sugars.

Fagan et al (13) explored this concept in detail. The kinetics for hydrolysis of cellulose in paper were experimentally determined over a range of 180° to 240°C with

TABLE 3. AMINO ACID CONTENT OF SELECTED FUNGI, PEANUT MEALS, AND SOYBEAN MEAL
(gram amino acid/100 grams protein)

Amino acid	*A. fumigatus* No. 3	*A. fumigatus* No. 6	*Penicillium* sp. No. 7	*Trichoderma viride* No. 9	*Chaetomium* sp. No. 10	*Geotrichum candidum* No. 11	Peanut meal[a]	Soybean meal[b]	FAO ref.[c]
Alanine	5.90	5.60	5.90	5.10	6.60	6.00	4.2	3.30	
Arginine	3.70	3.80	7.80	4.00	8.20	6.70	10.6	7.30	
Aspartic acid	8.80	8.30	8.90	7.70	10.70	6.40	15.1	3.70	
Cystine, half		0.40					1.60	1.9	1.2
Glutamic acid	11.00	12.30	13.30	9.90	11.70	11.30	17.40	18.40	
Glycine	5.30	3.80	5.70	5.90	5.60	4.20	5.00	4.00	
Histidine	2.20	1.90	3.30	1.60	4.70	3.20	2.10	2.90	
Isoleucine	7.30	7.20	4.50	4.00	5.60	3.90	4.00	6.00	4.2
Leucine	8.80	10.90	5.70	5.10	6.60	6.70	6.70	8.00	4.8
Lysine	4.40	5.60	5.70	4.40	5.60	5.30	3.00	6.80	4.2
Methionine	7.30	6.50	1.10	2.00		2.70	1.00	1.70	2.2
Phenylalanine	6.10	5.30	4.70	5.50	6.10	7.40	5.10	5.30	2.8
Proline	2.90	3.40	3.60	3.70	2.80	3.20	5.20	5.00	
Serine	5.50	4.10	4.50	2.60	4.20	5.00	6.60	4.20	
Threonine	7.00	4.40	5.60	4.40	4.80	7.40	1.60	3.90	2.8
Tryptophan									1.4
Tyrosine	3.90	3.00	6.10	3.70	4.20	4.20	4.40	4.0	2.8
Valine	2.60	5.30	6.10	4.80	6.60	12.40	4.40	5.3	4.2

[a] Block and Bolling (1951).
[b] *Chemical and Engineering News* (1967).
[c] Food and Agriculture Organization (1957).

0.2% to 1.0% acid in a batch reactor. The sugar solution obtained from refuse hydrolysis can be concentrated to 12% with the use of a multi-effect evaporator, and it can be used in commercial fermentation processes.

This hydrolysis study further indicated that development of continuous acid hydrolysis technology is needed to convert large tonnages of cellulose to a readily fermentable product for use in the production of fuels, foods, and chemicals.

Continuous Acid Hydrolysis

The EPA-supported experimental investigations of the dilute acid hydrolysis of waste cellulose to a glucose have been ongoing at the Department of Applied Science of New York University (NYU) over the past 5 years (14). The waste cellulose feedstock employed in these studies was primarily used newsprint.

Initially, the hydrolysis experiments NYU were carried out in a 1-liter stirred autoclave equipped with appropriate accessories, including electrical heating units and a quick-discharge ball valve for removing the reaction mixture from the autoclave after acid hydrolysis. The data obtained with the 1-liter stirred autoclave reactor experiments were analyzed to determine the glucose yield at various reaction conditions. This work was followed by additional testing in a 5-liter stirred autoclave reactor.

The batch-scale hydrolysis experiments showed that glucose yields up to 50% more of the charged available cellulose values could be obtained. The optimum reaction conditions were found to be temperatures of 220° to 230°C and reaction times of less than 30 seconds, with about 1% of sulfuric acid by weight. These conditions agree rather well with the results of the kinetic rate studies previously reported by Fagan et al (13).

The NYU work includes investigation of continuous processing technology for industrial-scale conversion of waste cellulose to glucose. From this part of the study emerged a continuous waste-cellulose-to-glucose pilot plant with a capacity of 1 ton per day. This pilot plant utilized waste paper and sawdust as cellulose feedstock, and a reactor device for continuously reacting cellulose at suitable elevated temperatures.

The Werner & Pfleiderer ZDSD53 (53-mm) twin-screw extruder was selected because of its capacity for conveying, mixing, and extruding the required amounts of cellulosic feedstock. This machine allows accurate control of temperature during intensive mixing.

For continuous processing, the extruder must be coupled with a feeding mechanism for cellulose slurries and a discharge system for reacted materials while maintaining pressure and temperature in the reaction zone. A steam-jacketed crammer-feeder made by Werner & Pfleiderer was integrated with the twin-screw extruder to maximize throughput with preheating as required. An intensive-service 2-in. ball valve (Kamyr Valve Company, Glens Falls, New York) was selected as the major component for the design of the discharge system. Other ancillary equipment includes a high-pressure steam generator for supplying energy to the reactor, an acid pump capable of high-pressure injection, and a slurry pump for introducing feedstock into the crammer-feeder.

The continuous acid hydrolysis optimization studies are continuing. Even though the study has achieved a 50% conversion of cellulose to glucose, further experiments are underway to optimize reaction conditions for maximum glucose yields.

Two-Stage Hydrolysis System

A proposed two-stage hydrolysis system development based on the NYU work (Figure 1) would consist of two extruder reactors -- one operated at 336°F for pentosan hydrolysis, and the second operated at 450°F for hexosan hydrolysis. The pentosan is hydrolyzed at lower temperature and lower acid concentration than hexosan. The feedstock is hydrolyzed in the first-stage reactor and discharged into slurry tank that connects the two hydrolyzers. The feed material containing the hydrolyzed pentosan and unhydrolyzed cellulose is mixed with water in the slurry tank and pumped into the second reactor. The pentoses are recovered by the action of the twin screws at the dewatering drain, and the cellulose (free of pentosan) is conveyed through the second unit and hydrolyzed to glucose. The prehydrolysis of pentosan is expected to improve further the 50% to 60% cellulose-glucose yields now being achieved with the 1-ton/day unit.

In the past, little or no consideration was given to recovering pentoses. Acid hydrolysis reactor development studies focused primarily on converting hexosan to glucose. Data on chemical analyses of agricultural residues and wood (Table 4) revealed that pentosan constitutes up to 29.5% of some agricultural residues (15). The

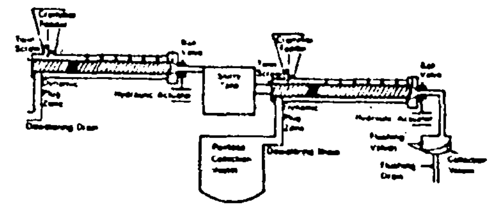

Figure 1 Two Stage Pentosan-Hexosan Hydrolysis System

pentosan fraction is important because it has been demonstrated that both pentoses and hexoses can be fermented to ethanol by yeast (14). If maximum feedstock utilization is to be achieved, acid hydrolysis technology must be developed to recover both the five- and six-carbon sugars efficiently.

Yield Projections

Investigators have used diluted and concentrated sulfuric acid in two stages to yield 95% conversion of pentosans to xylose and 90% conversion of hexosan to glucose (15). Optimization of the two-extruder process is expected to achieve up to 95% conversion of pentosan to xylose and 80% recovery of the sugar. With the removal of pentosan by prehydrolysis, we further expect to achieve values greater than 60% conversion of celluose to glucose.

The combined two-stage process has the advantage of (a) having a design potential for recovering up to 100% more sugars than the single-stage process, (b) reducing degradation products of pentose that are discharged as a glucose mixture, and (c) suppressing glucose fermentation.

Table 4 presents sugar yields that could be expected if the two-stage extruder reactor were optimized to recover 80%

TABLE 4 - CHEMICAL ANALYSES OF AGRICULTURAL RESIDUES AND WOOD

MATERIAL	PENTOSE %	HEXOSE %	LIGNIN %
Corn Stover	[illegible]	21.6	15.0
Corn Cobs	22.5	21.9	10.4
Wheat Straw	15.2	23.4	14.0
Rice Straw	13.6	23.6	10.0
Oats Hulls	29.6	[illegible]	[illegible]
Bagasse	16.3	26.8	19.9
Pine	5.9	31.4	26.6
Oak	15.7	26.9	24.8

pentose and 60% glucose from agricultural residues and wood.

In the United States, an estimated 271 million metric tons of agricultural residues from food production are unused (14). If this tonnage were used to produce ethyl alcohol, a considerable savings in corn could be achieved. At projected rates of gasoline consumption, 10 billion gal of ethanol will be needed by 1990 to achieve universal use of gasohol.

To calculate the amount of sugar available from the unused 271 million metric tons of agricultural wastes, consider the following. Total sugar potentially recoverable from the acid hydrolysis of agricultural residues ranged from 31.1% to 44.4% (Table 5). Thus, if we assume only a 30% sugar recovery from the hydrolysis of agricultural residues, 271 million metric tons of waste would yield 81.3 million metric tons of sugar.

In the project of alcohol yields, it is assumed that 15 lb of waste-recovered sugar (as opposed to approximately 14 lb of corn-recovered sugar) are required to produce 1 gal of alcohol. Ethyl alcohol yields from 271 million metric tons of agricultural residues are therefore calculated are follows:

271 million metric tons x 30% =
81.3 million metric tons of sugar

Gallons of ethyl alcohol

$$= \frac{81.3 \text{ million metric tons} \times 2{,}000}{15 \text{ pounds of sugars}}$$

$$= 6.0 \times 10^6 \times 2.0 \times 10^3 \text{ of alcohol}$$

$$= 12.0 \times 10^9 \text{ gal}$$

Thus ethyl alcohol requirements for gasohol can be theoretically produced from unused waste agricultural residues.

TABLE 5 - PERCENT RECOVERABLE SUGARS FROM AGRICULTURAL RESIDUES AND WOOD

MATERIAL	PENTOSE %	HEXOSE %	TOTAL SUGAR %
Corn Stover	12.0	21.0	33.0
Corn Cobs	22.5	21.9	44.4
Wheat Straw	15.7	23.4	38.6
Rice Straw	[illegible]	22.4	[illegible]
Oats Hulls	21.6	20.2	43.0
Bagasse	16.3	24.8	31.1
Pine	5.9	31.4	37.3
Oak	15.7	26.9	42.6

The corn equivalency is 4.4 billion bushels of corn: Divide the projected alcohol yield from agricultural residues (12 billion gallons) by the number of gallons of 190° proof alcohol derived from 1 bushel of corn (2.7). In 1979, about 7.8 billion bushels of corn were grown in this country.

Developing and implementing hydrolysis technology could contribute greatly to meeting our energy requirements by saving the energy needed to cultivate an addditional 119 million hectares of grain for the 10 billion gal of ethanol. Savings would also be effected on fertilizers and chemicals, and a more efficient use of total crop would be provided. Considering the potential of hydrolysis technology, it is incumbent that nothing less than a national effort be committed to the development and widespread implementation of this technology.

Conclusions

The widespread use of grain to produce alcohol as automobile fuel will likely cause a surge in food prices. It, therefore, appears that Alcohol produced from grain is not, therefore, likely to be cost competitive with gasoline derived from oil. The key to using ethyl alcohol as a gasoline extender depends on a technological development that provides for the conversion of cellulosic materials into simple sugars for alcohol production. Currently, research is under way to optimize hydrolysis conditions with the extruder reactor for maximum glucose yield.

The prospects for developing pretreatment technology to improve direct conversion of cellulosic materials by microbes into a protein product is not encouraging. Conversely, two-stage acid hydrolysis technology allows conversion of municipal and agricultural wastes into simple five and six carbon fermentable sugars. Complete development of acid hydrolysis is a preprequisite to production of chemicals, foods, and fuels from waste.

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ADVANCES IN THE RECOVERY AND UTILIZATION OF LANDFILL GAS

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ABSTRACT

Natural decomposition processes within a landfill produce gas consisting primarily of methane and carbon dioxide. The generation of this gas within a landfill poses many potential problems due to migration through the surrounding soils. In order to control migration, collection systems have been installed. The gas collected from the systems had traditionally been flared. Now, however, methane gas generated in landfills is being efficiently collected, processed, and used as a source of energy. Eight utilization systems are currently on-line, with several others scheduled for start-up within 1981.

INTRODUCTION

The amount of recoverable energy available from landfill gas is unknown; however, it appears that approximately 100-200 billion cubic feet of raw landfill gas is produced each year from disposal of municipal solid waste. While this is a very small amount in terms of U. S. natural gas needs, landfill gas can play a significant role in meeting industrial and utility energy requirements when considered on a case-by-case basis.

PRODUCTION

Decomposition - The Basic Process

The process of landfill gas formation is mainly an anaerobic process, not unlike that of a sewage sludge digester. Aerobic digestion takes place initially because large quantities of air are entrained in the waste during placement. The oxygen is quickly consumed and the process becomes anaerobic shortly after refuse placement.

Anaerobic refuse decomposition is a continuous process that stabilizes the organic wastes and results in the production of methane. The organic material, such as leaves, paper, and food waste, is used as food for the acid-forming bacteria. This organic material is then changed by the bacteria to simple organic material, mainly organic acids. Methane-forming bacteria then use these organic acids as food and produce carbon dioxide and methane gas.

When the waste stabilization process proceeds normally, approximately 40 to 60 percent of the gas produced will be methane. The remainder will primarily be carbon dioxide.

Methane formers grow quite slowly compared to acid formers since they obtain very little energy from their food. This results in the methane formers being very sensitive to slight changes in the environmental factors. The acid formers are rapid growers and are not so sensitive to environmental conditions. Thus the production of landfill gas is largely dependent upon maintaining optimum conditions for the methane-forming bacteria.

Environmental Factors Affecting The Decomposition Process

Unfortunately, the landfill decomposition process is different from a sewage sludge digestion process because critical environmental factors (temperature, pH, and moisture) cannot be easily controlled.

Temperature control is a key factor for successful anaerobic stabilization of organic matter because sudden temperature changes greater than two degrees centigrade will result in losing the buffering capacity and possibly incapacitating the digester. The temperature should also be controlled in the range of 29 to 37 degrees centigrade so that the optimum gas production may be achieved. Although the temperature in the landfill cannot be controlled, it has been determined that the internal temperature of many landfills falls within the optimum temperature range for gas production. It has also been observed that the core temperature of deeper landfills is not affected by diurnal temperature fluctuations.

The moisture content required for optimum anaerobic decomposition has been reported to be greater than 60 percent. This, again, often occurs in landfill situation, although many landfills with far lower percentages of moisture have been found to produce large quantities of gas. Moisture addition at landfills has been proposed to enhance gas production.

The optimal operating range for pH is from 6.8 to 7.2. Many landfills report lower pH levels but still produce significant quantities of gas. It is believed that the pH within a landfill does not fall below 6.2 when methane is produced.

The factor which is probably most critical to the landfill stabilization process, particularly when methane gas recovery is anticipated, is air infiltration. Whenever methane gas is removed from a landfill, there is a tendency for air infiltration due to leakage through the recovery wells and landfill surface. Air is toxic to the methane-forming bacteria and thus will stop the production of methane gas. Here the typical configuration (depth) of the landfill becomes an important factor because the oxygen in the infiltrating air is consumed in the upper portion of the landfill and does not hinder the anaerobic process at the bottom of the landfill. Depths greater than 100 feet are ideal for landfill gas recovery. Depths as low as 30 to 40 feet are suitable for gas recovery, but more control over minimizing air infiltration is needed.

RECOVERY

Control and Recovery Methods

In the last 10 years, landfill operators, owners, and engineers have become increasingly aware of the potential hazards caused by the methane components of landfill gas. Methane migrating through soils adjacent to the landfill has on occasion collected in nearby structures and ignited, resulting in structural damage, injuries, and even deaths. This has resulted in the technology for the collection and recovery of landfill gas.

Actual recovery of landfill gas for methane resulted from efforts to stop the migration of gas to adjacent properties. The first control methods used to prevent landfill gas migration were peripheral trenches filled with porous media or peripheral vent pipes which allowed gas to vent to the atmosphere. These control methods were found to be generally ineffective.

Recently, the technology has advanced to the point that most new control systems were power exhaust vent systems composed of wells and a header connected to an exhaust blower. This advance in the technology coupled with the impending natural gas shortage was the catalyst necessary to launch the landfill gas recovery industry.

In general, recovery of landfill gas for utilization employes one of the following two options. First, raw landfill gas can be used with minimum processing. Removal of moisture and some compression are necessary for initial upgrading. In this form, landfill gas can be used to generate electricity and fire boilers for space heating and industrial processes. The other option is carbon dioxide and, if necessary, nitrogen removal. This produces a gas which can be directly injected into an existing natural gas pipeline. These options are currently in operation at landfill methane recovery systems.

ON-LINE LANDFILL METHANE RECOVERY SYSTEMS

Mountain View Landfill, Mountain View, California

This is a demonstration project started in 1975 and jointly funded by Pacific Gas and Electric Company and U. S. Environmental Protection Agency. This facility recovers landfill gas from a 30 acre site by means of 33 wells. Since this is a shallow landfill (30' - 40' deep), a greater number of wells are necessary due to the lower rate per well. The gas is upgraded by compression and adsorption to remove water and carbon dioxide. The resultant 700 Btu/scf gas is then injected into a PG&E main transmission line.

Palos Verdes Landfill, Rolling Hills Estates, California

This is the first landfill methane recovery system. The plant is owned and operated by Getty Synthetic Fuels, Inc., and has been in operation since 1975. Severe corrosion problems experienced in the pretreater regeneration system adversely affected the system's operational reliability. A plant modification program was completed in 1976 and the system has operated reliably since January 1977. The product gas is sold to Southern California Gas Company and has a higher heating value of approximately 1,000 Btu/scf. In May 1979, further plant modification increased the capacity to two million cubic feet per day inlet capacity.

Azusa Landfill, Azusa, California

Since 1978 Azusa Land Reclamation Company, Inc. has been recovering and selling low Btu landfill gas to Reichhold Chemical Company. A well system consisting of 20 wells recovers 400,000 cubic feet per day of raw gas. After water removal and compression, the treated gas (500 - 520 Btu/scf) is transported via a 4,000' pipeline to Reichhold Chemical Company for use in their boilers. The concept of on-site electrical generation is being investigated.

Ascon Landfill, Wilmington, California

This system is owned and operated by Getty Synthetic Fuels, Inc. and represents an advancement over their Palos Verdes operation. This operation consists of dehydration and carbon dioxide removal to produce 4,000,000 cubic feet per day of pipeline quality gas at maximum capacity. The pipeline quality gas is sold to Southern California Gas Company for injection into their transmission line.

City of Industry Landfill, City of Industry, California

This system was designed by SCS Engineers to supply medium Btu gas as fuel for the boilers at the Industry Hills Convention Center. The system consists of dehydration and particulate removal to produce 500,000 cubic feet per day of treated gas.

Sheldon-Arleta Lan. .ll, Los Angeles, California

Completed in November of 1979, this project supplies low Btu gas to the Valley Generating Station for use as boiler fuel for the production of electricity. Fourteen recovery wells provide gas for the dehydration and compression system. A 1.8 mile 10-inch pipeline carries the gas to the generating station. At the power station, the landfill gas is used as a supplemental fuel supply during normal boiler operation. However, the landfill gas can also be used for ignition and boiler start-up when natural gas is not available.

Cinnaminson Landfill, Cinnaminson, New Jersey

Started in 1979; Public Service Electric and Gas Company of Newark, New Jersey, recovers raw landfill gas for the purpose of selling it untreated to a nearby sponge-iron factory owned by Hoeganaes Corporation. Initial quantity of gas delivered to the plant was 230,000 cubic feet per day. However, consumption has increased to 600,000 cubic feet per day with plans to deliver 1,000,000 cubic feet per day in the future.

Systems Nearing Completion

Getty Synthetic Fuels, Inc. is currently starting-up systems in Calumet City, Illinois, and the San Francisco Bay Area (San Leandro). Both of these systems are patterned after the Monterey Park Landfill recovery system.

Brooklyn Union Gas in conjunction with New York City Office of Resource Recovery and Waste Disposal and New York State ERDA will be conducting a one-year test on a landfill gas electricity-generating facility supplying 100 KW of electricity for on-site use.

In addition to the above projects, many studies are being conducted at various landfills to determine the technical and economic feasibility of recovery and utilization of landfill gas. These studies are concerned with the direct use of low and high Btu gas as well as the conversion to electricity.

ON-GOING RESEARCH

Corrosion Studies

Pacific Gas & Electric Company is currently conducting a study to determine the corrosion potential of landfill gas at the Mountain View Landfill. Corrosion problems were observed in the radiation cooling tubes prior to the injection of a corrosion inhibitor. Corrosion monitoring probes have been installed and this problem is currently being studied.

Industrial burner tests at the Fresh Kills Landfill have shown the recovered landfill gas to be a non-corrosive fuel for use in conventional natural gas designed equipment.

Controlled Landfill Process

Pacific Gas & Electric Company and Southern California Gas Company are conducting joint studies at the Mountain View Landfill concerning enhancing gas production and improving gas recovery. Initial studies have been performed and a field demonstration program is being developed. Factors such as moisture content, nutrient additions, buffering agents, and the effect of density on gas production will be investigated in the enhancement project. In the area of improving gas recovery, the effectiveness of different extraction systems and the effectiveness of different cover systems will be investigated.

Development of Models for Gas Production

Currently, one major problem involved in landfill gas utilization is the determination of production rates. Production rates determine the size of the landfill gas processing plant and are the guidelines for economic success. Presently, Dr. Charles Moore of Ohio State University is developing computer programs which will allow design engineers to assess the varying system parameters to optimize production.

Max Blanchet of Pacific Gas & Electric Company has also developed a model for predicting gas production over and beyond the operation life of the landfill by examining the various decomposition rates of the components of municipal refuse.

NEEDED RESEARCH

Gas Production

Further testing and development of models for gas production are needed. The need is not just for evaluation in conjunction with recovery systems, but also in conjunction with gas migration problems.

In reference to migration problems, there is a definite need for prediction of production rates over a time period for compliance with RCRA.

Pollution Aspect

There are generally two waste streams from landfill gas treatment technology. The first is a condensate from the dehydration process. The second is a low quality Btu blowdown stream from the carbon dioxide removal system. Currently, the condensate is recycled back to the landfill and the blowdown is vented to the atmosphere. Both of these waste streams should be further analyzed to determine their pollutional aspects.

Other Aspects

Further studies on corrosion including impurities in the pipeline need to be performed. Utilization of by-products, such as carbon dioxide, need to be further investigated, especially in the area of markets. Methods for reduction of air intrusion into the landfill also need further investigation, especially at shallow landfills.

In addition to the technological aspects, the following economic and institutional aspects need to be further investigated:

- o marketing difficulties
- o risk assessment
- o utility regulations

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The following is a list of contacts for the projects described in this paper.

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A REVIEW OF EPA-SUPPORTED RESEARCH ON PYROLYTIC OILS

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ABSTRACT

Summaries are given of two EPA-supported research projects to characterize pyrolytic oils. One project aims to separate pyrolytic oils into fractions that each contain a broad class of chemicals, and the other project is directed toward identifying the specific chemicals within those fractions. Separation (extraction) techniques show the greatest promise for processing the oil into the large fractions, and the distillation process appears to be the best method for processing an oil fraction into more highly refined and purified products.

INTRODUCTION

This report summarizes the results of two EPA-supported research projects on pyrolytic oils. One study was being conducted at Georgia Institute of Technology (EPA 600/2-28-122) to develop methods for the separation of pyrolytic oils into broad classes of chemicals (1), and the other is at Atlanta University (Grant #R804440-02) to identify specific chemicals that make up pyrolytic oils (2).

Large quantities of agricultural, forestry, and municipal wastes are produced each year in the United States. The proper utilization of these materials is extremely important if they are to become a resource rather than create disposal and environmental problems. Pyrolysis is one approach to using these materials that has received a great deal of attention in the past several years. Pyrolysis of lignocellulosic or cellulosic material produces char, pyrolytic oil, water-containing/water-soluble organic substances, and noncondensible gases. The char is primarily carbon that can be used as a fuel or converted to activated carbon. The major components of the noncondensible gases are hydrogen, carbon monoxide, and methane along with minor amounts of the other hydrocarbon gases. These gases can be used onsite as a clean burning, low-BTU, gaseous fuel. The pyrolytic oils are clean burning, with heating values that are approximately two-thirds of those for fuel oils. In addition to their value as fuels, these oils have great potential as a source of industrial chemicals or as a chemical feedstock. Such uses may have greater economic value than the use of these oils as fuels. Also, the use of pyrolytic oils as a source of chemicals would reduce the demand for the petroleum now used to make chemical feedstock. To realize the potential of pyrolytic oils as a source of chemicals, the processing technology must be developed to produce refined fractions of the oils.

Comparison of the Georgia Pyrolysis Process with the Original Wood Distillation Process

Pyrolysis is an old process that has been used industrially in the past on a batch basis to produce charcoal, pyroligneous liquor (mostly water with dissolved organic compounds), insoluble tars, and noncondensible gases. The process was used during and after World War I in this country, and it was known as wood distillation. With the use of petroleum as a chemical feedstock, however, the pyrolysis process became uneconomical and was discontinued. Various aspects of wood distillation and its products have been discussed in the literature (3, 4 and 5).

The distillation of wood was generally carried out as a batch process in a retort with external heat. The significant and important difference between the Georgia Institute of Technology pyrolysis process (1) and the old wood distillation process is that the Georgia process is self-sustained and continuous. The difference is significant because the pyrolytic oil produced in this manner from a given feed material under specific operating conditions is a reproducible product with definite physical and chemical properties. The product therefore has potential as a chemical feedstock for making other products on a commercial scale.

Potential Yield and Demand for Pyrolytic Oils

Pyrolytic oil from various wastes represents a potential feedstock for the chemical industry. Of all oil consumed in the United States, about 6% (or 50 million metric tons annually) is used to derive feedstock for the chemical industry (6). The yield of pyrolytic oil from lignocellulosic materials varies from 15% to 25%, depending on feed materials and operating conditions (7). Consequently, it would require 181 to 299 million metric tons of dry lignocellulosic material to supply pyrolitic oil in quantities comparable to the petroleum used by the chemical industry. This observation does not imply that pyrolytic oil would be processed in the same manner as petroleum feedstock or that 1 ton of pyrolytic oil is equivalent on a feedstock basis to 1 ton of petroleum.

Accurate estimates of wastes produced by different sources are difficult to obtain. Based on inquiries (particularly with the U.S. Forest Service), the amount of forestry waste in the United States is estimated to be 91 million metric dry tons annually (Heywood T. Taylor, Forest Service, Private Communication, June 1976). This quantity could yield pyrolytic oil tonnage equal to 33% to 50% of the petroleum tonnage now used by the chemical industry. The significance of these data is that the potential exists for pyrolytic oil from forestry wastes alone to make a significant contribution as a source of chemical feedstock. Anderson in 1972 (8) estimated that 1.1 billion barrels of oil potentially could be produced from the total organic wastes generated each year in the United States. Tillman (9) has recently reported that approximately 1 billion dry tons of cull or rough trees and salvable dead trees presently exist in the United States. The important fact is that large quantities of waste materials exist that have the potential of being converted to pyrolytic oils to help meet the Nation's energy needs.

Analysis and Characterization of Pyrolytic Oils

The chemical and physical properties of pyrolytic oils have been determined by standard analytical techniques. The oils are dark brown to black with a burnt, pungent odor. Their boiling range is about 100° to 200°C, above which thermal degradation beings to occur. The heating values of these clean-burning oils are approximately two-thirds of those for petroleum fuel oil. Pyrolytic oils are acidic and exhibit some corrosive characteristics. They are composed of many oxygenated compounds with a wide spectrum of chemical functionality. Results of this study showed pyrolytic oils to contain phenolics, polyhydroxy neutral compounds, neutral compounds of a high degree of aromaticity, and volatile acidic compounds.

Because the oils obtained from the pyrolysis of lignocellulosic materials are complex mixtures of organic compounds and usually contain some water, their characterization requires a variety of analytical and testing techniques. Properties that are of interest in characterizing pyrolytic oils include (but are not necessarily limited to) density, water content, heating value, acidity, flash point. corrosiveness, filterable solids, ash, solubility in various solvents, distillation range, viscosity and elemental content (particularly carbon, hydrogen, nitrogen, sulfur, and oxygen) (see Table 1).

Sources of Oil Samples

Samples of pyrolytic oils for this study were obtained from two major sources: (1) the 45 dry metric ton/day field demonstration pyrolysis facility at the pilot plant of the Engineering Experiment Station, George Institute of Technology, which is operated on campus. Some samples of oil were produced in a 6-in. tube furnace fitted with a condensation train and gas collection system. A complete description of this apparatus and the pyrolysis procedure has been reported on by Knight (1).

TABLE 1. PROPERTIES OF WOOD OILS FROM TECH-AIR 50 DRY TON/DAY FACILITY

Property	Condenser Oil	Draft Fan Oil	Method
Density	1,161 kg/m³ (9.525 lbs/gal)	1,107 kg/m³ (9.242 lbs/gal)	-
Water content (weight %)	16.0%	10.6%	ASTM D 95-70
Heating Value (wet basis)	21.2 MJ/kg (9,100 Btu/lb)	24.6 MJ/kg (10,590 Btu/lb)	ASTM D 240-64
pH	2.9	3.3	5% Oil dispersed in water
Acid Number	75 mg KOH/g	31 mg KOH/g	ASTM D-664-58
Flash Point	111°F (231°F)	121°C (240°F)	ASTM D-93-73 -
Filterable Solids (weight %)	0.3%	0.4%	Acetone Insoluble
Copper Strip Corrosion	1	1	Classification- ASTM D-130-[illegible]
Sulfur (weight %)	0.01%	0.01%	ASTM D-129-64
Pour Point	26.7°C (80°F)	26.7°C (80°F)	ASTM D-97-66 -
Ash (weight %)	0.08%	0.03%	-
Distillation			ASTM D-86
First Drop	98°C	101°C	Group 3
10% Point	103°C	105°C	-
44% Endpoint	NA	265°C	-
53% Endpoint	282°C	NA	-
Solubility (weight %)			
Acetone	99.6%	99.6%	-
Methylene Chloride	91.5%	97.8%	-
Toluene	Slightly	Slightly	-
Hexane	Slightly	Slightly	-
Elemental Analysis (weight %)			
Carbon	51.2	65.6	-
Hydrogen	7.6	7.8	-
Nitrogen	0.8	0.9	-

Methods for Identyfying Chemical Species and Compounds

The chemical species and compounds present must be identified along with relative quantities if methods are to be developed for using pyrolytic oils in applications other than as a fuel oil. Among the most useful techniques for obtaining these data are gas, thin-layer, and liquid chromatography (LC); gas chromatography/mass spectroscopy (GC/MS); and infrared and UV spectroscopy. The two methods used in the studies described here were LC and GC/MS.

Liquid Chromatography

Pyrolytic oils are heat sensitive and reactive, and they contain a relatively large number of organic compounds. A technique was needed for analyzing the oil fractions obtained by the different processing methods that would not change the chemical character of the fractions. LC appears to be the method of choice, because it is carried out at ambient temperatures, it is capable of high resolution of complex mixtures, and component detection is nondestructive. In addition, the pyrolytic oils are soluble in organic-aqueous solvent systems that are very useful in LC.

The variables that were studied to find satisfactory LC conditions were LC columns, UV wave length, solvent gradient and solvent flow rate. The first two variables are discussed briefly here.

LC Columns

To select the most suitable LC column, several columns were tested with the raw wood oil using a 1-ml/min flow rate and a UV detector at 254 nm. The chromatographic columns and conditions tested and the results are given below in the order in which the testing was carried out.

A. Vydac adsorption silica gel 30 column. Solvent, 0% to 100% 2-propanol in isooctane, 20-min gradient, 20 concave. Results: No resolution obtained; only one large peak.

B. Partisil adsorption silica gel 5 column. Solvent, 5% to 30% 2-propanol in isooctane, 20-min gradient, linear. Results: Resolution of only eight peaks.

C. Partisil PAC 5 column. Solvent, 0% to 100% 2-propanol in isooctane, 30-min gradient, 35 concave. Results: Resolution of 12 to 20 peaks.

D. Partisil ODS 5 column. Solvent, 10% to 100% acetonitrile in water, 30-min gradient, 35 concave. Results: Resolution of 30 to 40 peaks

E. Partisil ODS 5 column. Solvent, 10% to 100% acetonitrile in water, 10% to 40% with 20-min hold, then 40% to 100% 35 concave gradient. Results: Resolution of 47 to 50 peaks. Total run time: 60 min.

F. Partisil ODS 5 column. Solvent, 10% to 100% acetonitrile in water, 30-min linear gradient. Results: Better overall presentation of chromatogram and better resolution of later peaks without excessive run time.

The resolutions obtained with the conditions given in item D above are very suitable for our survey chromatograms; the conditions in E and F yield even greater resolutions.

UV Wavelength

UV wavelength of 200, 220, 254, 280, 300, 320, 360 nm were selected, and LC runs were made using constant conditions (E above) other than wavelength. The results were as follows:

a. Many component responses appeared or disappeared with the change in wavelength;

b. No single wavelength was entirely satisfactory at the shorter wavelengths of 200-220 nm peak resolution;

c. The longer wavelengths of 300 to 360 nm produced sharply resolved peaks, but only a small total number of peaks actually appeared;

d. The most satisfactory results for our purpose were obtained at 280 nm, with 254 nm being the alternative choice.

The sets of LC conditions for obtaining chromatograms of the oil samples are given in Polk (2).

Gas Chromatography/Mass Spectrometry

Qualitative analysis of pyrolytic oil distillate by GC/MS analysis was performed on a DuPont Model 21-490 GC Mass Spectrometer. The GC conditions were as follows:

Column ... 6ft x 1/8 in. Se-30 Stainless steel with 10 ml/min flow rate

He initial temperature ... -25°C

Programming rate ... . 4°C/min

Final temperature .... -200°C, detector flame ionization

Some of the mass spectral results are listed in Table 2. Details of the qualitative analysis of pyrolytic oils are reported by Polk (2).

Techniques for Separating Large Oil Fractions

The broad classes of chemical substances in raw pyrolysis oil are phenolics, aromatic neutral compounds (neutrals of high aromaticity, NHA), acidic compounds, and a group of substances with sugar-like characteristics that are termed polyhydroxy neutral compounds (PNC). The emphasis in the separation experiments has therefore been to focus on obtaining fractions of the oil that contain essentially one of the general classes of chemicals. The five major extraction techniques tested were:

1. Extraction of oil sequentially with water at 25°, 50° and 95°C.
2. Extraction of oil with sodium sulfate solution (salting-out effect).
3. Extraction of oil simultaneously with an organic colvent and water (three-phase system).
4. Extraction of sodium hydroxide soluble fractions of pyrolysis oil.
5. Extraction of organic solvent solutions of pyrolysis oil with water.

Results of a number of extraction and separation experiments on a batch basis with raw and vacuum-stripped pyrolytic oils,

TABLE 2 GC/MS OF CONDENSER OIL DISTILLATE

Scan No.	Components	m/e (Relative Intensity %)
1	Ethanol, Furfural, Acetaldehyde	29(86), 38(4), 39(14), 40(50), 41(100), 42(4), 43(7), 44(56), 45(24), 46(4), 69(4), 95(47), 96(50), 97(3)
2	Ethanol	29(49), 40(17), 41(100), 45(43) 46(26), 63(14), 95(3), 96(3)
3	Acetone, Heptanol	29(56), 41(63), 43(100), 45(17), 58(50), 67(5), 95(4), 100(6), 115(6), 116(8)
4	Phenol	39(18), 40(32), 41(23), 44(14), 65(20), 66(41), 93(1), 94(100), 95(5)
5	1-Octanol	29(25), 41(71), 44(100), 45(15), 58(69), 95(5), 97(5), 100(4)
6	O-Cresol, 5-Methylfurfural	29(55), 40(64), 41(98); 44(25), 56(29), 67(39), 77(34); 79(34), 107(59), 108(100), 110(20)
7	m-and p-Cresols	29(19), 40(51), 41(34), 44(14), 52(19), 56(16), 58(18), 69(15), 77(27), 79(29), 107(90), 108(100), 110(8)
8	Guaiacol	29(23), 40(27), 41(42), 54(25), 82(67), 109(100), 124(81), 125(4)
9	Veratrole	29(49), 40(31), 41(100), 44(45), 56(22), 95(28), 123(9), 138(8)
10	2,4 Dimethylphenol, Naphthalene	29(57), 40(38), 41(97), 44(33), 56(21) 91(29), 107(90), 121(48), 122(100), 128(24)
11	Naphthalene	29(19) 40(20), 41(31), 44(11), 52(13), 65(7), 77(5), 102(6), 127(11), 128(100), 129(9)
12	Estragole, Naphthalene, 2,4-Dimethylphenol	29(42), 40(53), 41(83), 42(43), 59(29), 77(34), 91(21), 107(100), 122(49), 128(52), 147(53), 148(33), 149(8)
13	2-Methoxy-4-methylphenol	29(10), 40(19), 41(12), 42(15), 52(13), 54(7), 56(18), 65(10), 66(10), 67(19), 77(19), 95(37), 107(4), 121(1) 123(47), 124(6), 137(7), 138(100), 139(9)
14	Methylnaphthalene, 2-Methoxy-4-ethylphenol	29(32), 40(32), 41(77), 44(31), 77(22) 91(24), 104(22), 109(25), 115(35), 138(53), 141(73), 142(100), 152(46)

indicated that vacuum-stripped oil gave better results than the raw oils. The vacuum stripping provides for the removal of the volatile organics and most of the water in the oil with potential subsequent recovery of these organic compounds. The analysis showed that the major organic component in the volatile fraction is acetic acid. Our preliminary separation techniques are therefore based on using vacuum-stripped oil. A 100-g sample of crude pyrolysis oil would yield 82.1g of vacuum-stripped oil, 10.8g of water, and 7.1g of acid when processed at 2mm and ambient temperature (see Figure 1).

Extraction of Oil Sequentially with Water at 25°C, 50°C, and 95°C

A sample of vacuum-stripped oil was extracted sequentially with water at 25°, 50°, and 95°C in an effort to separate the more water soluble substances. Figure 2 illustrates this separation process and the recovery of the different factions are given in Table 3.

The significance of these results is that the oil can be separated into water soluble and water insoluble fractions that offer the opportunity for recovery of useful fractions of aromatic compounds. The water insoluble fractions, based on our analysis, are composed of phenolics and neutral aromatics. The separation of this fraction into a highly concentrated phenolic fraction and a highly concentrated fraction of aromatic neutral compounds could probably be accomplished by either fractional distillation or extraction with alkaline solution. The aqueous phases could be combined and subjected to a separation of the components with an aqueous salt solution to yield a fraction with mainly phenolics and another fraction with mainly polyhydroxy neutral substances.

Other Extraction Techniques

Results from this evaluation of other extraction techniques tested are presented in Knight et al, (1).

Conclusions

The yield of pyrolytic oils from lignocellulosic materials vary from 15% to 25%, depending on feed materials and operational conditions. An estimated 1.1 billion barrels of oil could be produced from the

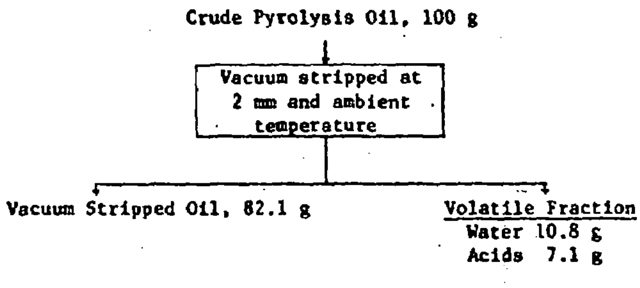

Figure 1. Removal of volatiles from pyrolytic oil.

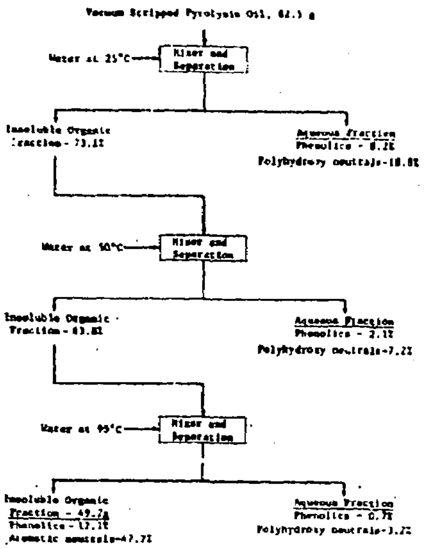

Figure 2 Extraction of oil sequentially with water at 25°C, 50°C, and 95°C.

total organic wastes generated annually in the United States. The extraction techniques reported here show promise of having the greatest potential for processing pyrolytic oils into fractions containing specific classes of chemical compounds. Further study will be required to determine if any of the oil fractions can be used as chemical feedstock in industrial applications.

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TABLE 3. YIELDS OF FRACTIONS FROM WATER EXTRACTION OF OIL

	Water Insoluble Fraction	Water Soluble Fractions			
		25°	50°	95°	Total
Phenolics	10 g	6.7 g	1.7 g	0.6 g	9.0 g
Aromatic neutrals	39.2 g	--	--	--	--
Polyhydroxy neutrals	--	15.4 g	5.9 g	2.6 g	23.9 g
Totals	49.2 g	22.1 g	7.6 g	3.2 g	32.9 g

STANDARDS FOR REFUSE DERIVED MATERIALS

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ABSTRACT

The American Society for Testing and Materials, through a grant from the U. S. Environmental Protection Agency, is developing standards and specifications for the reclamation of materials and energy from refuse. The need for such standards and four examples of typical tasks in this project is discussed.

Introduction

The pressures for the implementation of resource recovery are intensifying. Sanitary landfills, long considered to be the ultimate solution to the problem of solid waste disposal are frequently indicted as sources of ground water pollution and often represent a necessary nuisance to the community. Further, the cost of land close to the centers of solid waste production are forcing new landfills further away from communities, thus increasing transportation costs. In some communities, there simply are no further landfill sites, and alternate methods of solid waste disposal are needed.

One historically important alternative is incineration, or thermal volume reduction. Due to the extremely strict air emission standards now required by many states, and increasing value of energy from ever decreasingly reliable sources, the use of incinerators only as volume reduction processes has become economically questionable.

The only other alternative to the landfill is the recovery of energy and materials from municipal solid waste. This option not only provides a solution to the problem of disposal of refuse, but has the added advantage of providing secondary materials for industry so as to preserve our virgin sources and make us less dependent on foreign supplies. In addition, resource recovery contributes useful energy to our increasingly energy-limited society. In short, resource recovery solves two problems.

- disposal of solid wastes
- savings in energy and materials.

The promotion of this alternative is thus in all of our interest.

The Need for Standards

Although the secondary materials industry is an old one, the large scale recovery of metals, glass and organic fractions from municipal refuse is a fairly new problem.* The three major sectors in this process--the public, the refuse processor, and the user of the recovered materials--all have conflicting interests. The public simply wants the refuse to disappear since it (by definition) no longer has value to the individual. The processor would like to have the public perform separation of the waste materials, but since this represents a bother to the public, such source separation programs, with a few notable exceptions, have not caught on.

The refuse processor thus must separate the mixed components into individual fractions. His objective, however, is to produce as dirty a product as possible and still be able to market it to secondary materials users. Finally, the purchaser of these materials is seeking maximum purity since pure materials require the least cost for processing and subsequent manufacturing. In short, the three major groups involved with resource recovery all have different objectives, and yet need each other in order to make resource recovery successful.

One means of promoting and facilitating such cooperation is to develop standards for refuse derived materials and resource recovery processes. Quantitative and well-defined definitions of secondary materials, properties and the processes used to produce them will act as a catalyst in the promotion of resource recovery--to the benefit of all of us.

This recognition led the U. S. Environmental Protection Agency Office of Research and Development to fund a program to assist the American Society for Testing and Materials in the development of standards for refuse derived materials. This project, administered through ASTM's E-38 Committee on Resource Recovery, has been ongoing for four years and has significantly assisted in the promulgation of such standards. The objective of this paper is to report on the progress of this program.

*One of the first large scale resource recovery projects was started by Colonel Waring, in New York City, in 1880. The facility reportedly paid for itself in recovered materials, but was nevertheless closed within a year.

Organization

E-38 Committee on Resource Recovery is organized into a number of subcommittees. In addition to such service subcommittees as editorial, terminology, and research and planning, the line subcommittees (those charged with the development of standards) include the following:

E-38.01 Energy

E-38.02 Ferrous Metals

E-38.03 Non-ferrous Metals

E-38.04 Paper and Paperboard Products

E-38.05 Glass

E-38.06 Construction Materials

E-38.07 Health and Safety

E-38.08 Processes and Unit Operations

These subcommittees meet bi-annually and by the process of consensus and compromise, develop the standards as needed.

As a need for background information such as round robin testing and commercial laboratory analysis are identified, requests are made to the E-38 Management Board to assist in the funding of these tasks. If the need is judged to promote the development of standards, the task is funded.

At the present time E-38 has 21 standards in various stages of approval and development, of which all are financially assisted through this project. Ten of these standards will be published in the near future.

In this short presentation it is obviously not practical to discuss all of the ongoing projects. We thus have chosen only four tasks to illustrate the type of work being performed and the potential benefit from such studies.

Four Typical Tasks

Development of Test Methods and Specifications for Recovered Glass in Structural Clay Products

This project is under the guidance of E-38.06 Subcommittee on Construction Materials. The objective is to develop test methods and specifications for various resource recovered glass-rich fractions for use in structural clay products. This can be achieved by determining chemical and physical properties of glass-rich fractions as related to their effects on maturing temperatures, shrinkage, water absorption and compressive strength. The properties which require specifications include, for example, glass content, soluble salts, and fluxing effect.

The program involved a two-step effort: laboratory studies and production testing. The first phase of the work was successfully completed and the results published in a report "Development of Test Methods and Specifications for Resource-Recovered Glass in Structural Clay Products", presented at the IITRI Conference in August 1979. The next phase of the study is now on-going.

Structural clay products encompass a wide range of materials such as building brick, roofing tile and pipe. The building brick industry produces the largest volume of structural clay products. The initial commerical application of the proposed test methods and specifications are therefore to be tested in the production of building brick.

This phase involved three phases: 1) characterization of the glass-rich fraction by Bureau of Mines, 2) brick production tests to be performed by a manufacturer, and 3) testing by a commercial laboratory.

The Effect of Aluminum and Iron on the Heating Value of Refuse Derived Fuel

This task originates in E-38.01 Subcommittee on Energy, and addresses the problem of obtaining heating values for a refuse derived fuel which contains metals such as aluminum and iron. If a sample of RDF with these metals is combusted in a bomb calorimeter (the common method of measuring heating value of solids.) the results will include the heat generated by the exothermic oxidation of the metals. This oxidation, however, does not occur at the much lower temperatures experienced in RDF combustion chambers, and the calorific values can thus overestimate the actual heating value achieved in the combustion of RDF.

The objective of this task is to conduct round robin tests to establish what correction factors, if any, are necessary for describing the useful heating value of RDF when it contains significant amounts of aluminum and iron.

Method for Preparing a Gross Laboratory Sample from a Gross Lot of Refuse Derived Fuel

Refuse is a highly heterogeneous material, and thus any RDF produced from refuse can be expected to retain considerable heterogeneity. A shredded and air classified light fraction (commonly known as RDF-3) can have pieces of paper on plastics as large as 5 cm (2 in). Laboratory samples for such analyses as heating value must, however, be as small as one gram. The statistical problems involved in obtaining a representative sample are thus immense.

This task, under the leadership of E-38.01 Subcommittee on Energy, addresses the problem of how a truly representative sample can be obtained from a highly heterogeneous mixture such as RDF-3. The test has been developed, and the task is presently engaged in a series of round robin analyses to develop its precision and accuracy.

Development of a Test for Measuring Refuse Derived Fuel Pellet Characteristics

The organic fraction in refuse, separated out and used as a source of energy, can take many forms, depending on the processes used. One potentially useful fuel is pelletized or densified refuse derived fuel (dRDF). The organic fraction is first separated out using processes such as shredding and air classification. The material is next processed in a pelletizer which, under high pressure, extrudes or cuts the RDF into dense chunks. These pellets have significant advantages over other forms of RDF, particularly if the fuel is to be burned on grates. Pelletizing also enhances the ease of handling and increases the fuel stability.

The objective of this task is to develop and evaluate a test for determining the characteristics of pellets, including physical properties and pellet integrity.

The E-38 subcommittee on Processes and Unit Operations is developing a standard for evaluating the characteristics of pellets as well as pelletizer performance. In this task, a series of appropriate tests for measuring such characteristics are being developed.

This project is in three phases: a) review of existing information on pellet tests and testing procedures, b) development of specific test procedures and precision and accuracy statements, and c) round robin of pellet tests, using the test procedures developed.

Conclusion

The promotion of resource recovery is a well-established public benefit. Resource recovery can be facilitated by the development of standards for both the production as well as use of the secondary materials. The American Society for Testing and Materials through a grant from the U. S. Environmental Protection Agency, is developing such standards using a broad-based voluntary consensus mechanism. Significant progress has occurred to date, and the project is continuing. The E-38 Committee on Resource Recovery is a purely voluntary organization, open to all interested persons. Assistance and participation is welcomed and encouraged.

Acknowledgement

This project is supported by a grant from the U. S. Environmental Protection Agency EPA 68-03-2528 Carlton Wiles, Project Officer. Donald Mihelich is the chairman of E-38 and Pickett Scott is the chairman of the Management Board which oversees the project in behalf of ASTM.

ENVIRONMENTAL ASSESSMENTS OF WASTE-TO-ENERGY CONVERSION SYSTEMS

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ABSTRACT

This paper discusses the results of environmental assessments at five different types of waste-to-energy conversion systems: refuse pyrolysis; municipal incinerator fired with MSW; power plant boiler fired with wood waste and fuel oil; steam boiler fired with coal and d-RDF; and power boiler fired with RDF.

Introduction

Increased emphasis on energy and material recovery and the need for alternatives to solid waste disposal in landfills have generated growing interest in waste-as-fuel processes. The processes include, on a generic basis, waterwall incinerators, pyrolysis systems, combined fuel-fired systems (coal plus refuse derived fuel (RDF), RDF plus municipal sewage sludge, coal plus wood waste), and biochemical conversion of waste to methane.

For the past three years, Environmental Protection Agency's (EPA's) Industrial Environmental Research Laboratory (IERL) in Cincinnati has sponsored a program at Midwest Research Institute (MRI) to conduct environmental assessments of some of the above waste-to-energy conversion processes. The overall objective of this program is to evaluate the potential multi-media environmental impacts resulting from using combustible waste as an energy source and thereby identify control technology needs. As part of this program, MRI has undertaken extensive sampling and analysis efforts at the following waste conversion facilities.

- A 181.4 Mg/day (200 ton/day) refuse pyrolysis system
- A 108.8 Mg/day (120 ton/day) municipal incinerator fired with municipal solid waste (MSW)
- A 10 MW power plant boiler fired with wood waste and No. 2 oil
- A 31,752 kg/h (70,000 lb/h) steam boiler fired with coal and densified refuse-derived fuel (d-RDF)
- A 20 MW power plant boiler fired with RDF

A description of the facility, the sampling and analysis methods used, and the results obtained are individually presented below for each of the above facilities tested.

Refuse Pyrolysis System

The Union Carbide refuse pyrolysis system (PUROX) at South Charleston, West Virginia, was designed to pyrolyze 181.4 Mg/day (200 tons/day) of RDF. The refuse fuel was produced by shredding MSW to a 7.6 cm (3 in.) size and then removing magnetic materials from the shredded waste. The PUROX system is a partial oxidation process that uses oxygen to convert solid wastes into a gas having a higher heating value (HHV) of about 14.5 MJ/m^3 (370 Btu/scf).

Raw refuse is received by truck in the plant's storage building. It is moved and stacked in the storage area by a front end loader. The same loader picks up the stored waste, weighs it on a platform, and dumps it on a conveyor leading to the shredder, where it is shredded to a 7.6 cm (3 in.) size. Ferrous material is removed by a magnetic recovery system.

The refuse fuel is fed into the top of the reactor, the principal unit on the process, by two hydraulic rams. There are three general zones of reaction within the reactor (drying, pyrolysis, and combustion). The reactor is maintained essentially full of refuse, which slowly descends by gravity from the drying zone through the pyrolysis zone into the combustion zone. A counterflow of hot gases, rising from the combustion zone at the bottom, dries the incoming, moist refuse. As the material progresses downward it is pyrolyzed to form fuel gas, char, and organic liquids.

Oxygen is injected into the bottom hearth section at a ratio of about 20% by weight of incoming refuse. The oxygen reacts with char formed from the refuse to generate temperatures of 1370 to 1650°C (2495 to 3002°F) in the lower zone, which converts the noncombustibles into a molten residue. This residue is discharged into a water quench tank where it forms a slag.

The hot gases from the hearth section are cooled as they rise through the zones of the reactor. After leaving the reactor, the gases are passed through a recirculating water scrubber. Entrained solids are separated from the scrubber water in a solid-liquid separator, and recycled to the reactor for disposal. The water product discharged from the separator system is sent to a plant treatment system. The gas leaving the scrubber is further cleaned in an electrostatic precipitator (ESP) and then cooled in a heat exchanger prior to combustion in a flare combustor. During the tests the gas was burned in a package boiler transported to the site for these tests. The fuel gas consisted of about 40% CO by volume, 23% CO_2, 5% CH_4, 26% H_2, and the rest being N_2, C_2H_4, etc.

Sampling at the Purox facility was directed to the three effluent streams; slag, scrubber effluent, and gaseous emissions from a boiler when fired with PUROX gas and when fired with natural gas. An overview of the sampling and analysis scheme is shown in Figure 1. As can be seen in this figure, sampling and analysis of each stream was rather complex, being directed to conventional pollutants but including, among others, priority pollutants in water samples and sampling of both liquid and gaseous emissions for most of the analyses prescribed under EPA's Level 1 environmental assessment protocol. Particulate emission sampling in the boiler stack was conducted according to EPA Method 5, but using a High Volume Sampling System (HVSS) because of the expected low particulate loading. Boiler stack sampling also included use of the Level 1 Source Assessment Sampling System (SASS) train.

Water samples also underwent analysis for priority pollutants, but the data are too lengthy for inclusion in this paper. The results of these analyses showed that few of these pollutants were present at detectable levels in the scrubber effluent, but that the Unox system did effectively reduce their concentrations.

Results of the testing effort showed that, of the criteria pollutants, only NO_x and particulate emissions increased when burning Purox gas as compared to natural gas. NO_x and particulate levels were of the order of 350 to 400 ppm and 0.0046 to 0.011 g/scm (0.002 to 0.005 gr/scf), respectively. SO_2 emissions averaged 70 to 100 ppm. Particulate and SO_2 emissions were below present standards, whereas NO_x required further reduction. Also, analysis for metals and other pollutants indicated that these should not present any problems.

Because of the difficulty involved in interpreting much of the data collected in this test, especially the Level 1 analysis results, the environmental assessment work was extended to include application of the methodology known as the Source Analysis Model (SAM/IA) developed by EPA. Basically, this model compares the measured concentrations of pollutants with approximate emission concentration guidelines known as minimum acute toxicity effluents (MATE) values. These MATE values have been tabulated for several compounds or classes and there is a specific MATE concentration for each compound and for each type of effluent stream (solid, liquid, or gaseous). The MATE values are used to compute the ratio of the measured concentration to the MATE concentration, and this ratio is termed the "degree of hazard." The "degree of hazard" for each pollutant is then summed to provide the "degree of hazard" for the effluent stream under consideration. This value, when multiplied by the

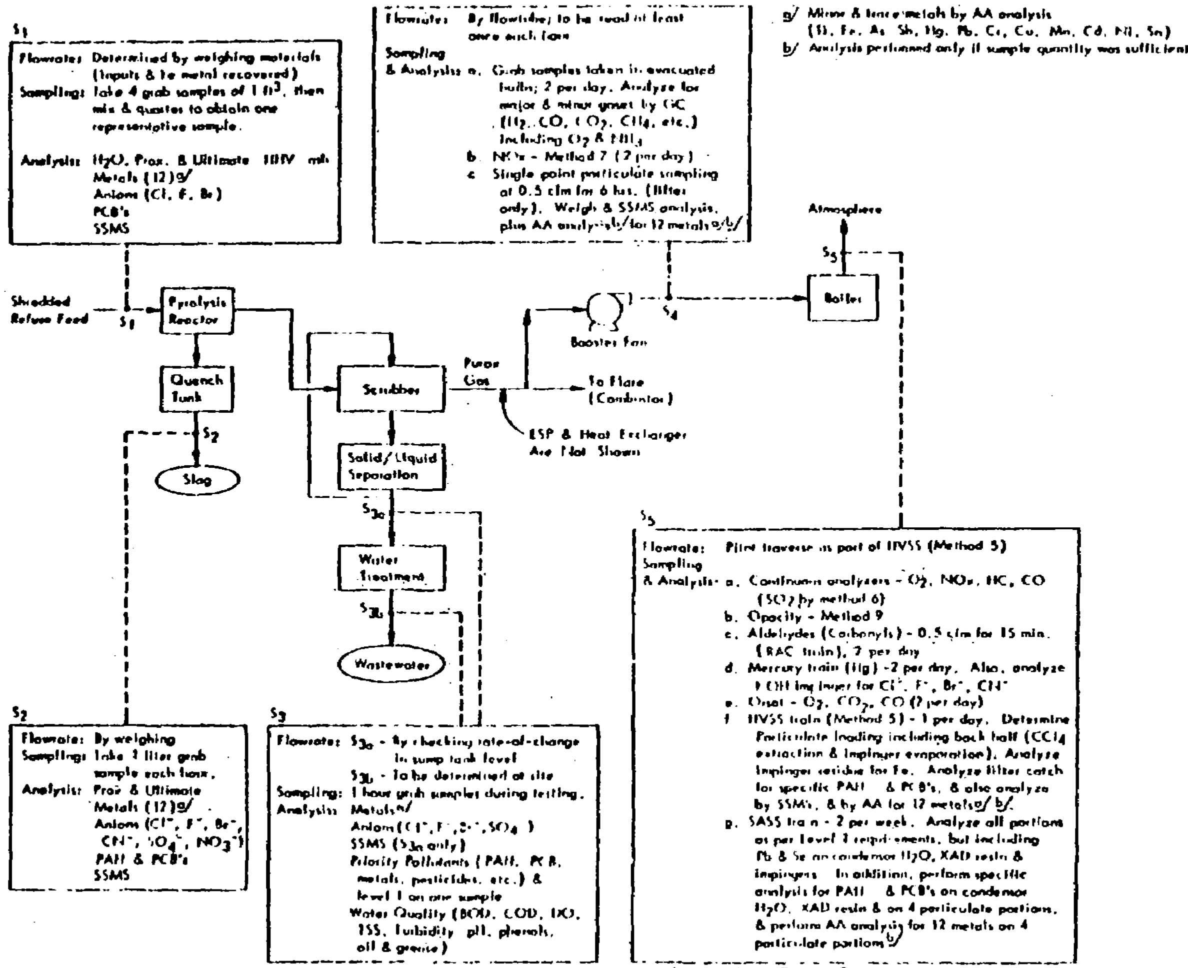

Figure 1. Sampling and analysis scheme for Purox® process.

effluent flowrate, in specific units (e.g., liters per second), establishes the "toxic unit discharge rate" (TUDR) for the stream.

The SAM/IA methodology, as described above, was utilized to analyze the data obtained for each of the three primary effluent streams from the Purox process (slag, scrubber effluent, and boiler stack gas). Based on the SAM/IA methodology, the scrubber effluent had the highest "degree of hazard," being considerably greater than the "degree of hazard" for the input river water. However, the slag stream had the highest "toxic unit discharge rate." The boiler flue gas effluent had the lowest "degree of hazard" and the lowest "toxic unit discharge rate." Both of these values were comparable to the baseline values computed for boiler flue gas when burning natural gas.

Municipal Incinerator Fired With MSW

The Braintree municipal incinerator (Braintree, Massachusetts), is a mass-burn facility consisting of twin waterwall combustion units, each with a design capacity of 108.8 Mg (120 tons) of MSW for a 24-h period. A portion of the steam produced (20 to 35%) is supplied to neighboring manufacturers and the remainder is condensed. Each furnace is equipped with an ESP and both ESP's exhaust to a common stack.

The Riley Stoker boilers are of the single pass design, each having a rated capacity of 13,608 kg (30,000 lb) of steam/h at 204.4°C (400°F) and 1,723.7 kPa (250 psig). The ESP units are single field, 12 passage precipitators with a specific collection area of 0.0068 m^2/acmh (125 ft^2/1,000 acfm); each has a design collection efficiency of 93%.

Environmental assessment of the incinerator facility was conducted using EPA approved sampling and analysis procedures similar to these identified in Figure 1. Results and conclusions of the testing effort are summarized below.

Of the criteria pollutants, SO_2, NO_x, and hydrocarbon emissions were low. However, CO levels were high and could not be explained considering the large quantities of excess air that were used. The average particulate concentration was 0.55 g/dscm (0.24 gr/dscf), corrected to 12% CO_2. This level exceeded the federal and state regulations. However, subsequent tests for compliance had an outlet particulate loading of 0.17 g/dscm (0.074 gr/dscf), which showed compliance.

Elemental analysis of the glass- and metal-free bottom ash revealed an overall increase in the elemental concentrations when compared to the refuse feed. The collected fly ash contained levels of chlorides, sulfates, and some trace metals which may be of concern. PCB's were not detected in the collected fly ash; 4 PAH compounds were identified.

Levels of BOD, COD, oil and grease, TSS, and TDS in the bottom ash quench water do not appear to be of concern. The phenolic content was found to be <0.1 mg/liter in all samples.

Levels of gaseous chlorides and other halides were low. Presence of PCB's was confirmed only in the SASS train XAD-2 resin at a concentration of 3.6 μg/m^3.

Results of the SAM/IA environmental assessment procedure showed the incinerator stack emissions to have the highest apparent degree of health hazard. Further analysis is needed to determine the exact composition of the organic components of the stack emissions to better ascertain the hazard potential. SAM/IA also showed that the bottom ash effluent had the largest toxic unit discharge rate due primarily to the abundance of phosphorus and metals in this stream.

Power Plant Boiler Fired With Woodwaste and Fuel Oil

The No. 1 unit at the Burlington Electric Plant (Burlington, Vermont) was originally a coal-fired boiler which was modified to fire wood chips with supplementary No. 2 fuel oil. Because of the high moisture content of the chips, the boiler cannot provide the desired steam output on wood alone. Therefore, No. 2 fuel oil is used. Steam production is rated at 45,360 kg/h (100,000 lb/h), which powers a 10 MW turbine generator. Residual ash from the boiler is discharged at the end of the grate into a hopper and is then pneumatically transported to an emission control system consisting of two, high efficiency mechanical collectors in series. For a flue gas flow rate of 101,940 acmh (60,000 acfm) at 165.6°C (330°F), the collectors were designed for an overall pressure drop of 1.6 kPa (6.5 in. H_2O) and a collection efficiency of 97.75%.

Sampling and analysis was based on the matrix shown in Figure 2. Major results and conclusions of the tests are as follows:

On a heat input basis, wood accounted for 80% of the boiler fuel, and oil the remainder. The heat of combustion of wood was 13.65 MJ/kg (5,870 Btu/lb) as received, and for oil, the heat of combustion was 45.36 MJ/kg (19,500 Btu/lb).

Bottom ash analysis indicated that most elements were more concentrated in the ash relative to the input fuels. No PCB's were detected in bottom ash but one PAH compound, phenanthrene, was present at a concentration of 0.89 µg/g. Primary and secondary collector ash contained no PCB's but several PAH compounds were identified in the secondary ash, with one sample containing 10 µg/g of phenanthrene.

Particle sizing at the collector inlet and outlet could not be established due to constant plugging of the optical counter's dilution system. Stack concentration of particulates averaged 0.18 g/dscm (0.08 gr/dscf) and the collector had a particulate efficiency of 94.2%. NO_x and SO_2 concentrations averaged 66 and 138 ppm, respectively. CO averaged 213 ppm and hydrocarbons 9 ppm. Analysis of Method 5 particulate indicated concentrations approaching 100 µg/dscm for Pb, Ba, Sr, Fe, and Ti in the stack gases. PCB and PAH tests of the stack gases were negative.

EPA's SAM/IA analysis indicated that the secondary collector ash contained the highest degree of hazard although all three ash streams were similar in the magnitude of their hazard values. Stack emissions showed a low degree of hazard. The primary collector ash had the highest toxic unit discharge rate.

Steam Boiler Fired With Coal and d-RDF

Emission tests were conducted on the GSA/Pentagon facility's No. 4 boiler in Arlington, Virginia during a test burn program coordinated by the General Services Administration (GSA) and the National Center for Resource Recovery (NCRR). The No. 4 unit is an underfeed-retort stoker boiler with a rated steam capacity of 31,752 kg/h (70,000 lb/h) at 861.9 kPa (125 psig) and 176.7°C (350°F). During the tests, the boiler was equipped with a multiclone collector for removal of particulates from the exhaust gases.

The test burn program included three fuel firing modes: 100% coal (baseline conditions), 20% d-RDF + 80% coal, and 40% d-RDF + 60% coal. Samples of coal, d-RDF, and the coal/d-RDF mixtures were collected hourly by NCRR and analyzed for moisture, ash, heating value, and chemical composition. Several daily samples of bottom ash were also collected by NCRR and analyzed for loss-on-ignition and chemical composition. MRI conducted sampling and analysis of the stack effluent. Parameters measured included particulate concentration, gaseous criteria pollutants (SO_2, NO_x, CO, and total hydrocarbons), and chlorides. The particulate samples were further analyzed for lead content.

Results of the emission tests showed that:

Particulate emissions were reduced from 22 to 38% when d-RDF was blended with the original coal fuel. Filterable particulate emissions were lowest when using the 20% d-RDF blend and rose again when the proportion of d-RDF was raised to 60%. This finding may not be conclusive, however, since the boiler load was held steady during the 20% RDF firing but not during the 60% mode.

The amount of particulate lead emitted when burning d-RDF with coal is substantially higher than that from combustion of coal alone (an average of 1,000 µg/m^3 with 20% d-RDF, and 2,260 µg/m^3 with 60% d-RDF, versus 330 µg/m^3 with coal only).

Chloride emissions showed no definite trend which could be used to correlate chloride emissions with RDF modes, though slightly higher concentrations of HCl were observed in two of the samples collected during combustion of the 60% d-RDF blend.

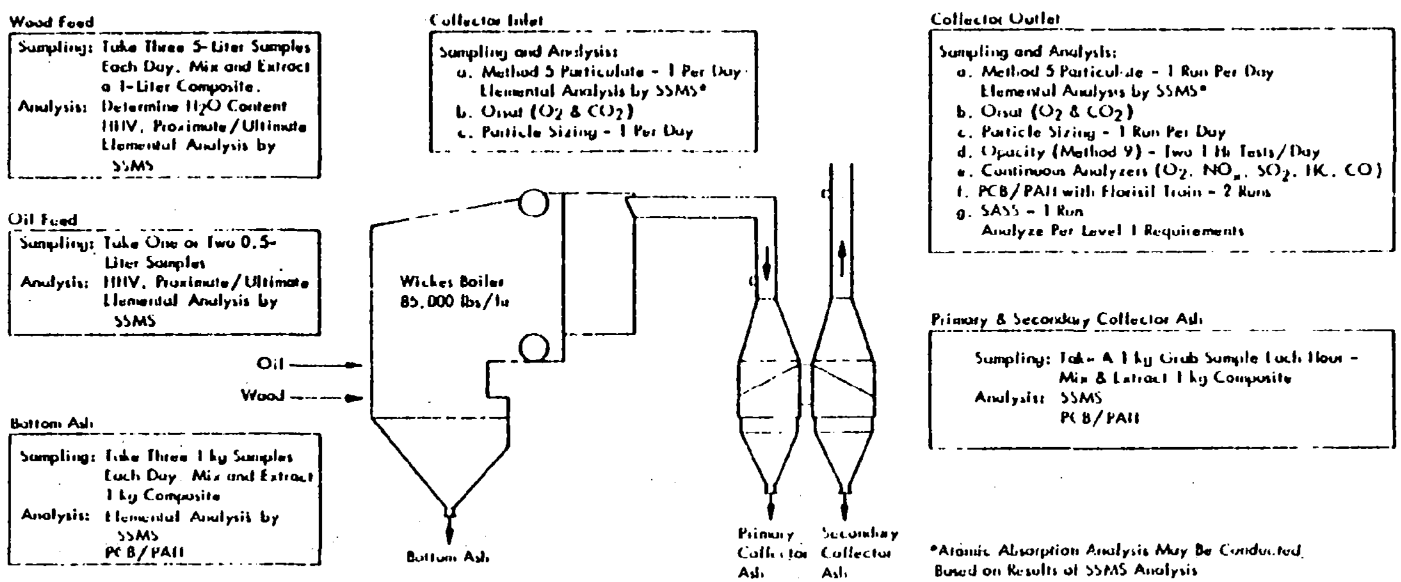

Figure 2. Test matrix for Burlington Electric's wood and oil-fired power plant.

Concentrations of sulfur dioxide, nitrogen oxides, and carbon monoxide all appeared to decrease slightly when the RDF was used with coal. Because of the very low sulfur content of d-RDF, SO_2 emissions were reduced progressively as the proportion of d-RDF with coal was increased. However, the reduction in NO_x and CO levels, may or may not have been the direct result of burning d-RDF since they are highly dependent on boiler combustion conditions.

Power Boiler Fired With RDF

The Hempstead Resource Recovery Plant (Long Island, New York) receives MSW, produces a RDF and converts the fuel to electrical power. The facility consists of two distinct segments: a refuse processing operation, utilizing the Black Clawson Hydrasposal system; and a power house, which contains two steam boilers and two 20 MW electrical turbine generators, plus the associated control equipment.

Tests were conducted by MRI on the No. 2 unit of the power house, which is an air-swept spreader stoker, waterwall boiler with a nominal capacity of 90,720 kg/h (200,000 lb/h) of steam at 4,309.2 kPa (625 psig) and 398.9°C (750°F). The boiler was fired with 100% RDF, although auxiliary oil burners were used for start-up and during fuel feed interruptions. Air pollution controls for the boiler consisted of a bank of 12 mechanical cyclones followed by an ESP.

The purpose of the assessment was primarily to investigate organic constituents of the stack gases and to quantify odorous components. However, other tests were also included. Emission streams evaluated included the boiler bottom ash, cyclone ash, ESP ash, and the stack effluent gases. Samples of the RDF were also collected and analyzed for moisture plus chemical and elemental composition. The three ash streams were analyzed for elemental composition. Stack emissions were continuously monitored for SO_2, NO_x, CO, O_2, and total hydrocarbon concentrations, and were also tested to determine levels of vaporous mercury and aldehydes. In addition, a sample was collected using the EPA SASS for analysis under EPA's Level 1 protocol.

Initial results of the test program did not indicate any pollutant emissions of major concern. Stack gases contained relatively low concentrations of SO_2, NO_x, and hydrocarbons. Carbon monoxide levels were slightly greater than anticipated.

Emission of carbonyl compounds (aldehydes) were detected at a maximum level of 7 ppm (2.95 kg/h).

Mercury vapor concentrations in the stack effluent were very low (<0.12 mg/m³), and it appears that mercury levels are greatest in the fly ash collected by the ESP. The concentration of mercury in samples of the RDF was constant at about 3 µg/g.

Several trace metals were detected in the stack gases at relatively high concentrations. Of these, lead, antimony, chromium, and arsenic were most notable. Their respective concentrations in the SASS sample were 580, 460, 640, and 560 µg/m³. Elemental analysis of the bottom ash, cyclone ash, and ESP ash streams also indicated that many of the more volatile elements were associated with the smaller sized particles.

Organic analysis of the SASS sample, using EPA Level 1 and additional gas chromatography/mass spectrometry (GC/MS) analytical techniques, showed a variety of organic constituents. No single compound group appeared to predominate, although several polynuclear aromatic hydrocarbons were detected. All organic results were qualitative.

Compounds consistently observed in all SASS component extracts included naphthalene, fluoranthene, acenaphthylene, pyrene, phenanthrene/anthracene, bis(2-ethylhexyl)-phthalate, and diphenylamine. The majority of additional compounds were found in the XAD-2 resin extract and included two chlorobenzenes, hexachlorobenzene, fluorene, and dibutylphthalate.

Detailed reports for all of the projects discussed in this paper are in various stages of publication. Requests for these reports should be forwarded to Incineration Research Branch, IERL-Cincinnati, Cincinnati, Ohio 45268.

WASTE-TO-ENERGY FACILITIES:
A SOURCE OF LEAD CONTAMINATION

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ABSTRACT

Resource recovery activities are rapidly growing in the United States and among the most actively pursued technologies are those that recover energy from Municipal Solid Waste (MSW). More than 80 Waste-to-Energy facilities may be operational by 1985, in which MSW is either directly burned to produce steam and/or electricity or processed into Refuse Derived Fuel (RDF) which can be subsequently burned to recover energy. These facilities will have the capacity to process about 30 million tons of MSW per year and will be potential sources of atmospheric contamination.

Lead is known to exist in MSW and RDF in relatively significant amounts, most of which can be released to the atmosphere upon combustion. The quantity of lead released from MSW and RDF combustion facilities may exceed 6,000 Mg per year by 1985. If resource recovery activities achieve their expected growth, these emissions can considerably double by 1990.

The toxic nature of lead, the fact that it is emitted in the form of particulates in the respirable size range, with aerodynamic diameters usually less than 2 µm, and the location of the facilities typically adjacent to densely populated areas require that the subject be given careful attention.

INTRODUCTION

Almost four pounds of MSW are generated per person per day in the United States, amounting to an annual 140 million Mg (160 million tons). If the rate of increase in waste generation maintains its historic growth of 1.5% a year, by the end of this century the U.S. will be faced with the problem of disposing more than 180 million Mg (200 million tons) of garbage annually (12).

Sixty percent of that waste is generated in the 150 major urban centers, populated by close to 140 million people. These areas have to dispose of almost a quarter million Mg of garbage daily (12) in an efficient cost effective and environmentally acceptable manner.

In these major urban areas, landfills which have in the past provided an immediate solution to the MSW disposal problems have become scarce, expensive and its use restricted by stringent environmental control regulations.

Ironically, at the same time the MSW disposal problems faced by these urban centers increased in magnitude, the U. S. entered a period of restriction on the availability of inexpensive fuels, which fostered the development of new sources of energy.

The ability to solve the MSW disposal problem of the cities, while simultaneously contributing to the solution of the energy situation became a challenging goal. Consequently waste-to-energy projects proliferated, using various technological approaches, most of which had in common combustion as the final fate for all or part of the MSW.

At the same time, concern rapidly surfaced about the environmental soundness of these alternatives relative to conventional disposal. The release to the atmosphere of pollutants either present in the MSW or formed during combustion were possibilities that had to be carefully investigated.

Lead is one of the toxic elements found to exist in MSW. Its deleterious effects on human beings have been known for centuries.(10) (13) Hence, the origin and the amount of that pollutant in MSW and refuse derived fuels (RDF), its fate during combustion and the degree of air contamination that could result from the proliferation of energy recovery facilities, have been the subject of an investigation sponsored by the EPA.(35)

OCCURRENCE OF LEAD IN MSW

Lead exists in both the combustible and the non-combustible fraction of MSW. In the non-combustible fraction it may be found in materials such as piping, cable sheathing, ceramics, glass, solder, etc. (28). In the combustible fraction it is primarily found in the pigments used in printing inks, in paper goods, and in the stabilizers used for plastics products (20) (21) (24).

Little information about lead analysis performed in representative samples of MSW is available, perhaps because of the enormous difficulty in obtaining such a sample. Nevertheless, results of analyses performed in different fractions of MSW indicate that between 1000 and 5000 ppm by weight of lead can be expected. (4) (32) (36)

The combustible fraction has been analyzed in different facilities, at various locations and using different sampling techniques and analytical methods. The values resulting from these analyses range from 7 to 1749 ppm of lead as shown in Table 1, the average being 350 ppm.

TABLE 1. LEAD CONTENT OF THE COMBUSTIBLE FRACTION OF MSW

Average or Typical Value ppm	Range of Weight %	Reference
230	110-1300	(37)
265	220- 300	(17)
12	7- 14	(15)
124	16- 124	(14)
390	85-1600	(4)
400	----	(26)
152	130- 178	(31)
466	----	(16)
956	447-1749	(9) (22)
500	----	(41)

The components of the combustible fraction of MSW, their contribution to its lead content, the origin of that lead and the ranges of concentration are presented in Table 2.

It is evident that MSW components bearing pigments and stabilizers carry the major responsibility for the presence of lead in the combustible fraction of MSW. Certain printing inks, probably rich in lead chromates, may have up to 20,000 ppm of lead. (17)

ENERGY RECOVERY TECHNOLOGIES

Several technologies have been developed to recover energy from MSW. The ultimate goal of these technologies is to burn MSW or its combustible fraction to generate steam and/or electricity. (42)

The technologies can be grouped in two basic categories:

(1) Separation processes, which produce different types of RDF.

(2) Thermal processes, which generate steam and/or electricity through the thermal processing of MSW or RDF.

The preparation of RDF can be achieved by the separation of the various

TABLE 2. LEAD CONTENT OF THE COMBUSTIBLE FRACTION OF MSW IN THE U.S.

Component	Lead Component	Lead Content-ppm
Corrugated board		0 - 50
Newspapers (26)	Pigments-Printing Method Recycle	1 - 69
Paperboard	Pigments	40 - 500
Paper packaging (26)	Pigments	2 -10,000
Office paper		- 10
Magazines, books (20) (21) (26)	Pigments, Glazes	8 - 3,600
Tissue paper, towels (26)	From recycle	2 - 150
Paper plates, cups		
Other		
Yard waste	Pesticides, Fungicides	
Food Waste		
Plastic (16) (21)	Stabilizers, Pigments	10 - 1,000
Wood	Paints, Primers	
Leather, rubber	Stabilizers	
Textiles		

components of MSW into specific fractions, one of which is a combustible fraction, usually organically rich in cellulosic and plastic materials. According to the separation process employed, the RDF produced may be classified as one of four different types: (33) (42) (45) (47)

(1) Fluff-RDF (f-RDF), essentially plastic and paper products, three inches or less in size, obtained by a combination of trommeling, shredding, air classification and magnetic separation of MSW.

(2) Densified RDF (d-RDF), obtained as f-RDF, shredded again and pelletized in a pellet mill.

(3) Powdered RDF (p-RDF), prepared as f-RDF and then chemically treated and put through a hot ball mill, resulting in a very fine powder.

(4) Wet RDF (w-RDF), where the shredding and separation of the combustible fraction is accomplished in an aqueous medium, the resulting fuel typically having about 50% moisture.

The thermal processes can also be divided into four categories, as presented in Table 3.

TABLE 3. TYPES OF THERMAL PROCESSES

Systems	Material Burned
Waterwall Incinerators	MSW Shredded MSW RDF
Co-firing Systems	RDF & Fossil Fuel
Modular Combustors	MSW
Pyrolysis Systems	MSW Shredded MSW RDF

LEAD EMISSIONS

Analyses performed in sediments and materials of biological origin indicate that the natural concentration of lead in the atmosphere should be about 0.0006 $\mu g/m^3$. (1)

However, the actual concentration is considerably above that level, due essentially to the widespread use of lead for a multitude of purposes.

The lead content of the ambient air varies with location and that variation can be related to the activities of the particular areas, i.e.,

- o Suburban areas, about 0.1 $\mu g/m^3$
- o Cities, on the order of 1.0 $\mu g/m^3$
- o Near highways, during heavy traffic, up to 20 $\mu g/m^3$
- o Near poorly controlled smelters, up to 300 $\mu g/m^3$

The major source of lead contamination in the U.S. is the antiknock additives used in gasoline. They are responsible for 88% of the lead pollution in the air. (1) The restriction in their use is expected to reduce lead emissions from mobile sources from 130,000 Mg (144,000 tons) per year, as they were in 1975, to less than 40,000 Mg (44,000 tons) per year by 1985. (1)

The second largest contributors to atmospheric lead are waste motor oil combustors and municipal incinerators, with combined emissions of about 12,000 Mg (13,200 tons) of lead per year. (1)

These contributors and other stationary sources, in particular coal-fired power plants which in 1976 were estimated to release approximately 640 Mg (706 tons) of lead to the atmosphere (8) and MSW/RDF burning facilities will become even more important as their numbers continue to increase.

Emission of Lead from Stationary Combustion Sources

Lead is emitted from stationary combustion sources such as coal, oil, and refuse burning facilities mainly as particulates, although the possibility exists of some fraction leaving the stacks in the vapor form. (16) (19) (22) (31) (39)

The concentration of lead in the fly ash generally increases as the particle size decreases, a phenomenon explained by vaporization-condensation theory (19) (20) (21) (24). Due to the high vapor pressure of lead and some of its compounds, much of the lead is volatilized during the combustion process and subsequently deposited on the surface of particulate matter by condensation in the cooler sections of the system. The smaller-sized particles, with their higher surface-to-mass ratio can be expected to have a higher proportion of lead than the larger-sized particles.

Figures 1 to 4 illustrate this phenomenon and are based upon data from emission tests performed at the St. Louis demonstration plant and at a coal-fired power plant respectively. (16) (7)

The characteristics of these emissions indicate that more than one-half of the lead emitted may be concentrated in the particulates with aerodynamic diameters less than 2 μm (25).

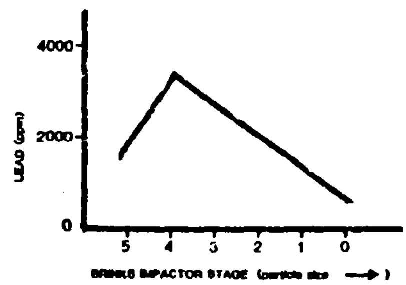

FIGURE 1. UNCONTROLLED PARTICULATE COLLECTED WITH BRINKS IMPACTOR AT ST. LOUIS DEMONSTRATION PLANT

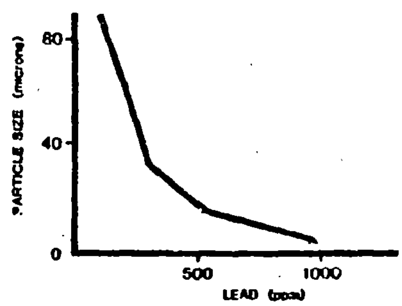

FIGURE 2. RETAINED FLY ASH COAL-FIRED POWER PLANT

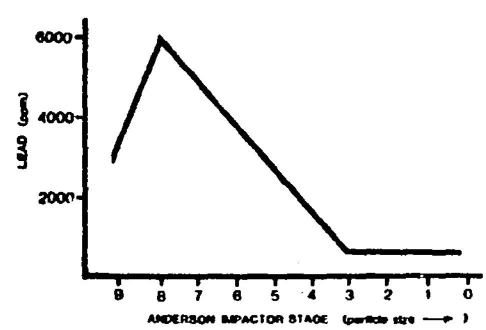

FIGURE 3. SUSPENDED PARTICULATE COLLECTED WITH ANDERSON IMPACTOR - ST. LOUIS DEMONSTRATION PLANT

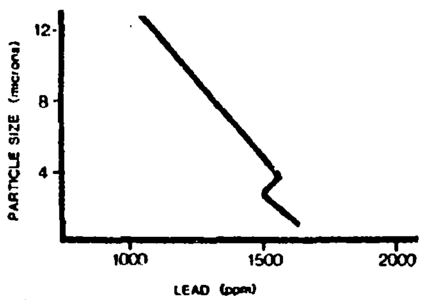

FIGURE 4. SUSPENDED PARTICULATE - COAL-FIRED POWER PLANT

When analyzing data from different sources it became evident that rarely do the mass balances close reasonably. It would appear that some of the lead simply cannot be accounted for. In the Ames facility, for example, 445 g of lead per Mg of fuel burned were expected in the emissions according to the mass balance, however only 203 g per Mg of fuel were detected by emission testing. In St. Louis, 43 g of lead per Mg of fuel was calculated to be released in the stack, however only 3.6 g of lead per Mg of fuel were found in the emissions. This situation has also been reported for coal-fired power plants (27) and for waste motor oil combustors.

Although in the case of MSW and RDF burning facilities some errors can be expected because of the heterogeneity of the materials to be sampled and hence, the difficult task of obtaining a representative sample, it seems puzzling that almost always, a "loss" of lead occurs. Furthermore, in the case of coal or waste oil, the lack of homogeneity excuse does not seem valid.

The problem could also be in the sampling of the bottom ash. This is suggested by the fact that a wide range of lead concentrations (from less than 1 ppm up to several hundred ppm) have been found in the bottom ash at the various plants.

The possibility exists also of lead exiting the stack in the vapor form or as very small particles, undetected by standard particulate collector trains. In any case, further investigation should be performed to determine the fate of that "missing" lead.

Particulate Emissions from Stationary Combustion Sources

Most of the lead that leaves the combustion zone is carried on the surface of particulate entrained in the combustion gases, with the relative concentration of lead on these particles a function of their size. Hence, the amount of particulate emitted and the size distribution of these particulates are important factors to be considered.

The amount and characteristics of uncontrolled particulates produced by stationary combustion sources depends upon several factors, including:

- o Type of the fuel burned
- o Mode of combustion (suspension firing, stoker, etc.)
- o Degree of mixing
- o Combustion chamber design
- o Boiler parameters (load, air supply, combustion zone temperature profile, heat rate, etc.).

Hence, substantial differences in lead emission levels can be expected for different waste-to-energy facilities.

Table 5 and Figure 5 present particulate emission rates for several stationary combustion sources and their effect on particle size distribution.

CONTROL OF LEAD EMISSIONS

The elimination of lead from MSW prior to burning does not appear economically feasible at this time. Separation of the inorganic fraction containing a portion of the lead is feasible and routinely performed in the manufacture of RDF. This, of course, will reduce the amount of lead per unit weight of the combustible (organic) fraction. Nevertheless, the RDF still contains a average 350 ppm of lead, as previously discussed. That lead is inherently attached to the very materials that form the combustible fraction and the RDF in the form of pigments and stabilizers. Although several methods exist for "de-inking" paper, the use of such techniques to

TABLE 5. PARTICULATE EMISSION RATES

Type of Plant	Emission Rates	(Kg of Part./Mg of Fuel)
Municipal Incinerators without heat recovery (39)	13	
Municipal Incinerators with heat recovery (5)	10	
Pulverized Coal (10% ash coal) (5)	80	(80% of total coal ash)
Stoker (10% ash coal) (5)	50	(50% of total coal ash)
Cyclone (5)	10	(10% of total coal ash)
Cofiring-Tangential Firing (7% RDF + 8.6% ash coal) (14)	46	(42% of total fuel ash)
Cofiring-Spreader Stoker (19)	45	(22% of total fuel ash)

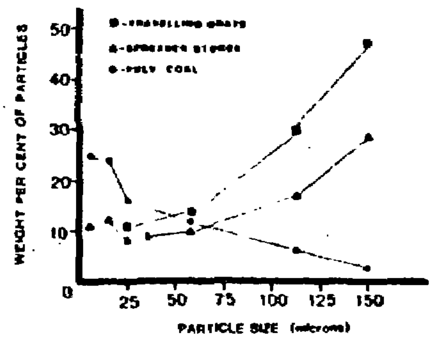

FIGURE 5. TYPICAL PARTICLE SIZE DISTRIBUTIONS OF VARIOUS COAL COMBUSTION SYSTEMS

remove lead from a material that will ultimately be used as a fuel is not economically attractive at this time. No other technology that would be used to eliminate lead prior to combustion has yet been commercially demonstrated.

No information about methods to retain the lead during the combustion process were found, although limited data from the combustion of MSW with sewage sludge suggests that a reduction in lead emission may be possible with co-disposal, another area deserving further investigation. (6)

At the present time it appears that the reduction of lead emissions from MSW/RDF burning facilities is restricted to particulate control in the stack gases.

The difference between various control systems in their capacity to retain lead is directly related to their capacity to control fine particulate. This is evident from emission data obtained from three different municipal incinerators for which it is valid to assume similar composition of the MSW burned. These data are presented in Table 6.

The difference between the total efficiency of particulate control devices and their efficiencies to control lead is evident from data reported from the Ames (16), St. Louis (22), and Braintree (15) facilities, as shown in Table 7.

POTENTIAL LEAD EMISSIONS

As previously discussed, there are a variety of factors that can influence the amount of lead emitted from stationary combustion sources. Unfortunately, only a few waste-to-energy facilities have been comprehensively tested for lead and the results published.

The criteria used to obtain samples from the different streams have not always been the same, neither have been the analytical techniques used to determine lead concentration in those streams. Furthermore, mass balances for lead were very difficult to close, hence to predict lead emission rates accurately based solely upon the data available is all but impossible. Nevertheless, an assessment of the magnitude of these emissions can

TABLE 6. LEAD EMISSION RATES FROM INCINERATORS WITH DIFFERENT AIR POLLUTION CONTROL EQUIPMENT

Incinerator	Particulate Control Equipment	Lead Emissions g/Mg of MSW burned
Nicosia	Plate (water, counter-flow) scrubber	280
Alexandria	Spray (baffle) scrubber	272
SWRS #1	Spray quenching/multiclone/ESP	35

TABLE 7. OVERALL AND LEAD REMOVAL EFFICIENCIES

Plant	Particulate Control Device	Overall Efficiency %	Lead Removal Efficiency %
St. Louis (coal/RDF)	ESP	90-99	47
Ames (coal/RDF)	Multiclone	82-92	7
Braintree (MSW)	ESP	74	53

be obtained making certain simplifying assumptions. Table 8 identifies the plants that have been tested for lead emissions, the type of fuel burned, the air pollution control equipment used and the lead emission factors based upon the combustible fraction of MSW. Whenever possible, emissions have been calculated through mass balance.

All the existing and planned waste-to-energy facilities in the United States can be grouped into four different categories represented by the plants in Table 8.

It can be assumed that all the plants in each category will behave, with respect to lead emissions, as the one that represents that category, indicated in Table 8. Then, knowing the nominal capacity of each plant (12) (36) (42) and using the lead emission rates from Table 8, the total lead emissions that can be expected, if all the plants become operational at full capacity can be calculated.

This esitmate assumes that all f-RDF and p-RDF produced will be cofired in facilities similar to those at Ames and

TABLE 8. PLANTS THAT REPRESENT DIFFERENT CATEGORIES OF WASTE-TO-ENERGY SYSTEMS

Plant (Category)	Fuel	Particulate Control Device	Stack Lead Emission Factors (g lead/Mg MSW) Combustible Fraction
St. Louis (14) (co-firing)	Coal/f-RDF (8%)	ESP	305*
Ames (19) (co-firing)	Coal/f-RDF (20%)	Multiclone	896*
Arlington (12) (co-firing)	Coal/d-RDF	Multiclone	82
Braintree (13) (w.w. incinerator)	MSW	ESP	52
North Little Rock (11) (MCU)	MSW	None	95
Baltimore (22) (pyrolysis)	MSW	Wet Scrubber/Dehumidifier	9

* Calculated through mass balances.

St. Louis; that d-RDF will be fired as in the Arlington plant; that water wall incinerators will produce emissions similar to those produced by the Braintree facility and that all modular combustors will behave at the North Little Rock Unit.

Table 9 identifies the number of facilities of each category which are planned to become operational by 1985, (10) (32) (37) (38) the total MSW that will be processed and/or burned and the expected lead emissions.

The figures indicate that if 30 million tons of MSW are processed and burned there is a potential for the emission of 1500-6000 Mg of lead per year and as it has previously stated, much of this emission will be in the form of very fine particulate matter, in the respirable size range.

If resource recovery activities advance at the expected rate (10), it is projected that by 1990, 50% of the MSW generated in the 150 largest urban areas in the U.S. will be processed in resource recovery facilities. This amounts to about 34% of the total MSW generated in the whole country. The technologies that are most likely to be pursued are those that allow for recovery of both materials and energy. Therefore, it can be readily appreciated that the potential emissions of lead from MSW/RDF combustion could reach 12,000 Mg/year by 1990.

The figures for the potential emission of lead can be put in perspective by comparing them to estimated atmospheric lead emissions from other sources. Thus, gasoline combustion is estimated to have been responsible for the atmospheric emission of about 140,000 metric tons of lead in 1975 (1). Projected lead emissions from MSW/RDF combustion are small compared to those of automobiles, they are similar to the 1975 estimate of 10,000 Mg of lead emissions from waste oil combustion (1), and are far greater than the 640 Mg emitted from coal combustion in 1975. (8)

POSSIBLE EFFECT ON THE AMBIENT AIR

One of the criteria by which emissions of lead from RDF/MSW combustion will be judged, is certain to be the effect of these emissions upon the national ambient air quality standard. The standard of 1.5 μg of Pb/m^3 is set on the basis of a time weighted average calculated over a calendar quarter.

Some simplified calculations were performed to determine the instantaneous effect of emissions from the St. Louis, Ames and Braintree facilities. (35) (46) The calculations were intended to show the maximum emission rates that can be tolerated without having the instantaneous maximum, ground level, downwind lead concentration in the ambient air exceed 1.5 $\mu g/m^3$

The values obtained must be viewed with caution. In the first place, the calculations assume that the emission source is sitting on flat, featureless terrain with a normal, rather than invert-

TABLE 9. NUMBER OF PLANTS, CAPACITY AND POTENTIAL LEAD EMISSION FOR EACH CATEGORY

Type of Plant	No. of Plants in U.S. (Operational, in Construction and Planned (12) (36) (42)	Total Nominal Capacity Mg of MSW Processed Per Day (12) (36) (42)	Potential Lead Emission (Mg/Year)
Waterwall Units	34	46,668	497
Modular Combustion Units	16	2,123	38
RDF Plants	29	33,100	925-4935
Pyrolysis	4	1,800	4
Undecided (RDF)	1	3,000	83-447
TOTAL	84	86,691	1547-5921

Possible Emissions were calculated for an average of 50 weeks a year at 6 days a week of operation, using emissions factors shown in Table 7.

ed, temperature gradient. Local topography and atmospheric conditions could, in a real case, give rise to results which may be dramatically lower or higher than those that have been calculated. Secondly, it must be noted that at any site, it is almost impossible that steady state conditions will occur for extended periods of time. In the natural meteorological progression, the emissions from a given source will be spread over 360° according to the local wind rows. Accordingly, the three month average of the lead concentration at any given site can be a fraction of the instantaneous values that have been calculated.

The results of these calculations indicated that for the St. Louis facility there is a broad set of conditions where the actual emissions from the plant are at a level that could cause the instantaneous, maximum, ground level concentration to be at least 25% of the standard. For the Ames and Braintree sources there are a number of conditions that would give rise to instantaneous, maximum downwind, ground level concentrations of lead that are 35% to 45% of the standard.

The standard is, of course, based on a three month average, and it is certain that changing atmospheric conditions will, in any three month period, tend to disperse the emissions over a much broader area than that considered in the calculations.

It is, therefore, highly improbable that the emissions from any of the sources studied in themselves would cause a violation of the national ambient air standard. On the other hand, allowing for changing wind directions and meteorological conditions, it seems possible that all of the sources could emit sufficient lead to consume a significant fraction of that allowed by the national ambient air quality standard.

The calculations made are of a type which serve to make preliminary estimates of concentration of species in the ambient air. However, the results do indicate that the effect of a given RDF/MSW combustor upon lead in the ambient air, cannot be dismissed lightly. It would seem prudent to extend the calculations in a more rigorous manner prior to making any definitive statements.

CONCLUSIONS

- Lead mainly in the form of pigments and stabilizers, is an inherent part of much of the combustible fraction of municipal solid waste.
- Lead in the combustible fraction of municipal solid waste, as well as in refuse derived fuel, is present at about 350 ppm.
- Good mechanical separation of the combustible and non-combustible components of municipal solid waste will help to reduce the amount of lead in MSW and RDF. However, it will not solve the problem.
- At present there are no economically feasible, commercial methods for disassociating lead and its compounds from the combustible fraction of municipal solid waste.
- When MSW or RDF is combusted, much of the lead is emitted with particles that are extremely small and difficult to retain effectively in conventional particulate control devices. Multiclones are very inefficient in the retention of lead and ESPs have a better performance although they retain only about 50%. Baghouses probably could be the solution to the problem.
- The assessment of lead emissions via the collection of particulate material on a 0.3 μm filters, may be underestimated. Since a significant proportion of lead is likely to be associated with submicron particulate matter, or may even be in the vapor phase, it is possible that some proportion of the lead may not be captured in the sampling train.
- The studies of lead emissions published in the literature are not consistent in two critical areas - the collection of representative samples and the analysis of these samples. These deficiencies make for difficulty in the comparison of data.

- Emission of lead from the combustion of MSW or RDF may be responsible for the emission of 1500-6000 Mg of lead per year into the atmosphere by 1985. The figure could approach 12,000 Mg/year by 1990.

- At least 50% of the lead will be emitted on particles with aerodynamic diameters below 2 μm.

RECOMMENDATIONS

- The suspicion that emissions of lead may be underestimated as a result of lead passing through the sampling device, warrants further investigation.

- Although particulate control devices can capture a portion of the lead-bearing particulates, there is considerable room for improvement. Effort in this direction would be well advised.

- Selected MSW or RDF combustion units should be studied in a specific, carefully designed, well thought manner, for the purpose of accurately determining lead emissions.

- Atmospheric modeling calculations should be performed to provide realistic estimates of the effect of individual emission sources upon the concentration of lead in the ambient air.

- The idea of curtailing the use of leaded pigments in paper should be studied.

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HEALTH AND SAFETY ASPECTS OF RESOURCE RECOVERY

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ABSTRACT

Health and safety concerns have been addressed by all major sectors of the resource recovery community. To date, there is no evidence that resource recovery poses any significant and unmanageable risks to health or safety but there have been concerns raised about dusts, airborne microorganisms, noise, explosions and fires that may be encountered during refuse processing. The response of the resource recovery community to these concerns is reviewed for the examples of microbiological aerosols and explosion protection.

EPA, particularly the Municipal Environmental Research Laboratory, has played a major positive role in identifying and helping to resolve health and safety problems. Important roles have also been played by other governmental agencies, by private companies and by non-profit organizations.

Although some issues have been mishandled and some remain to be resolved, the response has generally been straightforward, technically sound and marked by an unusually high degree of government-industry cooperation.

Introduction

Not long ago, a headline in a major U.S. newspaper began with the phrase, "Health Hazards Beset Trash-Fired Plant." The rest of the article then proceeded to describe a variety of problems allegedly associated with this plant but, beyond the headline, there was no further mention of any specific health hazards or health effects attributable to the plant. The purpose of this illustration is not to comment upon the issue of whether health problems really did exist at this plant, but simply to point out that health hazards make headlines.

Several years ago, a major U.S. magazine included in an article on problems facing resource recovery the reported emission of bacteria from a demonstration facility in concentrations of up to one million (per cubic foot of exhaust air). The implication of the article was that large numbers of airborne microorganisms meant large risks to human health. No attempt was made in the article to quantify the risks or even to explain that the measured emission concentrations did not represent human exposures. The purpose of this illustration is not to criticize the magazine but only to indicate the difficulty of expressing health risks in straightforward, quantifiable terms.

Both because of the attention it attracts and the confusion it can create, the subject of health and safety aspects of resource recovery is difficult to address. The middle ground between alarmism and Pollyannaism is often difficult to find, not just when writing news articles but, more importantly, when attempting to identify and control whatever health or safety hazards may exist.

Generally, the resource recovery community--governmental agencies and private companies alike--have acted responsibly to protect the health and safety of those who work in the industry and those who live near resource recovery facilities. This is not to say that every potential hazard has been remedied immediately or that there have not been a few false alarms raised, but on balance, the record is a good one. To date, there is no evidence that resource recovery poses any significant and unmanageable threats to health or safety.

A historical review of the handling of health and safety issues in resource recovery suggests that there has been a pattern to the way in which these issues have been dealt with. The pattern has often begun in an atmosphere of anxiety and confusion but has often ended in a condition of reasoned response. In between, a process has been evolving that may well signal two encouraging trends. One trend is towards the application of state-of-the-art science to clarify the nature and extent of health or safety hazards at resource recovery facilities and to develop methods for controlling these hazards. The second trend is toward increasing government-industry cooperation in identifying and correcting potential health or safety problems.

As a means of illustrating how this process seems to be working, it is worthwhile reviewing two examples. These examples are chosen because they cover two of the three major health and safety areas that are of concern to the resource recovery community. These two areas are: a) microbiological aerosols generated during refuse processing; and b) explosion protection, especially during refuse shredding. A third major area, air emissions from refuse combustion facilities, has already been covered in two preceding papers.

Microbiological Aerosols

It is obvious to any observer of a refuse-processing facility (whether processing is for resource recovery or not) that the processing generates airborne dusts. Not as obvious, but of concern, is that, because these dusts originate in municipal refuse, they may contain chemical compounds and/or microorganisms of potential health significance.

The first published reports in which airborne dusts from a resource recovery plant were sampled and analyzed for microbiological content were based on testing of the St. Louis Resource Recovery Demonstration Plant.[24] This plant was constructed and operated as an EPA-supported demonstration of the processing of refuse to produce refuse-derived fuel (RDF) and to recover ferrous metals. Over the period 1974-1975, EPA's Municipal Environmental Research Laboratory (MERL) sponsored a series of tests at the St. Louis plant, including an environmental evaluation.

The 1974-75 environmental evaluation of the St. Louis plant was designed to include noise sampling, wastewater sampling and determination of total particulate emissions. What attracted most attention and raised serious concerns, however, was a small series of bacterial and viral analyses conducted on samples of dust emissions from the exhaust ducts of the air classifier and the RDF storage bin.

By EPA's own description, these early measurements of microbiological aerosols at the St. Louis plant were "cursory" and were not intended to be representative of conditions at the St. Louis plant itself, much less all refuse processing facilities. Cursory or not, the reported bacterial concentrations of one million per cubic foot and the reported detection of viruses aroused serious and understandable concern within the resource recovery community and identified the need for a much more thorough assessment of microbiological aerosols at resource recovery plants.

The limitations and inadequacies of the 1974-75 tests of microbiological aerosols at the St. Louis plant were acknowledged by EPA and included:

a) lack of background data on microbiological concentrations in ambient air or in other types of waste-processing facilities;
b) lack of sampling in areas where workers or the public could actually be exposed to the microbiological aerosols;
c) absence of standard methods for sampling airborne bacteria or viruses;
d) sampling confined to only one plant, a demonstration facility not designed for long-term operation and therefore not equipped with a dust cleaning system;
e) lack of quantified data on the concentrations of specific pathogens that may have been present among the large reported

counts of total microoganisms;

f) lack of confirmatory data on the presence of viruses; and

g) lack of health effects data on which to judge the potential significance of measured concentrations.

Because of these acknowledged deficiencies in the initial St. Louis report, EPA-MERL supported a second series of tests at the St. Louis plant. The tests took place over the 1976-77 period.* For this second series of tests, sampling protocols were carefully designed and reviewed, ambient concentrations (both upwind and downwind) were measured, samples were taken in areas where workers might be exposed, analyses for specific pathogens and for viruses were performed, and the effect of dust cleaning was evaluated. Importantly, the tests were extended beyond the St. Louis plant to include an incinerator, a landfill, a transfer station, a sewage treatment plant and the back of a refuse collection truck.

The results of the 1976-77 tests suggested that bacterial concentrations recorded in and around the St. Louis plant fell on the high side of the range of concentrations measured in and around other waste treatment facilities.[8] The quantitative differences in concentrations between resource recovery plants and other facilities were shown to be much smaller for specific pathogens than for total organisms. No viruses were detected in any of the facilities studied. A small number of baghouse system tests revealed that conventional dust cleaning equipment was effective in removing airborne microorganisms.

This second series of St. Louis tests did not overcome all of the shortcomings of the initial series but, both directly and indirectly, the second series represented significant progress in the assessment of the "microbiological aerosol problem." Among the direct accomplishments were:

a) first-of-a-kind comparison of microbiological concentrations in in-plant and ambient air at several types of waste processing facilities using a fixed set of sampling and analytical protocols;

b) reporting of concentrations of potentially pathogenic organisms as well as total and indicator organisms;

c) acknowledgement that the previously reported detection of viruses could not be confirmed and may well have been in error;

d) illustration of the large degree of temporal and locational variability among reported concentrations of airborne bacteria and of the imprecision of the sampling and analytical protocols;

e) review of the literature on infective dosages in an attempt to guide the interpretation of the health significance of reported concentrations; and

f) empirical demonstration of the ability of conventional dust cleaning equipment (i.e., fabric filters) to remove airborne bacteria.

The 1976-77 tests at St. Louis were still based on sampling at a plant without dust controls and did not resolve such issues as the effects of employing a dust control system in a full-scale plant or the health significance of exposure to airborne bacteria. The St. Louis tests did, however, stimulate a number of efforts to better understand and control microbiological aerosols at solid waste processing facilities.* Government-sponsored efforts included: EPA-MERL support for testing at refuse processing pilot plants at Richmond, California and Houston, Texas;[4,18] Energy Research and Development Administration (ERDA, now Department of Energy or DOE) and EPA support for testing at the Ames, Iowa resource recovery facility;[12] and DOE support for development and evaluation of improved sampling methods at

*Actually, by the time this second series of tests were conducted at the St. Louis plant, the demonstration program had ended and the plant had been closed. Therefore, the plant had to be returned to operation solely for the purpose of conducting the microbiological aerosol tests.

*It is noteworthy that although this paper focuses on solid waste processing, there has been considerable research on the microbiological aerosols generated during sewage treatment and spray irrigation.[1,2,10,25,26] Much of this research has been supported and/or stimulated by EPA and has complemented the solid-waste related research.

the Ames-DOE Laboratory.[15] Industry-sponsored efforts included testing of dusts at the National Center for Resource Recovery's pilot plant in Washington, D.C.,[6] and several unpublished studies of microbiological aerosols at full-scale resource recovery plants. Interest in airborne microorganisms extended to other countries and sampling programs were conducted at waste processing facilities in England, Sweden, Switzerland, and Brazil.[3,5,17] An action taken independently of governmental agencies and specific companies was the formation of a health and safety subcommittee (designated as E-38.07) within the American Society for Testing and Material (ASTM) Committee E-38 on Resource Recovery.[7] Functions of this ASTM Subcommittee are discussed later in this paper. The results of the St. Louis studies and the other efforts cited above were a better understanding of the microbiological aerosol issue and a refinement in the technique employed to address the issue.

Building upon the experience of these earlier efforts, the National Institute for Occupational Safety and Health (NIOSH) is currently sponsoring a series of industrial hygiene surveys of selected full-scale resource recovery facilities. The NIOSH contractor for these surveys is the Midwest Research Institute. Included within these surveys is a microbiological aerosol sampling and analysis program which is more extensive, more technically advanced, and more carefully controlled than any previous program of its type. The NIOSH-sponsored program includes quantitative analysis of specific pathogens, size fractionation of airborne bacteria, detailed quality control procedures and an experimental attempt to detect viruses. It is interesting that municipal and corporate operators of the selected resource recovery facilities have voluntarily agreed to have their plants surveyed and, in some cases, have actually requested that their plants be included in the survey.

The NIOSH survey is still in progress and no final reports have yet been published. Preliminary data has been presented, however, and these suggest several findings.[16] For example, conventional dust control systems, as installed in most full-scale resource recovery facilities, have been shown to reduce airborne concentrations of microorganisms to levels 10 to 100 times below those recorded in pilot plants not equipped with dust controls. Reported concentrations from the full-scale plants are still generally higher than concentrations reported for ambient air or for air within manufacturing plants but are at or below the levels reported for other types of waste-processing facilities. Some specific pathogens have not been detected at all (e.g., Salmonella, Shigella, Nocardia asteroides) and others have been detected sporadically and in low concentrations (e.g., Staphylococcus aureaus, Mycobacterium sp.). Some microorganisms (e.g., Klebsiella pneumoniae and Aspergillus fumigatus) have been recovered in as many as one-third of the dust samples collected but in concentrations that, on a daily basis, could account for no more than 10% of the reported infective dose.[9,13,14] No viruses have been recovered in any of the samples to date. The final report of the NIOSH-sponsored study is scheduled to be available by June, 1981.

Explosion Protection

Interest in explosion protection arises from two features of refuse processing plants. First is the fact that the solid waste stream can contain flammable and/or explosive materials, including gasoline, solvents, propane, and even discarded military ordnance. Second is the opportunity, during various stages of processing, for these materials to accumulate and mix with air to form explosive concentrations before encountering a source of ignition. Shredders, dust hoods, pneumatic ducts, cyclones, and storage bins are examples of places where explosions have occurred in refuse processing plants.

Refuse processing is not unique in providing an opportunity for explosions. Dust explosions during the milling of grain have been reported since early in the 1900's. Coal dust explosions within ball mills continue to be of great concern to utilities and others using pulverized coal as a boiler fuel. Explosions involving gasoline, solvents and propellants have been reported among scrap processing plants and other industrial facilities.

Within these other industries and

within the refuse processing community, most of the concern for explosion protection has been focused on shredders, or more generally, size reduction equipment. This is understandable for several reasons. Shredders are often the first step in the process flow through a refuse processing facility. In some cases (e.g., shred and landfill operations), shredding may be the only processing step, and many resource recovery plants that recover materials employ some type of size reduction equipment. Also, shredders can provide the conditions (enclosed space and metal-to-metal sparks) that can lead to accumulation and ignition of explosible gases or vapors.

The first detailed investigation of explosions within refuse shredding plants was sponsored by ERDA (now, DOE) in 1976. Just as in the case of the initial St. Louis tests for microbiological aerosols, the ERDA-sponsored study of explosions came about almost as an afterthought. During ERDA's review of plans for a demonstration plant for biological conversion of refuse to fuel gas (the Pompano Beach, Florida project), questions were raised about the safety of shredding refuse in preparation for biological digestion. To answer these questions, ERDA commissioned a survey of explosions that had occurred in refuse shredders.

The ERDA-sponsored study documented over 100 explosions that had taken place at refuse processing facilities (primarily shred-landfill operations) over a three-year period.[27] The study excluded such incidents as "pops" due to aerosol cans and reported that three of the 100 explosions had resulted in injuries (none fatal) and five had caused more than $25,000 in damage. The study determined that most shredder explosions are due to flammable vapors and gases rather than dusts. An important feature of the study was the identification of approaches to preventing and controlling explosions in refuse processing plants. These include: removal of explosive materials from the waste stream; provision of a venting system to relieve pressures; use of chemical explosion suppression agents; and the isolation or shielding of plant personnel from likely explosion areas.

The reaction to the ERDA-sponsored survey of shredder explosions was more muted than had been the reaction to the EPA-sponsored St. Louis tests. The explosion survey did not immediately launch a series of follow-up studies nor did it attract as much attention in the news media. There were, however, several follow-up activities that did occur. A subcommittee on explosion safety was formed within the Waste Equipment Manufacturers Institute of the Natural Solid Waste Management Association. Several articles appeared in the trade journals of the solid waste industry.[22,23] Approaches to controlling shredder explosions were developed by shredder manufacturers and at least one operator of a refuse shredding plant[20,21] but the interest in such approaches had not yet peaked within the industry.

Unfortunately, and peculiarly, the event which probably accounted for renewed interest in refuse shredder explosions was a highly publicized explosion that did not occur in a refuse shredder. This was the explosion that occurred in November 1977 at the East Bridgewater, Mass., resource recovery plant. The explosion killed one worker at the plant. Apparently, the explosion took place in a cyclone designed to de-entrain pulverized refuse-derived fuel from a pneumatic conveyor. The causes of this explosion were never conclusively determined.

The renewed interest that followed the tragic accident at East Bridgewater was sustained by several other explosions at resource recovery facilities and eventually stimulated a major EPA-supported investigation of explosion venting systems for refuse shredders. This study, which is still in progress, is significant not only because of its technical subject but also because of the way it was originated and is being managed.

Technically, the explosion venting study is the first rigorous (and non-proprietary) investigation of explosion protection for refuse shredders. Venting is viewed by many as an essential form of passive explosion protection for industrial equipment in which explosions may occur.[19] The current study is designed to apply generally recognized principals of explosion venting to the specific circumstances of a refuse shredder. This is being accomplished by actual explosion testing of various vent configurations on a mock-up of a refuse shredder. Details of this testing program are described in a paper presented earlier in this conference.

The results of the shredder venting tests are to be available later this year and should be useful as a guide for the design of venting systems.

The initiation and mangement of the current shredder venting investigation represents an unusual degree of cooperation among all parties involved. As noted, there had been considerable industry interest stimulated by the ERDA-sponsored survey and by the explosions that had occurred. This interest was noted by another agency, EPA-MERL, and, in late 1978, EPA tentatively decided to support a follow-up study in the general area of explosion protection. Before deciding on the specific scope for the study, however, EPA sought the opinions of refuse processing system designers and operators familiar with the explosion protection problem. The major vehicle for seeking such opinions was a newly-formed explosion protection task group within the aforementioned ASTM subcommittee on the Health and Safety Aspects of Resource Recovery (E-38.07). This task group contains representatives of shredder manufacturers, engineering firms, governmental agencies, research organizations and other explosion protection specialists. The group recommended that EPA focus the study on the design and testing of venting systems and offered its services for periodically reviewing the results of the study. [To avoid any potential conflicts of interest, the task group was not involved in selection of an EPA contractor to conduct the study.] As the study has progressed, the EPA contractor (Factory Mutual Research Corporation) has reviewed its research plan with the ASTM task group and has presented formal progress reports at the regular (semi-annual) meetings of the group. Current plans call for the task group to be the vehicle through which the results of the EPA-sponsored study will be incorporated into an ASTM standard for the explosion venting of refuse shredders.

Conclusion and Research Needs

Despite some dissimilarities, the microbiological aerosol and explosion protection examples seem to fit a pattern that has also been followed for such topics as stack emissions from refuse-combustion facilities and physical and chemical characteristics of dust concentrations within refuse processing plants. The pattern begins with an initial (sometimes inadvertent) finding or event that usually generates concern and controversy, but not understanding. The intermediate steps in the pattern tend to document the nature of the concerns. The later stages employ advanced techniques of sampling, analysis and control to provide sound advice on how best to reduce any risks to health or safety.

Obviously, it is oversimplification to suggest that all safety and health problems in resource recovery have been handled smoothly and according to a fixed pattern. It is fair to say, for example, that EPA mishandled some of the early publicity on the St. Louis microbiological aerosol results and that private companies were slow to respond to the early warnings on shredder explosions. On balance, however, the pattern has been a positive one and has been marked by honest concern, careful analysis, informed application of control technology and productive industry-government cooperation.

One vehicle for industry-government cooperation has been the above-mentioned ASTM E-38.07 subcommittee. ASTM is the world's largest voluntary consensus standards-setting organization and it provides an excellent setting for cooperation of the type needed on health and safety topics. The membership of the E-38.07 subcommittee is drawn from all major segments of the resource recovery community. Among the subcommittee's current activities are the development of a standardized method for sampling microbiological aerosols, the compilation of explosion protection guidelines, and the preparation of recommended practices for health record-keeping in resource recovery facilities. Both NIOSH and EPA have used the subcommittee as a mechanism for independent and interested review of the progress of studies of health and safety issues in resource recovery.

It is encouraging to note the progress that the resource recovery community has made in addressing health and safety issues. It is now almost common practice for the design of a resource recovery facility to include dust cleaning systems and shredder explosion venting systems. EPA has played a major--and generally positive--role in enabling resource recovery to make such progress. NIOSH, DOE (especially the Ames Labs) and several companies have also made large contributions.

There are, however, health and safety issues which remain to be resolved. Among these are: documentation of health and safety experiences among resource recovery workers as compared with workers in other industries; development of improved sampling methods for airborne viruses; validation of explosion venting guidelines in actual refuse shredders (as a follow-up to the current tests of a shredder mock-up), and determination of whether recently-imposed federal hazardous waste regulations will indirectly increase the amount of industrial wastes illicitly entering the municipal waste stream and, if so, what effect this might have on health and safety within a resource recovery facility.*

*The controversy surrounding the presence and potential health significance of dioxins, specifically 2,3,7,8-Tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD), in stack emissions from refuse combustion facilities could well be added to the current list of issues in need of resolution. To date this issue has not been addressed with either the scientific rigor or the government-industry cooperation which has characterized the handling of earlier health-related issues. There are some signs that this situation may soon improve.

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VERMICOMPOSTING OF MUNICIPAL SOLID WASTES

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ABSTRACT

This paper is an engineering and scientific assessment of municipal solid waste management by vermicomposting. Vermicomposting is the conversion of waste materials by earthworm consumption to castings which may be used as a soil amendment. The cost of vermicomposting is estimated to be high compared to those of alternative methods. For this reason, and because of the lack of established market for the castings, it is believed that communities have available to them technologies that are more attractive than vermicomposting.

Introduction

Vermicomposting is the degradation of organic wastes by earthworm consumption. Some species of earthworm (Eisenia foetida and Lumbricus rubellus) thrive in managed conditions on a diet and substrate composed almost entirely of organic matter. They feed on the wastes, consume a portion of the organic matter and expel the remains as feces, or castings.

After the worms have fed on the waste and converted it into castings, they are usually separated from the castings. Worms can be recycled into new vermicomposting beds or, possibly, marketed in some form. Castings, once dried, have properties that might make them a desirable soils amendment. A portion of the wastes is usually not biodegradable and simply remains as residue for disposal. The end products of vermicomposting, therefore, are worms, castings, and solid-waste residue.

The role of earthworms in nature has been recognized since ancient times and was studied extensively by the biologist Charles Darwin in the late 19th century. Despite this awareness, and despite the fact that successful culture of earthworms need involve no new technology, the practices of raising worms (vermiculture) and using them for waste management (vermicomposting) have not been advanced until recently.

There are now numerous individuals, gardeners and entrepreneurs raising worms in a soil/peat/manure bedding in indoor bins or outdoor plots; most of those practicing vermiculture depend heavily on the baitworm market to realize some income from the business.

Only since 1970 has the vermicomposting of wastes (including municipal solid waste) been attempted at more than backyard scale. Pioneering efforts commonly mentioned in the literature (3, 4) include a demonstration project at Hollands Landing, Ontario (Canada), which was begun in 1970 and has since been operated under private ownership. A pilot-scale, one-time demonstration of vermicomposting municipal solid waste (MSW), was conducted in 1975 at Ontario, California. Neither operation was conducted under the controlled conditions that would yield reliable engineering design parameters. The Hollands Landing facility has vermicomposted small amounts of manure, food-processing wastes, and sludge (Klauck, personal communication); the Ontario, California, project involved the vermicomposting of municipal refuse in a program jointly conducted by the City and North American Bait Farms Inc. The short-duration project involved a total of 10 tons of mixed municipal refuse, which was hand-picked to remove glass, metal, plastics, and rubber. The remaining 9 tons were windrowed adjacent to established earthworm beds at a wormbreeding farm. Reportedly, consumption of organics was 90-percent complete in 68 days. Only castings, bulky materials such as tree limbs, and inorganic residues remained.

In a later experiment at the same facility, a shredded and air-classified organic fraction of municipal solid waste was transported from a local resource-recovery facility. Reportedly, consumption of the wastes was faster and more complete than in the earlier experiments, even though the process was hampered by large quantities of plastic present in the waste and by very dry conditions resulting from the windrow's direct exposure to sunlight. No documentation is available on the amount of castings produced during the Ontario tests or their ultimate use.

Another demonstration of solid-waste vermicomposting was carried out in 1978-79 by the American Earthworm Company (AEC) in Florida (Wesley Logue, personal communication). This project involved vermicomposting, over a 12- to 18-month period, of about 500 tons of municipal solid waste. Wastes were trucked to a 1-acre vermicomposting facility in Sanford, Florida, where cans, large objects, and newsprint were removed by hand. The remainder was fed to a hammermill shredder, which reduced the wastes to a 3-in particle size. The shredded waste was placed in windrows about 6 in deep, which were irrigated to increase moisture. Moisture levels achieved and other pertinent data are not known. AEC used approximately one ton of earthworms in the vermicomposting operation. Reportedly, some of the finished castings, which contained glass, were utilized by a local nursery. The facility is no longer in operation.

Other work has been carried out in Japan, where some pulp and food processing industrialists have turned to vermicomposting techniques for management of sludges and waste byproducts (8). Information was obtained through two sources in the vermiculture industry: Aoka Sangyo Co. Ltd and Toyohira Seiden Kogyo Co. The Aoka Sangyo Co. reports they have three 1,000-ton-per-month plants processing wastes from pulp and food processing companies (Shizuro Aobuchi, personal communication). The operation appears to be labor-intensive, and the economics appear to depend heavily on disposal fees paid by the industry. Reportedly about 400 tons of casting and 10 tons of earthworms are produced per month. The earthworms are freeze-dried and sold as fish feed. Worm castings are also sold.

The Toyohira Seiden Kogyo Co. reports that rice-plant straw, municipal sludge, sawdust, paper-making wastes, food-processing wastes and manure are vermicomposted (Katsumi Yamaguchi, personal communication). They estimate that about 20 private companies with monthly capacities of 2,000 to 3,000 tons are in operation. An additional 3,000 individuals may be vermicomposting 5 to 50 tons of wastes per month. However, these estimates are only approximate as the enterprises are not well-organized.

In Europe, no commercial-scale vermicomposting operations have been reported in the literature. A demonstration facility was recently established in Modena, Italy, however (Carla Chiesi, personal communication). Reportedly, a screened and composted municipal refuse is fed to *Eisenia foetida*. In several other European countries, university laboratory research in waste vermicomposting is underway (5, 7).

Ogden, Utah Vermicomposting Pilot Program

When this study was conducted, the vermicomposting pilot facility operated at the Weber County Refuse Disposal Facility in Ogden, Utah, by Annelidic Consumption Systems, Inc., was the only operating vermicomposting facility in the United States exclusively utilizing municipal solid waste.

At the Weber County Refuse Disposal Facility, which is operated by Teledyne National, about 350 tpd of mixed, residential and commercial wastes are burned. Before combustion, the wastes are shredded to a nominal size of 6 to 8 in, and ferrous metals are removed by a magnetic pulley.

In early August 1979, operators at the Weber County Facility used front-end loaders to transfer approximately 47 cubic yards of shredded waste to three windrows in an area prepared for a sanitary landfill operation (Figure 1). Based on a field measured density of approximately 240 lb/cu yd, about 5.6 tons of wastes were windrowed. The windrows, each measuring 20 to 35 ft long and about 9 ft wide, were spaced 10 ft apart. The maximum depth of each windrow was approximately 3 ft. The windrows were watered to increase the moisture content.

After several days, temperatures began to increase in the windrows due to bacterial breakdown of organic matter (composting). The elevated temperatures continued through 27 August; windrow temperatures on that day were measured at about 32°C.

The windrows were wet down on 27 August, in order to drop temperatures within the range at which vermicomposting can begin. (After wetting, the windrows had a temperature of 24°C). At this point, some 1,450 lb of earthworms were applied to the windrows. The worms reportedly infiltrated the windrows within a day.

On three occasions during the next 35-day period, 1-ft increments of shredded and unshredded wastes were added at the top of each windrow. About 36 cu yd (4.4 tons) were added during this period; in all, a total of 83 cu yd (and 10 tons) of solid wastes were vermicomposted. For the next 1-1/2 months, the earthworms converted the waste to castings.

On 31 October 1979, four additional windrows were constructed between existing windrows. The new windrows contained about 13 tons of solid wastes and occupied about 1,050 sq ft. No new earthworms were added to these windrows. Some of the earthworms migrated from the first three windrows to the second set of windrows in search of more attractive food sources.

Facility workers began harvesting portions of the first three windrows on 14 December 1979, 100 days after earthworms were first added and about 130 days after wastes were first windrowed. In the judgment of Ronald E. Gaddi of Annelidic Consumption Systems, Inc., 90 percent of the wastes had been converted at this point.

Based on the screening results obtained later, however, a much lower percentage had been converted.

Harvesting was accomplished using an inclined cylindrical, rotating screen driven by a small motor, a type of device commonly used in vermiculture (Figure 2). In normal operation, this type of screen separates castings (which fall through the screen) from earthworms and residual solid waste (which travel the length of the screen and are discharged). Because of the large amount of plastic in the waste stream, however, and perhaps because not all wastes had been shredded properly prior to windrowing, the harvesting screen did not work very well. It was apparent that less than 50 percent of the material fed to the device was screened out as castings. Most of the material either had to be removed by hand from the front of the machine, which clogged repeatedly, or was discharged through the length of the harvester as residue. Very few earthworms were separated. Figures 2 also shows the castings recovered and the residue discharged. Figure 3 is a closeup of the discharge end of the screen.

In the spring of 1980, new windrows of prepared solid wastes were placed adjacent to the existing rows. It was anticipated that the worms would migrate into the ne material and begin producing castings there. The area was struck with heavy rains at about that time, and the worm populations migrated away from the piles. At that point, the project was abandoned.

In the literature, estimates of worms' performance in vermicomposting vary widely. Entrepreneurs working in the vermiculture industry routinely report that worms will consume one-half to twice their weight in waste each day. To provide a rational basis for the design of facilties, we calculated a consumption rate based on the experience at Ogden.

At Ogden, 10 tons of wastes were processed during a 110-day period using 1,450 lb of earthworms. This time does not include 3 weeks of composting prior to the introduction of earthworms, even though this preliminary composting is essential in order to maintain optimum temperatures during vermicomposting. The calculated conversion rate of vermicomposting at Ogden is, therefore, about 0.13 lb waste processed/lb of earthworms per day.

Area requirements for vermicomposting are determined from the ratio of the weight of earthworms utilized per unit of area. At Ogden, 1,450 lb of earthworms were applied to about 800 ft of windrows. The resulting worm: area ratio of 1.8 lb/sq ft compared with ratios used in vermicomposting of wastewater sludge of 0.4 to 2.3 lb/sq ft. (1).

Based on the conversion rate (0.13 lb wastes/lb earthworms per day) and area requirements (1.8 lb earthworms/sq ft of wastes) observed at Ogden, a loading rate of 0.23 lb/sq ft per day is calculated. Stated another way, each ton/day of waste requires about 0.2 acre, plus about 20 percent to allow for composting before worm addition.

In practice, earthworms would be added to the initial set of windrows. After 130 days, new windrows would be constructed between the existing windrows. This allows the earthworms originally added to the first set to migrate to the second set of windrows. Then the initial set of windrows are removed and screened. In this way, the land is used in 130-day cycles and earthworms are reused.

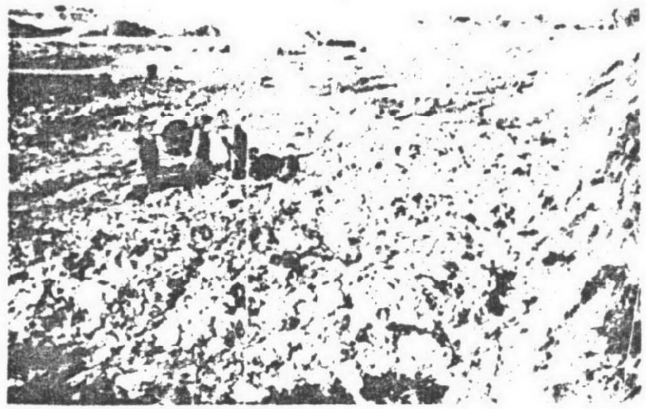

Figure 1: (left) Ogden, Utah, Vermicomposting Pilot Facility

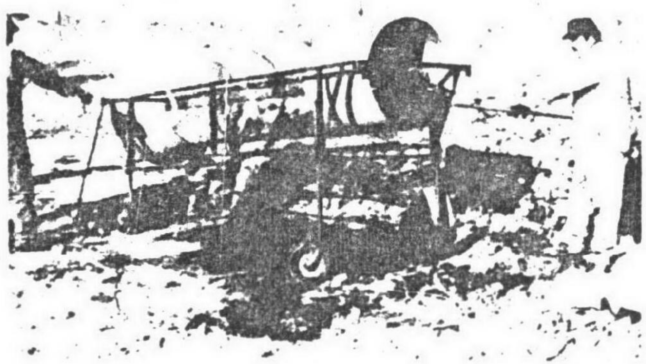

Figure 2: (left) Rotary Screening Device

Figure 3: (above) Solid Waste Residue

ACS speculates that under more favorable climatic conditions, and/or with an earthworm that is acclimated to solid wastes, only 70 days would be required for conversion (Gaddie, personal communication). If this were so, only 0.13 acre would be required for each ton/day of municipal wastes. Additional research could establish the time required for conversion under various loading and climatic conditions.

Analysis of Feasibility

For this purpose, CDM examined a hypothetical small facility and large facility. The small facility was defined as one receiving 100 tons per day of wastes, 6 days per week, representing the total mixed residential and commercial wastes of a municipality of about 50,000 persons. Bulky items such as "white goods" (large household appliances) and demolition wastes would be managed by separate collection. For a facility of this size, three other candidate waste processing techniques would be (1) sanitary landfill, (2) incineration of wastes in a modular combustion unit (MCU), a technique becoming economically attractive for small- and medium-sized communities with a large and stable market for the recovered energy and (3) windrow composting.

The large facility would receive 1,200 tpd of wastes, 6 days per week, representing residential and commercial wastes generated in a city or metropolitan area of about one-half million persons.

Area requirements for windrows alone, in the 1,200-tpd facility, would total 250 acres. Dedication of this much land to the vermicomposting process is inconceivable, and mechanization (for example in silos) has not been demonstrated. In this report, therefore, it is assumed that the municipality would already have in operation a 1,200-tpd facility converting solid waste to refuse-derived fuel (RDF) and recovering steam energy from incineration of the RDF. Only a small portion (92 tpd) of the shredded wastes would be diverted to the vermicomposting facility. This diversion would allow for production of humus material for local use. The fact that the necessary preprocessing would have been completed as part of an existing processing train would be expected to make the economics of vermicomposting as attractive as possible for a facility of this size.

Materials Balance

In a vermicomposting facility, different materials are removed at various steps in the process. In the process shown in Figure 4, ferrous material is removed in magnetic separation, moisture and volatile material is lost in vermicomposting, and residue from the screenings step is landfilled. Most likely, economics would not warrant further removal of material, but glass, aluminum and paper could be removed.

Figure 5 presents a materials balance adapted from Gaddie for a 100-tpd facility. In the figure, a large portion (36 percent by weight) would be removed before vermicomposting. Substances removed would include paper, glass aluminum, ferrous metals, and other items (23). Of the 64 tpd of solid waste to be vermicomposted, about 18 tpd would be ultimately landfilled. Of the remaining 46 tpd, about 70 percent (33 tpd) would be converted to castings, and 30 percent (13 tpd) would be volatilized or evaporated.

Figure 6 shows a materials balance for a waste stream exposed only to processes of shredding and ferrous removal prior to vermicomposting. In this case, approximately 92 tpd of the total received would go to vermicomposting. The

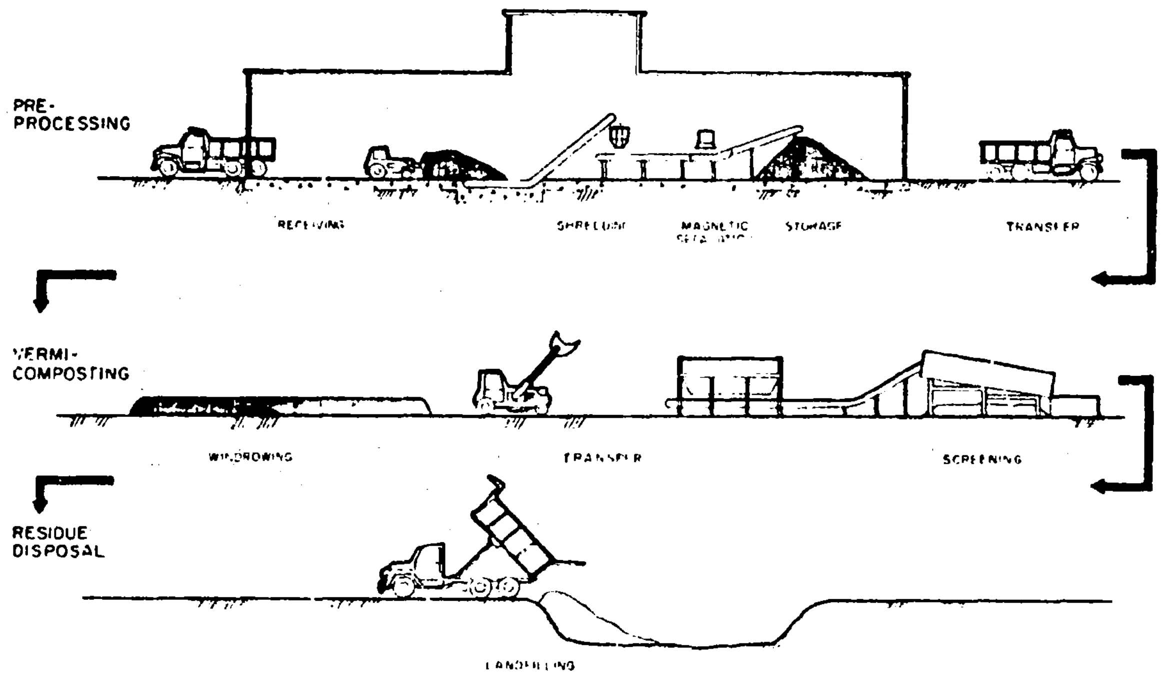

FIGURE 4. VERMICOMPOSTING FACILITIES

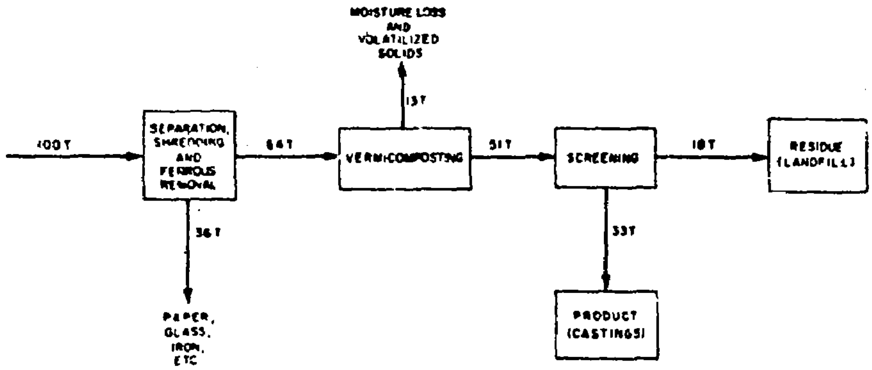

FIGURE 5 VERMICOMPOSTING MATERIALS BALANCE
(BASED ON ESTIMATES DEVELOPED BY ANNELIDIC CONSUMPTION SYSTEMS INC.)

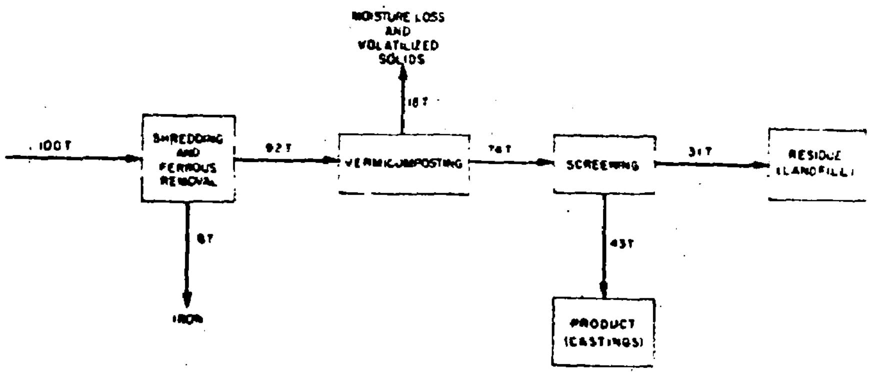

FIGURE 6. VERMICOMPOSTING MATERIALS BALANCE

remaining 8 tpd would consist of ferrous material recovered for sale. (Ferrous recovery may range between 6 and 10 percent, depending on local waste composition and facility design and operation.) The vermicomposting facility would also receive the 92 tpd of shredded wastes with ferrous material removed from the 1,200 tpd facility.

Of the 92 tpd diverted to vermicomposting, about 31 tpd -- including glass, rubber and wood wastes -- would be landfilled. The amount of castings produced would be 70 percent of the remaining portion, or 43 tpd. The other 30 percent (18 tpd) would be volatilized or evaporated.

It is important to note that none of the above estimates has been verified at actual demonstration facilities. The rotary screening operation at Ogden has not yielded the quantities of castings used for this report. As noted above, however, much of the work at Ogden has been carried out at less than optimum conditions and with some unshredded wastes present. The materials balance is optimistic in order to provide the most favorable economic analysis.

Preprocessing Facilities

Preprocessing facilities can be subdivided into units for receiving, shredding, magnetic separation, and storage of solid wastes. Figure 4 shows preprocessing, vermicomposting and residue disposal facilities for the 100-tpd facility. For the 1,200-tpd facility, separate preprocessing would not be required. Shredded wastes would be introduced directly to the windrows.

Collection and transfer of municipal solid waste would terminate at a receiving building, where refuse would enter the preprocessing system. There, the transfer-haul trucks would tip their solid waste onto the floor, where a front-end loader would stockpile it into the center of the building. Large bulky items, such as tree stumps and white goods, would be sorted out of the process stream by front-end loader, prior to dumping onto conveyors. Hand-sorting could be performed during the conveyor stage to eliminate a large portion of other unprocessable items.

Refuse then would pass into the shredder building. Particle size of the shredded product could be varied to meet the requirements of vermicomposting. A shredder would be expected to reduce refuse to a nominal 4- to 6-inch size. Annual maintenance costs for the shredder and building would be high in comparison to other equipment, due in part to the relatively frequent occurrence of damaging explosions.

For the 100-tpd facility, only ferrous removal could be economically justified. Aluminum recovery may or may not be justified, but its exclusion from this analysis will not affect the cost of vermicomposting relative to other methods. Further preprocessing, including the mechanical removal of glass and paper is not economically feasible at a small facility.

In the smaller facility (100 tpd), the shredded product would be bunkered in a passive, three-walled tipping floor arrangement. The waste would then be fed to trucks by front-end loader and transported to the vermicomposting facility.

For the larger, 1,200-tpd RDF facility, the processed waste (RDF) would pass from the shredder building via conveyor to a storage bin. This facility would incorporate live bottom hoppers to feed conveyors which, in turn, would feed semi-suspension boilers or transfer-haul vehicles. Prior to reaching the storage bin, approximately 92 tpd of processed waste would be redirected via a conveyor into trucks dedicated to hauling the processed waste to the vermicomposting facility.

Vermicomposting and Residue Disposal Facilities

The 92-tpd remaining after removal of ferrous material would yield a volume of about 900 cu yd/day at a density of approximately 200 lb/cu yd.

Figure 4 shows the major steps in vermicomposting: windrowing and screening. Shredded wastes would be trucked to nearby windrows and spread by a second smaller loader. This method would be less expensive than utilization of loaders alone because of the distance and time required to travel to the windows in a typical operation.

To determine the area required for vermicomposting, the assumptions presented above are followed. Total residence time would be 110 days, resulting in a loading rate of 0.23 lb waste/sq ft per day. An additional 20 percent is added to the area to provide space for preliminary composting. For a daily average loading of 92 tpd, the area requirement would be 23 acres, including land for an access road.

One possible site arrangement would be a configuration approximately 1,000 ft square. About 95 500-ft-long windrows could be accommodated on each side of a central access aisle. Each windrow would be 10 ft wide and 3 ft deep. Initially, wastes would be windrowed in every other row. About three 500-ft windrows would be constructed daily, and, during the first month after earthworm addition, three additional top-dressings of wastes would be applied to each windrow, as at Ogden. After one-half of the total area for windrows was constructed, shredded wastes would be windrowed on the alternate rows. The site would be equipped with a sprinkler system for initial moistening of the windrows to achieve the proper moisture content.

Based on pilot-plant experience, earthworms would be added to one-half of the windrows (480,000 sq ft) at a rate of 1.8 lb/sq ft; a total of approximately 430 tons of earthworms would be required for this initial earthworm addition. Earthworms recovered during harvesting would be reused for new windrow construction. Some of those working in the field (6) have suggested that excess earthworms could be produced during vermicomposting, but more research is needed to determine the rates at which earthworms will breed under conditions of vermicomposting. In order to reduce capital costs, several vermicomposting operators have suggested that only one-fourth to one-third of the total required stock might be purchased initially, with the process phased into full operation over a period of several months as excess earthworms are produced. For this report, we have assumed that one-half of the total area would be stocked with purchased earthworms because of the lack of data on earthworm production during vermicomposting. Even if minimal costs were included for earthworm purchase, the net costs of vermicomposting would be relatively unchanged with respect to other alternatives.

After a total residence time of 130 days, the wastes would be recovered from the windrows by a front-end loader. At this point, nearly all of the biodegradable portion that can be converted by earthworms would have been consumed. Approximately 450 cu yd (74 tons) of material would be removed daily. The wastes would be transported by front-end loader to a movable surge hopper located above a central collecting conveyor, which would move material to the screening area.

Two rotary harvesting screens, each approximately 6 ft in diameter and 12 ft long, would be employed; one screen would serve as a standby. The screens would be fed directly by the variable-speed conveyor. Castings would fall through the screen to a product storage pile. The operation could be expected to produce approximately 300 cu yd (43 tons) of castings per day. Residual waste would be discharged at the low end of the inclined screen to a conveyor, which would remove the material to another storage pile. These wastes --totalling about 150 cu yd, or 31 tons of residue per day -- could then be recovered by a front-end loader and trucked to the landfill.

The harvesting screen would also be able to collect earthworms for reuse. The compacted residue volume would be about 19 acre-ft per year. Based on a total lift of about 10 ft, about two acres of landfill would be required each year. For a 20-yr period, a 38-acre landfill site would be required. The site might be developed in 5- to 10-acre modules.

Costs

The costs of vermicomposting municipal solid wastes can be divided into three components: preprocessing, vermicomposting, and residue disposal. The costs are shown in Table 1.

Preprocessing costs include receiving, shredding, and storage facilities. About two-thirds of the capital costs of vermicomposting is for purchase of the initial stock of earthworms. Amortization of capital costs accounts for about 60 percent of the total annual costs of vermicomposting. Costs for residue disposal include development and operation of sanitary landfill.

The net costs of vermicomposting include the credit for revenues generated by the sale of ferrous metals and earthworm castings. Ferrous metals can currently be sold for $30 to $50 per ton. Based on a recovery of 2,500 tons per year, the revenue is between $75,000 to $125,000 for the 100-tpd vermicomposting facility.

There are no existing markets for the sale of earthworm castings derived from municipal solid waste. Several vermicomposting operators have suggested potential market prices. Estimates range from $0 to $15 per ton, reflecting the lack of marketing experience. Based on 13,400 tons of castings recovered per year, up to $200,000 in annual revenues might be accrued. Taking into account potential product revenues, the total costs of vermicomposting are about $750,000 to $1,000,000 or approximately $24 to $32 per ton processed.

For a municipality producing 100 tpd of solid waste, three alternative methods of solid waste management are a sanitary landfill, combustion in a modular combustion unit and windrow composting. Costs of these methods compared to vermicomposting are shown below:

Method	Approximate Net Cost ($/ton)
Sanitary Landfill	6
Modular Combustion Unit	15
Windrow Composting	24-28
Vermicomposting	24-32

The vermicomposting process is at the high end of the scale. In the case where a portion (100 tpd) of the solid waste from a large community (1200 tpd) would be vermicomposted, vermicomposting would not be attractive, primarily due to substantial lost revenues from reduction in the refuse/fuel stream.

Findings

Vermicomposting of municipal solid waste is not an economically feasible technology. Although the technique appears to offer the

TABLE 1. TOTAL COSTS OF VERMICOMPOSTING 100 TPD MUNICIPAL SOLID WASTES

	Capital	Annual
Preprocessing Facilities	$1,800.000	$ 450,000
Vermicomposting Facilities	3,150,000	520,000
Residue Disposal	575,000	95,000
Sub-Total (rounded)	$5,500,000	$1,100,000
Revenue:		
Ferrous Metals		$ 75,000-125,000
Earthworm Castings		0-200,000
Net Cost (rounded)	$5,500,000	$1,000,000-750,000
Cost per Ton		$32 - $24

advantage of resource recovery, it has several major disadvantages compared to other management methods. Briefly, some of the disadvantages are:

- Expensive preprocessing required (shredding)
- Large land area requirements (23 acres of windrows for a 100 ton per day (tpd) facility)
- High capital costs ($5.5 million for a 100 tpd facility)
- High net unit costs ($24 $32 per ton)
- An unknown product market (for castings)

Acknowledgement

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ENERGY AND MATERIALS RECOVERY FROM MUNICIPAL SOLID WASTE

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ABSTRACT

In this study, selected research and development documents dealing with energy and materials recovery from municipal solid waste are reviewed and synthesized by a Committee of the Building Research Advisory Board (BRAB). Eleven review documents represent projects sponsored by the U.S. Environmental Protection Agency and other federal agencies over a five year period. In its report, the BRAB Committee presents a summary of the documents reviewed, a discussion on the state of the art of resource recovery implementation, impediments to implementation, on-going and needed research, and conclusions reached by the Committee as a result of its study.

INTRODUCTION

As a result of the Resource Conservation and Recovery Act of 1976 (PL 94-580, 1976) numerous projects have been sponsored by various agencies of the federal government to promote the protection of health and the environment and to conserve valuable material and energy resources. Considerable attention has been given to the investigation of existing and emerging technologies for recovery of resources from solid waste and to the potential for implementation of recovery systems. As is usually the case, investigations were undertaken by a variety of investigators under individual contracts or grants with several federal agencies and dissemination of the results of these studies was limited and ad hoc in nature. Thus no collective knowledge was available to assess the state of the art and the conclusions and recommendations arrived at through these research, development and demonstration projects. The Environmental Protection Agency believed that a review and synthesis the results of these studies would provide a valuable information service and asked that the Building Research Advisory Board undertake the task.

Conduct of the Study

Under contract to the Environmental Protection Agency, an ad hoc committee was appointed in accordance with the policy and procedures of the National Research Council to review and synthesize eleven research and development documents selected by the sponsor. The reports selected for review were:

1. Energy Conservation Waste Utilization Research and Development Plan.

2. Energy and Resource Recovery from Solid Waste

3. Materials and Energy from Municipal Waste.

4. National Recycling Research Agenda Project.

5. Waste Resources as a Potential Topic for Integrated Basic Research.

6. Unit Operations in Resource Recovery Engineering.

   Resource Recovery.

7. Present Status and Research Needs in Energy Recovery from Wastes.

8. Study of Processing Equipment for Resource Recovery Systems, Volume I - State of the Art and Research Needs.

   Study of Processing Equipment for Resource Recovery Systems, Volume II - Magnetic Separators, Air Classifier and Ambient Air Emissions Tests.

   Processing Equipment for Resource Recovery Systems, Volume III - Field Test Evaluation of Shredders.

9. Resource Recovery Research, Development and Demonstration Plan.

10. Waste-to-Energy Technology.

11. Fuels and Feedstocks from Solid Waste.

The review documents were reviewed by the Committee, abstracts of each were prepared and the Committee's report was developed. Included in the report is a discussion of the rationale for energy and materials recovery from municipal solid waste; a discussion of the state of the art in terms of implementation of existing techniques; impediments to resource recovery; and research and developments needs. The Committee also presents its findings and conclusions based on the documents reviewed and the collective expertise represented by the Committee.

Committee on Energy and Materials Recovery from Municipal Solid Waste

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RECYCLING IN THE UNITED STATES: THE VISION AND THE REALITY

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ABSTRACT

National attention on the growing solid waste problem was first evidenced by enactment of the Solid Waste Disposal Act in 1965. Subsequent legislation relating to solid waste management and resource recovery has been passed by the U.S. Congress, the most recent being the Energy Security Act in 1980. Public anticipation that recycling will eventually solve the waste management and conserve limited natural resources has persisted for more than a decade now, but progress toward these goals has fallen considerably behind initial expectations. Various reasons for the lag in recycling have been offered, and federal research efforts have concentrated particularly on solution of the technological difficulties encountered by recycling plants.

The United States Environmental Protection Agency in 1978 contracted with Mathtech, a division of Mathematica, to evaluate the impediments to recycling and their economic effects. Facilities selected for indepth study represented a broad cross-section of recycling technologies, ownership types, geographical locations, and recovered products. Adjustments for differences in accounting procedures and normalization of data were made and economic performances for eight plants compared on a net cost of disposal basis. Performance based on cost of disposal permitted comparison with alternative modes of disposal, mainly landfills.

Based on the recent financial data, none of the facilities were found to be economical in the sense of providing the least cost mode of disposal for municipal solid waste; all facilities experienced net losses in operations. Indications were that performance for the projected year (1979) would improve somewhat allowing at least one facility to realize a slight profit. A major deterrent to recycling was the predominance of lower-cost landfills. Competition from landfills is expected to diminish in some areas when new environmental regulations for land disposal of solid waste become effective. Results of the Mathtech study have the usual limitations imposed by sampling, missing data, and possibly computational errors. The results, however, provide useful information to policy-makers and decision-makers having responsibility for efficient management of municipal solid waste.

Introduction

In 1970 Richard M. Nixon, President of the United States, wrote "We can no longer afford the indiscriminate waste of our natural resources; neither should we accept as inevitable the mounting costs of waste removal. We must move increasingly toward closed systems that recycle what now are considered wastes back into useful and productive purposes."(1) Soon afterwards, in October 1970, the U.S. Congress enacted the Resource Recovery Act of 1970 which included among its purposes the demonstration, construction, and application of solid waste management and resource recovery systems.(2)

A number of issues concerning recycling and resource recovery systems for municipal solid waste arose in the decade that followed. The federal government sponsored numerous symposia, funded a long list of research and demonstration projects, encouraged industry, and gave orders to federal agencies to implement recycling activities. The Resource Conservation and Recovery Act, enacted in 1976, established a Resource Conservation Committee comprised of representatives from various departments and agencies of the federal government.(3) The recent passage of the Energy Security Act of 1980 which authorizes federal price supports and loans for waste-to-energy activities constitutes yet another step in the continuing efforts to increase recycling.(4)

This paper is limited to an appraisal of the problems with recycling municipal solid waste. In particular, it discusses the findings of recent case studies conducted by Mathtech under contract to the U.S. Environmental Protection Agency. The discussion of these findings will hopefully clarify many issues on recycling and increase the understanding of local officials and others interested in resource recovery programs for municipal solid waste.

Optimism Changes to Pessimism

The initial expectations were that recycling would reduce or eliminate the mounting solid waste problem and also conserve valuable resources. (5) Newspaper articles containing captions such as "American Trash Could Be Bonanza As Source Of Ore" led the public to believe that recycling was an immediate and forthcoming answer(6)Carlsen in Environmental Affairs stated that "recycling will soon become an increasingly important phase of economic activity. It represents the solution to both the problems of increasing solid waste with its attendant insatiable demands of land and those associated with the growing scarcity of natural resources." (7)

Not all prognosticators agreed with the initial optimism expressed by some. Early in 1971 the privately supported National Center for Resource Recovery cautioned that managing municipal waste through resource recovery might be 5, 10, or even 20 years away.(8) The Institute of Scrap Iron and Steel estimated that at the end of 1975 unrecycled ferrous scrap including that discarded by households could cover the Nation's capital 100 feet deep.(9) Observers became more pessimistic. Sylvia Porter in the New York Post questioned whether recycling was in a tailspin.(10) The Solid Waste Management/Refuse Removal Journal, a trade publication for the solid waste industry noted that the initial experiences consisted of "delays, breakdowns, cost overruns, misconceptions".(11)

From Materials to Energy Recovery

The energy crisis in late 1973 shifted attention away from materials to recovering the potential energy value in municipal solid waste. Some facilities were subsequently designed solely for energy recovery (Table 1). As with materials recovery, reports of success were soon dampened by reports of failure. The May 1978 issue of American City and County published the article "Despite higher costs than expected, this Iowa City's refuse-to-energy project is still going strong after 18 months of operation".(12) The New York Times reported "L.I. Town a Pioneer in Recycling Its Garbage Into Electric Energy".(13) Meanwhile, a private consultant to the industry declared at an annual meeting "...our dreams have taken us into what now seems to be the clouded skies of resource recovery - of refuse to energy - of burning to earning. We are not facing up to the truth about the expense, inefficiency and impracticability of the waste recovery projects that make Monday morning headlines..." (14)And Dr. Rocco A. Petrone, president of the National Center for Resource Recovery, wrote "even now, with 30 plants operating, under construction, or well past commitment, resource recovery has not reached the operating stage." (15) Three years after the multimillion dollar waste-to-energy recovery facility began construction in 1976 in the city of Chicago, Easterbrook observed that the SSFF (Southwest Supplemental Fuel

TABLE 1. CHARACTERISTICS OF PLANTS RECYCLING MUNICIPAL SOLID WASTE IN U.S.*

Facility	Starting Date	Status+	Investment (mil.$'s)‡	Throughput§ Design	Throughput§ Oper	Resource Recovery Activity: Materials Design	Materials Operat.	Energy Design	Energy Operat.
Altoona, PA	1963	op	--	50	--	x	x		
Ames, IA	1975	op	6.3	400	200	x	x	x	x
Ansonia, CN	1975	op	--	200	250	x	x		
Baltimore City, MD	1975	op	30.1	1000	600	x	x	x	x
Baltimore Co., MD	1976	op	10.0	1500	550	x	x	x	x
Blytheville, ARK	1975	op	0.8	50	--			x	x
Braintree, MA	1971	op	3.3	240	186			x	x
Chicago(Crawford) IL	1977	st	20.0	1000	--	x		x	
Chicago(NW), IL	1971	op	23.0	1600	1000	x		x	
Chicago(SW), IL	1963	cl	6.8	1200	--	x	x	x	x
Crossville, TENN	1978	op	--	60	--			x	x
East Bridgewater, MA	1976	op	12.0	1200	550	x	x	x	x
Franklin, OH	1971	op	3.4	150	50	x	x		
Groveton, NH	1975	op	0.2	30	--			x	x
Harrisburg, PA	1972	op	14.1	720	430	x	x	x	x
Hempstead, NY	1979	sh	81.1	2000	--	x		x	
Lane Co., ORE	1978	sh	5.0	500	-	x	x	x	x
Lewiston, ME	1977	op	1.3	130	--	x			
Madison, WIS	1979	op	2.5	400	200	x		x	
Menlo Park, CA		cl	--	100	--	x	x	x	x
Miami, FLA	1956	cl	2.5	900	--			x	x
Milwaukee, WIS	1977	op	28.9	1600	640	x	x	x	x
Monmouth Co., NJ	1976	op	3.6	400	375	x	x		
Mt. View, CA	1978	op	0.8	1	0.5			x	x
Nashville, TENN	1974	op	24.5	1060	400			x	x
New Castle, DEL	1972	op	2.4	800	300	x	x	x	
New Orleans, LA	1976	op	9.1	700	650	x	x		
Norfolk, VA	1967	op	2.2	360	360			x	x
No. Little Rock, ARK	1977	susp	1.5	100	82			x	x
Oscelo, ARK	1978	op	--	25	--			x	x
Pompano Beach, FLA	1978	sh	3.6	75	--	x		x	
Portsmouth, VA	1976	op	--	160	115			x	x
St. Louis, MO	1972	cl	2.3	300	--	x	x	x	x
Salem, VA	1978	op	1.9	100	--			x	x
San Diego Co., CA	1977	susp	15.0	200	0	x		x	
Saugus, MA	1976	op	50.0	1200	950	x	x	x	x
Siloam Springs, ARK	1975	op	0.4	20	16			x	x
Tacoma, WASH	1978	op	2.5	500	--	x	x	x	x

Source: Various government reports, trade publications and newspaper articles.

* Excludes plants in planning or construction stage in 1978.

§ In standard tons except Mt. View facility is in million standard cubic feet daily(mscfd).

+ Op = operating; sh = shakedown stage; cl = closed; st = starting; susp = suspended.

‡ Dollars expended in year of investment.

Facility) was still in 'shakedown', and "the city may be better off without it." (16)

Late in 1977 and early 1978, a U.S. congressional committee visited 8 recovery sites to observe the state of the art in recycling. The committee subsequently issued a report that (1) claims made in behalf of recycling were overstated and costs understated, (2) technologies needed further development, and (3) the economics for recycling would become more favorable as the costs of disposal rise. (17)

Conflicting reports on the success or failure of recycling materials and energy have local officials and the public in general greatly confused over what projects should be undertaken. The confusion stems from issues over lack of demand and available markets for reclaimed materials, inadequate and undependable supply of waste, conflicting public policies such as tax laws and transportation regulations favoring extraction and use of virgin materials, institutional impediments, and the failure of markets to fully reflect environmental externalities in land disposal of waste and increasing scarcity of mineral deposits. These issues form a mixed bag of social, economic, technological and institutional problems that inhibit the growth of recycling.

EPA-Mathtech Case Studies

The U.S. Environmental Protection Agency (Office of Research & Development) initiated research in 1978 to identify and evaluate the impediments to recycling municipal solid waste. (13) Answers were sought to three basic questions: 1) Are recycling facilities in operation economical? 2) If not, what are the impediments to economical operation? and 3) What changes are needed for economical operation?

The context in which the term "economical" was applied differs from the theoretical definition which includes the consideration of social costs and benefits. As employed in the Mathtech study, the term was limited to an accounting comparison of private revenues and costs, synonymous with successful operation from a private market perspective. The evaluation of "economical" was restricted to the above definition because of the many difficulties involved in quantifying social costs and benefits.

Selection of Facilities

Evaluating the financial performance of facilities required accessibility to the financial records and operating experience of sufficient duration for representativeness of probable long-term results. The facilities selected for case studies were screened from a total number of plants believed to have progressed beyond the "startup" or "shakedown" stage. This greatly limited the number available for study. Privately owned plants and those with operating difficulties tended to be more reluctant to provide access to data. Table 1 lists the facilities initially designed for energy and materials recovery and indicates whether these intentions were realized at the time of the study. Whether a plant was in "startup" or "shakedown" stage appeared to be arbitrary in some cases. Capital investment included initial and subsequent capital costs, including expenditures for pollution control equipment.

The selection of eight facilities was based on criteria requiring at least one year of operating history and accessibility to adequate financial records. These facilities were selected to obtain a valid representation of technologies and actual financial experiences in recycling, given the selection restrictions previously mentioned. About half of the facilities were situated in the densely populated Northeast where intense land use and greater waste disposal problems exist. Half of the facilities were owned and operated by municipalities, representing the type of government managing the major portion of residential waste in the United States. The remaining facilities included ownership or operations by a county, a large private corporation, an investor-owned utility, and a joint venture by one county and small private corporation. All of the sample facilities were constructed within the past 10 years and included a variety of technologies currently in use. Plant capacities ranged from 100 to 1600 tons per day (tpd), a range generally considered adequate for the disposal requirements of communities with populations between 50,000 and one million.

Significance of Impediments

Impediments to recycling were grouped according to effects on: 1) quantity and composition of solid waste supply, 2) capital cost and facility design, 3) operating costs and efficiency of operations and 4) market demand for energy and materials reclaimed. The impediments within these broad categories are listed (not necessarily in the order of their importance) in Table 2. The significance of these impediments are discussed in the following sections.

At most facility locations, land disposal was a lower-cost alternative to recycling. The few exceptions to this general rule included one location where all landfills within the county had been closed, and several locations where an adequate inflow of waste was assured through contractual arrangements. The majority of recycling facilities were unable to effectively compete with nearby landfill charges. Tipping fees were generally below actual operating costs in order to attract sufficient quantities of waste; even so, a number of plants were unable to attract sufficient quantities to match the design capacity for the facility.

In the United States waste collection is mostly organized by local jurisdictions.(19) This dispersion of authority resulted in less waste available for re-

TABLE 2. CATEGORIES OF IMPEDIMENTS ACCORDING TO EFFECTS ON RECYCLING OF MUNICIPAL SOLID WASTE

1. Restrict quantity and/or composition of solid waste supply.
   a. Pricing land disposal of solid waste below full social cost.
   b. Source separation programs.
   c. Mandatory deposits for beverage containers.
   d. Fragmentation of local solid waste management/authority.
   e. Seasonal and business cycles.

2. Increase capital cost and/or restrict facility design.
   a. Inadequate existing technology.
   b. High prices for equipment and/or parts.
   c. Limited facility design experience.
   d. Restrictions on municipal financing.
   e. Low bid approach to public contracting.

3. Increase operating costs and/or decrease efficiency of operations.
   a. Limited managerial and/or operating experience.
   b. Limited availability of spare parts.
   c. Shortage of skilled labor.
   d. State and federal regulations for air quality.
   e. Regulations for disposal of ash and residue.

4. Diminish the market potential for reclaimed energy and/or materials.
   a. Facility siting restrictions.
   b. Franchise restrictions on energy sales
   c. Tax subsidies for extraction of virgin materials.
   d. Regulated prices for oil and gas.
   e. Lack of future markets for reclaimed (secondary) materials.
   f. Unpriced social costs for extraction and processing of virgin materials.
   g. Rate regulation of electric utilities.
   h. Restrictions on use of ash, residue, and shredded materials.
   i. Product labeling restrictions.
   j. Government procurement policies.

cycling than desired at several of the case study locations. The effect of reduced volume on cost of operations is illustrated in Table 3.

Community programs involving source separation and mandatory beverage container deposits appeared to have only a negligible effect on facility performance. These programs were varied but potential losses of revenues were generally insignificant. The fraction of aluminum recovered, was generally small. Seasonal fluctuations in waste supply caused minor rescheduling of winter operations at one plant but did not significantly affect operations at the other facilities.

Recycling operations were hampered by technological problems in at least half of the facilities studied. Technology problems, including facility designs and limited operating experience, are usually symptomatic of a new activity as it progresses from pilot plants and demonstration projects to commercial size operations. Facilities designed for RDF (refuse-derived fuel) and recovery of materials had relatively greater technological difficulties, mainly because the materials handling processes were more complex than for other recycling systems.

Environmental regulations also tended to impede recycling efforts. Conversions from coal to oil during the 1970's due to air pollution regulations resulted in a greatly reduced number of boilers available for co-firing RDF with coal, particularly in the industrial areas of the Northeast. Several states also had restrictions on the reuse of ash and secondary materials as an alternative to disposal. Uncertainty over whether existing environmental regulations would continue or be revived was found to produce a wait and see attitude and consequently delayed recycling decisions.

TABLE 3. ESTIMATED UNIT OPERATING COSTS FOR SMALL AND LARGE RECYCLING FACILITIES

Facility Type**	Breakeven tipping fee* Small design***	Large design***
Modular incineration	$ 8.83	$ 3.91
Mass burning waterwall incineration	$ 5.79	$ 3.06
Semi-suspension waterwall incineration with ferrous recovery	$ 4.68	($ 0.25)
Refuse derived fuels with ferrous, aluminum and glass recovery	$16.43	$10.70
Ferrous, aluminum, and glass recovery	$11.25	$ 8.30

Source: U.S. EPA Contract No. 68-03-2761. Draft report. Appendix A, Table 5.

* In 1977 dollars per standard ton.

** Incinerator systems assume sale of steam.

*** Small design assumes 50 tons per day (tpd) for modular incinerators, 500 tpd for all others; large design assumes 100 tpd for modular incinerators, 1500 tpd for all other.

The federal tax code contains certain provisions relating to the extraction of virgin materials. These provisions in effect amount to subsidies which lower the supply price for virgin materials. It was estimated that the likely increases in revenues from recycling a ton of municipal solid waste would be small if the tax advantages were removed. These estimates, however, were based on short-run elasticities of supply and demand; the long-run investment patterns and resulting elasticities might provide more favorable price relationships for recycled materials. (29)

Regulation of prices for domestically produced oil and natural gas can in certain circumstances result in retail prices below what they would otherwise be, and lower than world equilibrium prices. These artificially maintained low prices can consequently result in lower demand for energy from solid waste as appears to be the situation in the United States today. Regulated utility rates which provide for "pass through" incremental fuel costs are generally assumed to weaken the demand by utilities for energy from solid waste; however, six of the eight facilities were recovering energy from waste and utilities were actively involved at four sites. Franchise restrictions on steam and electric sales did not appear to adversely affect revenues for the facilities. Perhaps because of the increasing fuel prices, revenues from sales of energy are less affected by impediments than reclaimed materials. Of the eight facilities, five had undertaken materials recovery but sales of reclaimed materials were generally small compared with revenues from energy.

Aluminum recovery was limited to hand picking of bulky items at the several plants where it was undertaken; recovery of aluminum cans was not generally practiced because the technology for separation is not well developed rather than lack of markets. Lack of uniformity in product standards caused abandonment of some materials recovery in two instances while institutional restrictions on the use of reclaimed materials curtailed plans for marketing certain products at three facilities.

The difficulties involved in siting facilities are often asserted to be a major problem in expanding recycling; the study found this impediment existed in one case. Siting considerations were found to be important, however, in delineating the market area for products relatively costly to transport.

Other factors frequently described as impediments to recycling, such as restrictions on interstate movement of waste and restrictions on financing and contracting by public authorities were found to have generally minimal effects on recycling in the selected facilities. Uncertainty over future recycling policies in state governments contributed to reduced capital investment at two plants and a high sensitivity to risk exhibited by public officials in one community resulted in a decision favoring private ownership and operation of the facility.

Financial Experiences of Selected Facilities:

Analysis of the financial performance of selected recycling facilities indicated that none of the case study facilities were successful from an accounting or market sense for the fiscal year 1978 (Table 4). Net losses ranged from $0.60 to over $36.00 per ton in fiscal year 1978. With two exceptions, the projections were that financial performances would improve during fiscal year 1979.

The comparison of financial statements encountered considerable difficulty due to differences in accounting systems, financing techniques, and peculiar circumstances at individual plants. Financial data were adjusted for these differences and in several instances adjustments were also made because operations were temporarily suspended for mechanical difficulties and failure to meet air pollution regulations. About half of the plants kept their records on the basis of tons processed; these were converted to tonnage received to maintain comparability among plants.

Performance Based on Net Disposal Cost:

The financial performance for each facility was computed as the total operating cost less revenues from sale of reclaimed materials and energy. This was defined as the net disposal cost incurred by the recycling plant. The computation permitted comparisons of financial performances on a per ton basis and also compari-

TABLE 4. FINANCIAL PERFORMANCES OF SELECTED FACILITIES IN FISCAL YEARS 1978 AND 1979

Facility*	Total Cost+ 1978	Total Cost+ 1979	Profit(Loss) 1978	Profit(Loss) 1979+
Ames (RDF)	$30.59	$24.83	($17.49)	($10.60)
Braintree (WI)	46.91	22.24	(36.17)	(10.89)
Harrisburg (WI)	18.02	21.17	(5.90)	(2.60)
Milwaukee (RDF)	24.31	26.70	(9.97)	(9.18)
Monmouth (S)	15.85	11.98	(11.94)	(7.96)
Mountain View (LG)	8.26	8.60	(1.04)	0.76
New Castle (S)	7.77	9.81	(0.60)	(1.94)
N. Little Rock (MI)	19.27	20.61	(6.10)	(8.17)

Source: U.S. EPA Contract No. 68-03-2761.

*Legend: WI=waterwall incinerators, MI=modular incinerator, S=shredder, RDF=refuse derived fuel, and LG=landfill gas recovery.

+Dollars per standard ton includes annualized capital cost; data for 1979 based on partial year's results.

sons with disposal alternatives. Disposal costs for the competing alternatives (mainly landfills) ranged from $2.50 to $20.00 per ton (Table 5). The disposal charge or tipping fee collected by recycling facilities was generally less than their actual net cost of disposal. This meant that recycling facilities were subsidized through general taxation or, in the case of privately-owned facilities, by corporate funds.

Although most of the facilities were expected to improve their financial performance in fiscal year 1979, it was estimated that only one facility would reach a breakeven point or realize a profit (Table 4). These projections were based on financial results up to the time of study. Revenues at Harrisburg, for example, were projected to rise substantially in 1979 because of increased steam sales. At Braintree, air pollution control modifications had been completed and an expanded operating schedule was in effect. Several facilities also had improved their equipment and increased throughput over the previous year.

Performance Based on Capital Cost:

Community officials and local solid waste managers contemplating recycling base their decisions on today's costs and expectations for the future. Facility disposal costs were therefore recalculated to reflect current instead of historical capital costs. In recent years, construction costs have increased at a more rapid rate than operating expenses and product categories. As expected, the calculated net disposal costs on a capital replacement basis showed even less favorable financial performance by the facilities (Table 5).

Summary of Case Studies:

Inability to compete with disposal fees at nearby landfills was a common impediment for recycling facilities whose

TABLE 5. RECYCLING NET DISPOSAL COST
BASED ON ORIGINAL AND CAPITAL REPLACEMENT
COMPARED WITH LANDFILL DISPOSAL*

Facility	Net Disposal Cost[+] Original	Replacement	Landfill
1. Ames, Iowa	$11.40	$20.50	$ 8.00 - $12.00
2. Braintree, Massachusetts	19.00	28.33	17.00 - 20.00
3. Harrisburg, Pennsylvania	14.03	20.42	4.50 - 7.50
4. Milwaukee, Wisconsin	22.78	25.27	8.00 - 12.00
5. Monmouth Co., New Jersey	11.95	12.56	2.50 - 7.50
6. Mountain View, California	5.88	6.45	6.84
7. New Castle Co., Delaware	9.81	10.92	N.A.
8. No. Little Rock, Arkansas	11.46	14.02	3.33

Source: U. S. EPA Contract No. 68-03-2761.

*Projected for fiscal year 1979 based on partial year's data.

[+]Dollars per standard ton computed as total costs less revenues from resource recovery and excluding transportation costs to the facility.

financial records were examined. The relative importance of this and other impediments in terms of frequency of occurrence is shown in Table 6. As indicated earlier, facilities were reluctant to collect tipping fees equal to their net operating costs for fear that solid waste would be diverted to landfills. Two facilities had an advantage in not having to compete directly with landfills; one facility had received prior commitments for the wastes from the communities which it served and in another instance the county had closed the nearby landfills.

Technological difficulties coupled with limited experience in recycling solid waste resulted in excessive costs and thus also impeded successful financial performance. The technological difficulties included corrosion and abrasion problems, explosions, difficulties with the aluminum separation, and over-sized or bulky wastes. Excessive amounts of impurities and contaminants caused problems to users of the recycled materials.

Another major impediment to successful financial performance was the inaccurate projections. Projections of the quantities available for markets and revenues to be received failed to develop to expected levels in most cases. These projections were particularly important for energy which accounted for the major portion of recycling revenues.

Due to faulty projections and overoptimism, excess capacity was observed in over half of the facilities studied. Underestimation of capital and annual operating costs were additional causes of poor performance; these errors caused higher recycling costs. Expenditures for capital structures and equipment were 40 percent higher than original engineering esti-

TABLE 6 RELATIVE SIGNIFICANCE OF SELECTED IMPEDIMENTS TO RECYCLING FACILITIES

Impediment	Occurrence
Inability to compete with landfill disposal fees	xxxxxxx
Technological difficulties and limited experience	xxxxxxx
Unrealized projections of revenue from product sales	xxxxxxx
Government intervention in market pricing and resource allocations	xxxxxxx
Overdesign of plant capacity	xxxxx
Underestimation of initial capital costs	xxxx
Environmental regulations	xxxx
Fragmentation/conflicts of governmental authorities	xxxx
Underestimation of O & M costs	xxx
Overestimation of materials recovery	xxx
Overestimation of available waste quantities	xx
Pricing energy below market replacement value	xx
Public opposition to siting	xx
Local politics and labor-management problems	xx
Source-separated waste programs	x

mates in one case; in another instance they were 60 percent higher. The increased capital costs added as much as $5.00 per ton to a facility's net disposal cost. At one facility, start-up and minor equipment costs were nearly five times above the initial estimate.

Environmental regulations affected recycling facilities in several ways. In the Northeast a major shift from coal to oil and natural gas during the 1970's in response to air quality regulations greatly limited the availability of boilers for utilizing refuse derived fuel (RDF). Environmental considerations also restricted reuse of residue from energy and materials recovery. Decentralization of solid waste management was an impediment in obtaining a sufficient supply of waste in about half of the cases. Local jurisdictions are frequently reluctant to relinquish their authority in order to establish regional solid waste management. In one case, however, federal and state activities created a climate of uncertainty which later resulted in government competing directly with an existing recycling facility.

Failure to properly price energy obtained from recycling reduced the revenues for several facilities. Existing contracts had inadequate provisions for adjusting steam prices as energy costs rose. Lack of information about the cross-elasticity of demand for disposal through recycling vis-a-vis landfilling may have played a role in incorrect pricing of the recycling disposal service; in one instance, however, a facility had a monopoly position for the disposal service but yet failed to impose a tipping fee equal to its incremental operating cost.

Public opposition to siting impeded recycling in at least one case. Local politics and labor-management disputes resulting in downtimes and delays caused additional costs at several facilities. Source separation programs, although active in about half of the locations involved, were not extensive and had no significant effect on financial performance. Mandatory beverage container deposits programs also had little effect except at one facility where it may have contributed to the discontinuance of the aluminum separator. Restrictions on interstate movement of solid waste did not appear to adversely impact on recycling facilities. In several cases these restrictions actually helped reduce competition from nearby out-of-state landfills. Seasonal variations in waste quantities generally had little effect on financial performances of the facilities.

Limitations of Results:

The EPA-Mathtech study on financial performances of actual recycling facilities represented a pioneering effort in recycling analysis. Past studies on recycling were mostly concerned with technological performance, comparative economic evaluations were usually based on engineering cost estimates and hypothetical operations. While the small sample size and choice of facilities may have unintentionally biased the results, the sample was limited by the small number of operational plants in the United States and cooperation of owners or managers. A number of plants had not yet reached full scale operations at the time of the survey. Limited research funds also dictated the sample size. The facilities selected for indepth study thus represented the broadest cross-section of technological processes, scale of operations, ownership arrangements, marketable products, and geographical locations obtainable under the circumstances.

As in most studies of an economic nature, data gaps necessitated interpolation and extrapolations. Financial data for the various facilities were standardized to a common accounting base, and adjustments made where necessary. Uncertainties exist with respect to the true values for the universe. And the nature and direction of biases was generally recognized but not quantified in the study, nor was the simultaneous effects of the various impediments fully evaluated.

The comparison of net disposal costs assumed that recycling facilities competed primarily in the waste disposal market; consequently, recycling was viewed as an alternative disposal mode. Recycling can also be viewed as competing with virgin materials in the products market. From the perspective of influencing prices, however, for the forseeable future recycling is likely to have greater potential for in the waste disposal market and will probably continue to be a price taker in the material products market.

Recycling might be viewed not as a separate activity, but as one component of a total systems approach to solid waste management. In this context Sullivan suggests for efficiency reasons the private sector should be given the responsibility for recycling as private firms are better able to evaluate its feasibility in conjunction with the collection service. (21) Ultimate disposal, it is suggested, is more likely to produce externalities and therefore should be the responsibility of the public sector.

It should be mentioned that the current emphasis on waste-to-energy recycling probably constitutes a short-run perspective of conservation. Energy can be provided from renewable resources, while the non-combustible materials in solid waste represent non-renewable resources. While no credit was given to disposal costs for materials conserved, a long-run perspective of recycling suggests that perhaps greater emphasis should be given to the value of conservation of nonrenewable resources.

Recycling Municipal Solid Waste
What's Ahead?

In spite of the early optimism for recycling in the United States, the record todate has been considerably below general expectations. The results obtained from the recent EPA-Mathtech study indicate that recycling of municipal solid waste todate has not been the least cost means of disposal. Low-cost competition from landfills has been a major obstacle to successful recycling operations. Landfilling costs, however, may increase sharply if the regulations proposed under Subtitle D of RCRA become effective. Landfill disposal costs presently average slightly more than $4.00 per ton.(22) An increase of 88 percent in costs as projected by Hart Associates would provide a considerable impetus for recycling, particularly in areas where land use is intensive and considerable investment would be needed to comply with the new regulations.(23) The U. S. Congress recently passed the Energy Security Act which provides loan guarantees and price supports for waste to energy systems. Critics of the legislation note, however, that the principal problem in energy from waste is insufficient demand rather than the supply side of the market.

It remains to be seen whether the future economic climate for recycling will improve and whether new facilities now under construction or beginning operations will benefit from experiences of the earlier plants. Local community officials and waste managers are interested primarily in disposing of solid waste in the least-cost manner. Recycling need not be economical to the extent that revenues exceed costs, however, net disposal costs incurred through recycling need be competitive with any environmentally acceptable disposal alternatives unless additional credit and subsidies are included for energy and materials conservation. In testimony for a Senate subcommittee recently, Abert predicted that only about one-third of the available waste in the U.S. would be recycled by the turn of the century. (24)

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OPTIONS FOR RESOURCE RECOVERY AND DISPOSAL OF SCRAP TIRES: A REVIEW OF TECHNOLOGIES AND ECONOMICS

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ABSTRACT

This paper summarizes the results of a study of the scrap tire problem sponsored by the United States Environmental Protection Agency. An overview of the problem is presented, and the technology and economics of retreading, rubberized asphalt and energy recovery are briefly discussed.

INTRODUCTION

Each year approximately 200 million automobile and 40 million truck tires are removed from service, a total of some 4 million tons, most of which find landfills as final resting places. Although various new resource recovery options (mainly energy recovery) for the use of these tires have appeared at least superficially attractive, the economics of these processes have permitted only a very slow growth in the utilization of them. Traditional industries for the reuse of these scrapped tires, rubber reclaiming, tire splitting and retreading have all experienced zero to negative growth in recent years, with the result that an increasing proportion of these tires are placed in landfills.

There are a number of impacts associated with this situation that tend to make the costs of managing waste tires higher than the minimum necessary. Basically, there are two such impacts:

1. Resource Impacts. Tires are nearly wholely produced from petroleum derivatives. Since a large percentage of this petroleum is imported, there is an obvious negative impact on the nation's balance of payments, especially in a world of cartelized oil prices. Further, these tires displace volume in landfills that in many communities is increasingly scarce in supply, raising disposal cost. This is a problem primarily in densely populated areas, where the distribution of scrap tires closely parallels the population density. Reducing the size of the tires by splitting or shredding in order to save landfill volume is costly. Charges imposed to cover the cost of shredding creates an incentive for tires to be illegally dumped or littered, causing negative esthetic impacts.

2. Health and Safety Impacts. These impacts are principally the greater risk of fire and disease from stockpiled and/or littered tires. Tires have been implicated in mosquito borne encephalitis cases in at least one community.

The causes of the scrap tire problem are to be found in the interplay of technological and economic factors. On the technical side, such factors as lack of simple processes to reclaim high quality rubber and/or constituent materials such as carbon black from used tires means that such products, if obtained, are costly and not competitive with virgin materials, although the rise in virgin feedstock prices should begin to reduce the cost differential. Technical difficulties that American companies encountered with the construction of steel-belted radial tires have made them virtually unretreadable, probably leading to a higher rate tire scrappage than would have otherwise occurred.

The fact that a tire problem exists indicates that the market for tires is not functioning properly. This means that the tire market, as an institution, is improperly guided by the various resource prices that affect its operation - in particular, tires are improperly priced, since the costs they impose on individuals and communities are not reflected in the prices consumers pay for them. Corrections of these institutional shortcomings would do much to solve this problem.

One of the manifestations of this imperfection can be seen in the proliferation of tire sizes, which, apart from demand considerations, leads to a reduction in the percentage of tires that are retreaded. This percentage is reduced because retreaders do not find it profitable to maintain a variety of molds to match all the variations in tire size that tire manufacturers offer. This proliferation in sizes is caused by two factors: (1) the profit motive leads tire companies to exploit the various dimensions of demand in the tire market, and (2) the auto companies have been integrating tire design into the design of automotive suspension systems. The latter source will probably diminish in importance as the auto manufacturers reach a new equilibrium with respect to smaller auto sizes, but this will have little to no impact on the incentive that tire companies have to increase the number of tire sizes.

TECHNICAL OPTIONS FOR TIRE REUSE

At the moment, there are four technologies in various stages of current use and development that lead to reuse of scrap tires in some form, and may lead to greater future use. These technologies are retreading, shredding, rubberized asphalt and energy recovery. Of these, we discuss only retreading, rubberized asphalt and energy recovery. Shredding is a fairly well developed technology, and is an intermediate processing step for disposal, rubberized asphalt and energy recovery.

Retreading:

Currently, approximately 13 million truck tires and 31 million auto tires are retreaded annually; the figure for passenger auto tires has been declining throughout the decade of the seventies, and stood, for example at 36 million in 1974. The state of the art is such that well-made retreaded tires are produced with relative ease, but that the variable performance that is observed is due mainly to the many small retread shops that do not have the proper equipment for good retreading and/or seek to avoid the cost of producing high quality retreads.

Also, it is true that the shift to radials is having a significant negative impact on the rate of retreading. In 1978, for example, the retread rate for bias-belted tires produced in 1976 was 38%; for radials, it was 6%. Unless American tire manufacturers can solve the technical problems of radial tire construction that have made their radials unretreadable, and unless retreaders get the equipment in place to retread these radials, there will be a significant further decline in retread rates, leading to a substantial increase in the number of tires discharged for disposal.

Rubberized Asphalt:

The concept of adding rubber to asphalt is an old one, although the use of scrap tires as the source of the rubber component in the mixture has received serious attention in only the last 10-15 years. There are two very similar processes in use, both developed in Phoenix, Arizona. Essentially, the process consists of adding crumb rubber derived from a rubber reclaiming process to hot asphalt in an asphalt distributor truck and spraying it on the road surface in the usual fashion, covering it with stones ("chips"). The anticipated benefits in road applications (potentially the largest use for the material) are two: prevention or retardation of the rate at which cracks reflect through new asphalt courses that have been overlaid on older and failing pavements, and as a waterproof membrane, for use on bridge decks, for example. The most effective use may be in prevention of pavement failure resultant from expansive soils, such as clays, which stimulate "alligatoring", so named because of the dense and interconnected nature of the cracks. The effectiveness of rubberized interlayers in two other major types of pavement failure, lateral and transversal cracking, is more problematical. Lateral cracking stems from weather caused expansion and shrinking of concrete pavements, and transversal cracking from pavement and/or base failure, often caused or exacerbated by excessive weights in vehicles.

The technical potential for rubberized asphalt to prevent and/or retard each of these sources of reflective cracking is currently under study in a multi-year set of test projects being conducted by the Federal Highway Administration with support from EPA. The analysis of the technical and economic data will begin next fiscal year, and hopefully will provide more precise answers to the technical and economic questions that have been posed about the use of this material.

For example, rubberized seal costs are about 70% ($.45/yd^2) more costly than the conventional non-rubberized treatments. Table 1 shows the discounted payback periods implied by various combinations of discount rates and cost savings on a square yard basis. As yet, there does not exist good information on what the savings in fact are. In the case of the stress-relieving interlayer (placed between the old pavement surface and a new, thicker overlayer or finish course), some preliminary evidence from one application of the material in Arizona indicates an annual maintenance cost savings of $.26/yd^2, suggesting a discounted payback of four to five years at rates of discount of six to ten percent.

Another important use of rubberized asphalt is in crack and joint sealing compounds. The preliminary evidence suggests that the rubberized sealer is technically superior to conventional sealers, which often fail in less than a year, and the cost premium is only 30%. Thus, the likelihood of the cost effectiveness of the material is high, although again, the answer to this question of cost effectiveness is not known with precision.

Energy Recovery

Essentially, two basic technologies are being considered by a number of firms as methods of recovering the energy content of tires: direct combustion and pyrolysis, both of which normally require shredded tires as feedstock. Neither of these technologies in the various forms in which they appear are much beyond experimental or pilot stages, and many cases have not even reached the pilot stage. The economics of the processes for the most part present an obstacle yet to be surmounted.

Direct combustion techniques have taken tires, whole or shredded, and burned them either singly or mixed with other fuels, especially coal, typically for steam production. There does not exist any comprehensive information on the air pollution impacts of burning tires, but past experiences with the process suggest that proper feed rates and standard emissions control equipment will be able to deal with tire related residuals.

TABLE 1. DISCOUNTED PAYBACK PERIODS FOR AN ASPHALT-RUBBER SEAL COAT (years)

Discount Rate	Annual Maintenance Savings (Cents Per Square Yard					
	.10	.15	.20	.25	.30	.40
6%	6	4	3	2	2	2
10	7	4	3	2	2	2
15	8	5	3	3	2	2
20	13	5	4	3	2	2
25	50	7	4	3	3	2

Large scale combustion of tires becomes dependent on an adequate supply of tires for the process - as such it is quite sensitive to the cost of collection, especially transportation costs, and to prices to be paid (positive or negative) for delivery of tires to a facility. Processing costs do not seem to be an important consideration, at least in terms of plants of 30 tons per day or more. A study of a hypothetical facility in New England suggests that the process would be profitable if as few as six percent of tires in New England were collected and delivered to the plant. As of today, there are still no important facilities for shredding or otherwise processing tires for energy recovery. The cost of collection and the insufficiently high prices of alternative fuels seem both to serve to make energy recovery from tires uneconomical at present.

Pyrolysis of whole or shredded tires is a process that has attracted and still attracts the attention of many chemical engineers. Such companies as Firestone, Goodyear, Tosco and others have made substantial investments in the past seeking to recover fuel oil, carbon black and gases from pyrolized tires. Typically the quality of the carbon black, a major ingredient in tires, is of insufficient quality to make it competitive with virgin blacks without further processing. Again, economics proves to be the hurdle that remains to be surmounted before energy recovery from tires becomes profitable.

Why the rise in relative energy prices has not led to a more favorable economic environment for energy recovery from tires is not really understood. Federal prices control and entitlements programs surely have something to do with this problem, and it may also be that the process is itself sufficiently energy intensive in the collection phase to leave a margin between revenues and costs too small to be attractive, except at very high prices for alternative fuels.

SUMMARY AND CONCLUSIONS

At present, the only technologies in use for reusing tires in any significant fashion are retreading, rubber reclaiming, tire splitting and rubberized asphalt. To an unknown, but probably small extent, there is direct combustion occurring in various plants and shops around the country.

None of the trends suggest that there will be any significant increase in scrap tire recovery in the near future - indeed the trends are distinctly downward, save the small and slowly increasing use of tires in rubberized asphalt application. Since collection costs are relatively high, this aspect of the used tire cycle will likely remain relatively unorganized and possibly inefficient until large scale tire recycling becomes more profitable. A significant rise in the relative price of petroleum is a necessary condition for creating a strong demand which may in turn stimulate the development of a more efficient collection system. In the absence of this strong demand, the disposal and littering problems that exist may require some external mechanism such as product charges to ensure that tires are disposed of in an environmentally acceptable manner. Such a charge on the order of two cents per pound of tire would probably be sufficient to finance a nationwide system to stimulate tire collection and appropriate disposal. Little is known in detail, however, about how such a mechanism might work.

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RCRA STUDY OF GLASS AND PLASTIC RESOURCE RECOVERY

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ABSTRACT

The research program was initiated as an objective of the Resource Conservation and Recovery Act. It had the overall objective of assessing and evaluating State-of-the-Art for recovery of glass and plastic resources from solid wastes. Currently, labor-intensive source separation of glass and plastics predominate, although mechanical and thermal recovery will achieve greater importance in the years ahead.

Literature was gathered from numerous sources, contacts were made with industrial and recycling organizations, and questionnaires were distributed among applicable firms involved in glass and plastic recovery. Data derived from literature was collected, reduced and evaluated for technical, economic, and environmental content.

This report was submitted in fulfillment of Contract No. 68-03-2708 by Pacific Environmental Services, Inc. under the sponsorship of the U.S. Environmental Protection Agency, Stephen James, Project Officer. The report covered the period May 1978 to January 1980, and work was completed as of July 1, 1980.

INTRODUCTION

The objective of this RCRA mandated study was to define the state-of-the-art for recovery of plastic and glass resources from waste as determined from available literature. Resource recovery technologies, both mechanical and labor intensive, were assessed for municipal and industrial waste sources. Where data was available, these technologies were discussed in terms of technical, economic, environmental, and social aspects. Current trends in plastic and glass waste recovery practices outside the United States were assessed. Past and present research efforts were identified, and research needs to enhance recovery of resources were addressed. Study findings are discussed following.

MANUFACTURING AND INDUSTRIAL BACKGROUND FOR PLASTICS AND GLASS

Plastics Manufacturing and Plastics Industry

Plastics is a generic term describing strong, durable, light, easy to fabricate, fairly inexpensive materials derived from petrochemical feedstock. Plastics are available in over 40 "families" or material types with a broad range of performance characteristics (1). Plastics are a rapidly increasing segment of the economy, and new and variable uses and markets make industry characterization difficult.

All plastics are either thermosetting or thermoplastic. Thermosetting plastics are set into permanent shape by the application of heat and pressure and on reheating, cannot be reshaped. Thermosets account for over 20 percent of the total U.S. polymer production and are often used for durable goods such as counter tops, pot handles, knobs, highly engineered applications, and do not significantly add to the municipal solid waste stream (1).

Thermoplastics soften upon reheating and harden upon cooling. Ease of use of thermoplastics, plus specific resin characteristics enhance their use. Thermoplastics are often found in the municipal solid waste stream, (1) and they account for approximately 80 percent of polymer production (2).

Plastics manufacturing is a diversified and complex operation. From the raw material input to the final consumer product, the various operations within the plastics industry are integrated into various segments. Figure 1 shows the interrelationship among the various operations involved in the manufacture of plastics (3). Integration of operations within the plastics industry is extensive; thus, one company can be a resin producer, compounder, and fabricator; and a manufacturer/packager can sometimes operate as fabricator and converter. As a plastic product is made, starting from the resin, it normally passes through manufacturing facilities that progressively become smaller in size, and more dispersed geographically. The wholesaler/retailer and consumer segments are dispersed according to population density and end use markets.

Glass Manufacturing and Glass Industry

Glass has the following characteristics: chemically inert, impermeable to all liquids and gases, sanitary and odorless, can be made transparent, and versatile and adaptable in that it can be molded to almost any shape and size (4). The manufacturing process is usually a fully integrated one step process which begins with raw material feedstock and a finished product at the same location. Basic raw materials include soda ash, limestone, and sand. Limestone and sand are cheap and abundant. Cullet, or waste glass, can be used in lieu of soda ash, which is in demand.

As of 1980, there were 125 primary glass producing companies which altogether operated 340 individual plants (5). These glass manufacturing facilities are located throughout the United States and are usually situated near the markets they serve. Plants are found in 34 states with the majority located in the following 10 states: California, Illinois, Indiana, New Jersey, New York, Ohio, Oklahoma, Pennsylvania, Texas and West Virginia.

STATE OF THE ART FOR PLASTICS RESOURCE RECOVERY

Plastic Waste Generation

Plastic waste is generated from industrial-manufacturer, commercial and municipal sources. The amount of plastic wastes generated in 1977 and projected for the years 1980-1990, is presented in Table 1

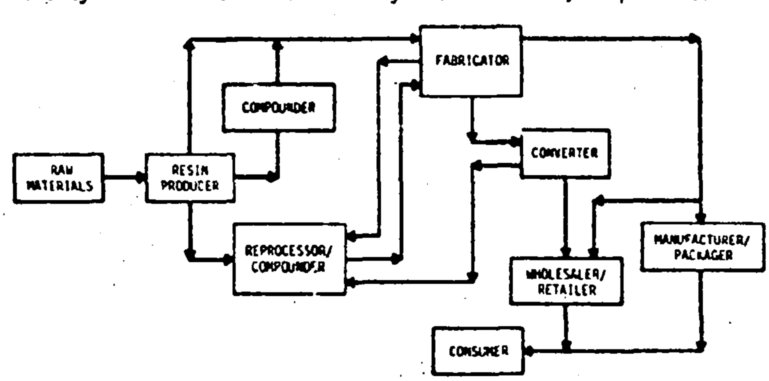

Figure 1. Interrelationships among various operations in the manufacture of plastics.

and was scaled from 1974 data. They predict a steady increase of plastics. This would occur principally due to expanded uses of plastics as a substitute for other items. Substitution arises from transportation costs accrued during distribution and the need to conserve materials. wastes as received at landfills, the breakdown by source is 84 percent for households, 10 percent for commercial/institutional and 6 percent for industrial. As a fraction of the municipal waste stream, plastics represent a small portion of approximately 4 to 5 percent (6). Plastics as a component of municipal refuse has increased about 50 percent in the last decade.

in the municipal waste stream are normally plastics packaging. No hard data exist to indicate exact quantites of plastics recovered from waste streams. Estimates indicated that of the 7,500 Gg (16,500 million lbs) generated annually from all sources, about 2,200 Gg (4,850 million lbs) were recovered, primarily through industrial recycling (1). Solid wastes are produced at essentially every step in the manufacture of plastics, with the post-consumer segment accounting for the majority of wastes.

TABLE 1. ESTIMATES AND FORECASTS OF PLASTICS WASTES GENERATED AND RECOVERED

Category	Quantity by year (million tons and Gg)[a],[b]							
	1977		1980		1985		1990	
	MT	Gg	MT	Gg	MT	Gg	MT	Gg
Total solid waste	140	127	160	145	180	163	200	181
Municipal generation	6.9	6.3	8.4	7.6	11.2	10.1	13.4	12.1
Commercial generation	0.8	0.7	0.9	0.8	1.2	1.1	1.4	1.3
Industrial generation	0.6	0.5	0.7	0.6	1.0	.9	1.2	1.1
Recovery[c]	1.4	1.2	1.6	1.4	2.4[d]	2.7	2.8[d]	2.5
Total waste as generated	6.9	6.3	8.4	7.6	11.0	9.9	13.2	11.9
Percent plastic in mixed wastes	4.9	4.9	5.3	5.3	6.2	6.2	6.6	6.0
Plastics recovery as a % of plastic wastes (municipal) for energy recovery	0	0	4.2	4.2	13.4	13.4	24.3	2[illegible].3
Total wastes as disposed	6.9	6.3	8.0	7.2	9.6	8.7	10.0	9.0

a - Assume no variation in industrial-municipal, commercial ratios of generation
b - Composite of Midwest Research Institute and PES estimates.
c - Recovery is composite of source separation and energy recovery.
d - Incorporates PET recycling at 25 percent efficiency.

Plastics production in 1977 totaled 15,411 Gg* (33,948 million lbs) (1). Of that amount, approximately 80 percent were thermoplastics, which are amenable to remelting and, thus, refabrication, to a certain extent. The largest single end-use for plastics is in packaging, although most plastics are utilized in long-term uses. As a result, plastic wastes found

* Gg is the metric abbreviation for 10^9 grams.

Plastics Waste Resource Recovery

Due to the tremendous growth in the use of polymers or plastics, especially in short-term packaging usage, increasing attention has been focused on its recovery. However, the recovery of plastics from municipal refuse within the United States is basically embryonic. Currently only specific plastics which are uncontaminated and segregated from other polymers and wastes have potential for recovery. PET bottles, PVC scrap, polyethylene containers, and HDPE film are currently sporadically recovered for recycling. As a result, energy derived from combustion in waste to energy plants most likely represents future prevalent plastics "recycling."

A less familiar but equally important area is that of "pre-consumer" wastes, those generated by producers, processors and fabricators of products. While recovery of plastics from municipal refuse is not extensive, industrial, and to a certain extent, commercial recovery is quite extensive. Essentially, scrap recovery has long ceased to be an afterthought in most plastics processing operations. Scrap handling has the potential of being as important a plastics processing operation in its own right as processing virgin polymers, since the rising costs of feedstocks makes even small loses significant. There are fewer and fewer operations that cannot justify either regrinding equipment or recovery of off-spec resin for sale (7).

Post and present recovery programs are listed in Table 2.

Reuse strategies have shown that clean and single material plastic waste streams derived from municipal waste (PET, for example) can be collected and recycled. However, this is limited and is useful only for beverage packaging.

Except on such limited basis, plastics materials recovery from the mixed municipal waste stream appears to be technically or economically infeasible at present. The greatest potential for successful plastics waste recovery seems to be (1) the derivation or recovery of energy from combustion of a mixed plastics/organics waste fraction in the municipal waste stream, or to enhance volume reduction through various forms of thermal treatment by utilizing the high energy value of plastics, and (2) selected source separation.

In the former, the presence of plastics enhances combustion due to a high BTU content. As waste contains a number of noncombustible items and significant quantity of moisture, plastics can be an important offsetting combustible fraction.

Thermal Treatment

Thermal treatment can be grouped into three general categories:

- Large scale and modular incineration (with and without energy recovery)
- Pyrolysis
- Preprocessing for refuse-derived fuel

For each of these methods, proponents desire the high energy content of plastics to enhance the overall energy content of the solid waste. Plastics found in MSW have heating values in excess of 42 kJ/g (19,000 BTU/lb). Refuse heating values range near 11 kJ (5,000 BTU/lb). As a comparative point, coal has a typical energy content of 28 kJ/g (12,000 BTU/lb).

An additional benefit of the thermal treatment systems is the potential for volume reduction of solid waste by as much as 90 percent.

Polyester-polyethylene Terephthalate (PET) Bottles

Recovery and recycling of post-consumer (municipal level) PET is established and growing. Prompted by bottle deposit laws, anti-litter movements and the need to conserve costly raw materials, recycling of PET is regarded as fully commercial. Both DuPont Co., Delaware and Goodyear Tire and Rubber Co., Ohio, have started up pilot plants for recycling. Industry estimates that PET recycled in 1979 amounted to approximately 3,499,090 kg (3,849 tons). This is estimated to almost double in 1980 (8). Owens-Illinois, a container corporation has published a guide to PET recycling which gives urgent attention to the recovery of PET in markets which have container deposit systems. In this guide, bottle fillers are recommended to include a reclamation system. Most bottling facilities can accomodate the necessary equipment. The major component is the granulator. It grinds all materials into scrap particles. Accessories to the granulator include variable feed hoppers, conveyers, air evacuation systems, and scrap shipping gaylords. A minimum of 400 square feet is required for the processing system, with additional space needed for transfer and storage operations (9).

TABLE 2 PAST AND PRESENT RECOVERY FACILITIES AND RECOVERY PROGRAMS AT MANUFACTURING OPERATIONS

Agency	Program
1. Cement and Concrete Research Institute	1. Ground plastic as sand replacement.
2. Chem Tec Specialties	2. Grinds rigid plastics for dissolving.
3. Chrysler Corporation	3. Sheds vinyl fabric and urethane foam scrap, impregnates the scrap with vinyl resin, and molds it into automobile mats
4. Cryogenic Recycling Int'l, Inc.	4. Freezes scrap to brittleness, then fine grind.
5. D.M. Fay	5. Explored possibilities of damage from plastic scrap.
6. Dow [illegible]	6. Reground high density polyethylene to tile, flower pots, etc.
7. Ford Motor Company	7. Recovers ABS
8. Free-Flow Packaging Corporation	8. Collects foamed polystyrene packaging materials from industrial users and recycles it so that it can be re-used in packaging operations.
9. Gold Plastics Services	9. Reprocesses polyethylene bottles to pipes.
10. Gulf Oil Company	10. Incorporates scrap polyethylene into the production of trash bags.
11. Hefner Industries	11. Uses selective solution to recover any plastic scraps.
12. Hoffer Plastics	12. Uses polyethylene scrap in plastic concrete composites.
13. Mobil Plastics Division	13. Recycles foam polystyrene egg cartons.
14. Packaging Industries	14. Converts film scrap to extruded [illegible].
15. Phillips Petroleum Company	15. Producing items such as planters, from recycled mixtures of plastics.
16. Polymer Recovery Corporation	16. Recovers polyvinyl chloride from a fellow substrate.
17. Upjohn Company	17. Converts rigid polyurethane to pellets.
18. Western Foam Packaging, Inc.	18. Recycles foamed polystyrene trays.
19. Poly 33	19. Polyesters into many different products
20. Recycle Unlimited	20. LDPE and HDPE
21. [illegible]	21. PET scrap
22. Sears-Roebuck	22. Polypropylene

Reclaimers are interested in high volume usage and purchase truck load quantities 22 to 24 gayloads which each are 4 x 4 foot square fiberboard containers. An average purchase price for PET is estimated at $0.03 per lb.

Markets for Recovered Plastics

Markets for plastics recovered from municipal refuse is limited. Most polymers will not find markets for reuse. The emerging market is for PET. Specifications vary according to market.

PET

Recycled PET currently finds its largest end use in strapping and fiber fill; insulation for winter clothing, carpet backing, thermoform sheeting for clear packaging. As of February 1979, PET recyclers were documented in literature (8) and are listed.

Building Components, Inc.
Van Nuys, CA

St. Jude Polymer Corporation
Mahonoy City, PA

E.I. DuPont de Nemours & Co.
Wilmington, DE

Midland Processing, Inc.
Pomona, NY

Plastic Recyclers
Richmond, CA

Plastic Recycling Incorporated
Dallas, TX

Plastics Development Corporation
Los Angeles, CA

Three M - 3M
St. Paul, MN

Willman Industries, Inc.
Johnsonville, SC

Pure Tech Industries, Inc.
Pinebrook, NJ

Ralco Industries, Inc.
Cumberland, RI

STATE OF THE ART GLASS WASTE RECOVERY

Source Identification

Waste glass generation in the United States stems from three primary sources: industrial, commercial, and municipal. Industrial waste glass for this analysis is assumed to be any glass waste generated during the manufacturing of glassware. Commercial waste glass is assumed to be any glass waste generated from sources where glass is used as an integral part of the establishment's product line. For example, waste commercial glass can emanate from bottle filling operations, the food packaging industry, the construction industry, food and beverage service industry (including bars), the automotive industry, and about any establishment that uses glass for their products. It is noted that commercial glass waste finds its way into the municipal waste stream or directly into landfills. Municipal glass waste is assumed to be that glass which is discarded after the useful life of the product has ended. Examples include beverage containers, food containers and windows, etc. Industrial waste may be included in municipal solid waste and can be disposed at landfills. Retail outlets and bars may contribute to these wastestreams.

Figure 2 presents an idealized drawing summarizing the major components of the industry, with sources of generation and recycle material flows (10).

Quantities of Glass Waste

The total glass production in 1978 was estimated to be about 18 Tg (20 million tons). About 70 percent of this glass was container glass. However, the amount of container glass found in municipal waste is reported to be about 90 percent (11). This is expected since the useful life for container glass is relatively short when compared with other glass types such as flat glass and fiberglass, in the absence of reuse systems. According to the latest available statistics, glass is reported to comprise up to 10 percent of the total municipal wasteload (12) of 134 Gg (148×10^6 ton). Table 3 presents waste glass generation estimates based on available data and inference.

Estimates of future quantities of glass waste in the municipal waste stream are numerous. Future projections of any sort are based on previous trends and many factors such as marketing conditions and competition. Table 4 presents a projection of glass waste and the amounts recovered from mixed municipal waste for the period 1980 to 1990, incorporating such factors, and beginning with the base year of 1972.

Review of Table 4 indicates that the total quantity of glass waste generated will increase slowly through 1980 while the percentage of glass in the total waste load will decrease. This is based on the assumption that glass waste recovery through 1990 will increase due to advances in recovery technology and wider community recycling efforts. This estimate could change if reuse programs and container deposit legislation efforts are successfully implemented on a wide scale.

Glass Waste Recovery

The recovery of glass from municipal waste within the United States today is more representative of an emerging technology, rather than an age-old practice. Nonetheless, a secondary materials industry does exist, and methods for recovering materials from municipal waste are achieving new levels of sophistication and success.

Within the recycling "closed system," three defined segments exist: (1) glass manufacturing and secondary materials users; (2) cullet dealers; and, (3) municipal and private collection programs. Glass manufacturers are the principal actors. Raw material users have traditionally utilized glass cullet derived from off-spec glass, etc. Most recycled glass from post consumer sources has been used by glass container manufacturers to produce

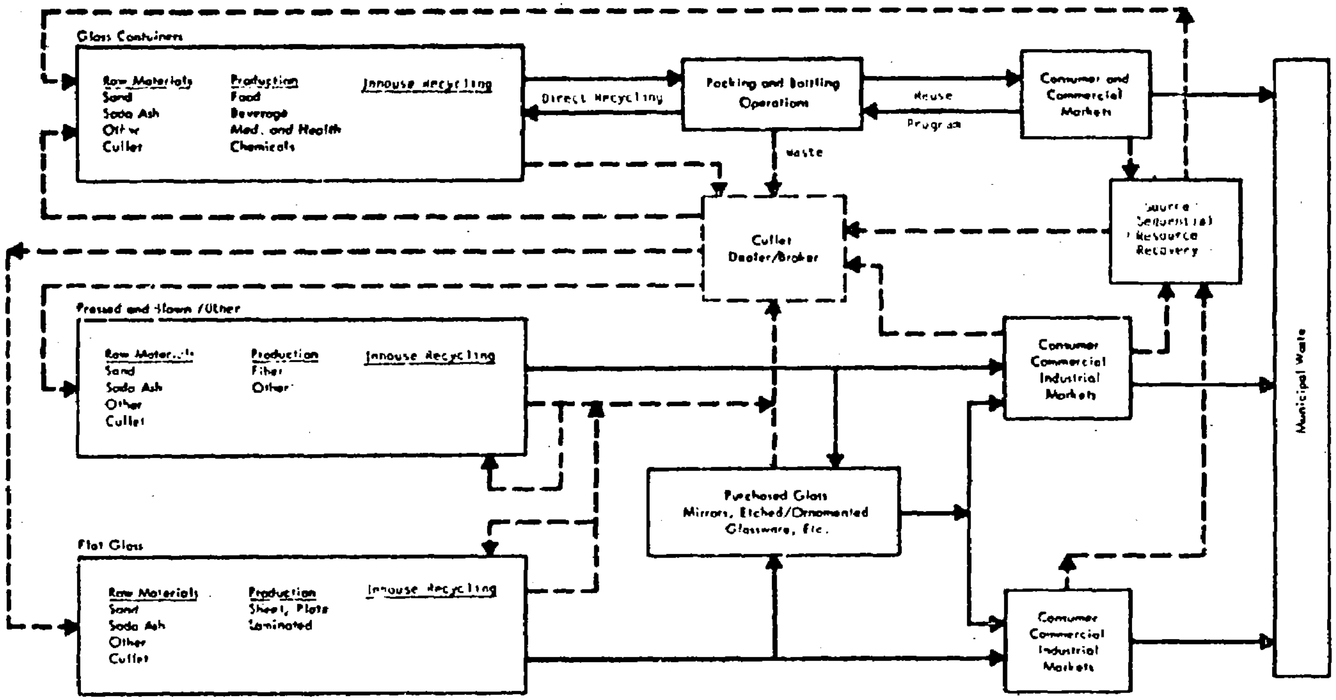

Figure 2. Glass industry recycle flowchart and sources of solid waste.

TABLE 3. ESTIMATED WASTE GLASS GENERATION BY SOURCE (1977)

Category	Total Waste	Residential %	Residential MT	Residential Gg	Commercial %	Commercial MT	Commercial Gg	Industrial %	Industrial MT	Industrial Gg
--	148,000	--	--	--	--	--	--	--	--	
Glass waste	14,800	82	12,136	10,983	16	2368	2143	2	296	267
Glass container waste[a]	13,220	82	10,840	9,810	16	2115	1914	2	264	239
Noncontainer glass waste	1,580	82	1,295	1,172	16	252	228	2	31	28

[a]90 percent of glass waste

TABLE 4. SUMMARY OF GLASS WASTE ESTIMATES, PROCESSING AND RECOVERY FOR MUNICIPAL WASTE, 1972-1985 (1,000 ton)[b]

Category	1972	1975	1980	1985	1990
Total solid waste	130,000	140,000	160,000	180,000	--
Glass available	13,200	14,500	16,400	16,600	16,900
Percent glass of total waste	10.1	10.5	10.3	9.3	
Glass processed for recovery[a]	0	20	170	540	660
Glass recovery					
- source separation collection	175	180	225	225	225
- cullet dealers	100	85	50	50	50
- waste recovery plants	0	10	100	350	600
Total resource recovery-glass	275	275	375	600	850
Percent recovery of total-glass	2.8	1.8	2.3	3.6	5.0

[a]Processed in central facility with glass subsystem
[b]Estimates by Midwest Research Institute

new containers. Recently there has been a shift to composites of glass, plastic and fibers. These new secondary uses promise glass recycling an expanded cullet capacity with reduced specification levels. Additionally, economic problems exacerbated by inflation and energy shortages have "improved" the economics of smaller scale enterprises. It has been theorized that small scale, local industries will be more apt to utilize locally-derived cullet, thereby eliminating high transfer costs (13).

Cullet dealers represent a second segment. As intermediate processors, they provide the important function of aggregation and quality control. Cullet dealers are, however, a diminishing segment of the industry. Less than 20 dealers exist today (conversation with glass cullet dealer).

Finally, the delivery or collection system, represented by grass roots recyclers, municipalities, and small businesses form the third segment. They often deal through intermediate processors, although larger programs may sell directly to a manufacturer.

Industrial Source Glass Waste Recovery

The glass manufacturing industry has traditionally recycled its in-house waste materials (factory cullet) for various economic advantages. Cullet added to the glass furnace assists the melting process of the virgin batch by lowering its melting temperature, and speeding up its melting time in proportion to the percentage change (14). As a result of heat reduction in the furnace, the life of the refractory furnace linings is extended and fuel consumption is reduced (14). Some manufacturers have also met air quality regulations by increasing cullet usage. Users report a significant reduction of particulates and high temperature related emissions (14).

In-house cullet is usually available from off-specification glassware and rejected or broken glass from within the plant. Generally, 20 percent of the batch material will end up as "in-house" cullet (14). Some additional cullet (foreign cullet) may be purchased from external sources such as bottling plants, cullet dealers, and municipal recovery programs to increase the quantity of quality cullet input to the furnace where quality control is stringently exercised (15). The maximum percent of cullet that can be introduced to a batch without altering the quality of the finished product is greatly dependent on the quality of the input cullet and how it compares to the batch recipe. Several furnaces in Europe and elsewhere are currently using more than 50 percent cullet in each batch, and some furnaces have been operated successfully on 100 percent cullet for short periods under special circumstances (16).

Municipal Glass Waste Recovery

Municipal waste, in general, is considered to be that discarded post-consumer material which is collected and disposed in the municipal solid waste system. In addition, industrial and commercial establishments discard wastes along with consumer waste, so that municipal solid waste can be a combination of all three types.

Glass waste in the municipal solid waste stream, as previously noted, represents about 10 percent of the total waste load. In addition, about 90 percent of the glass waste originated from container glass. As such, the container industry has been interested in recovery of this material both from an economic and public relations perspective.

The glass recovery system actually incorporates three basic operations: (1) collection or delivery; (2) processing; and (3) recycling. All three, which together comprise the closed recycling system, are interrelated and interdependent upon each other.

Glass can be recovered from municipal waste by source separation systems, mechanical recovery systems or by various reuse strategies. Source separation is the simplest and oldest method of glass waste recovery, and requires separation of discarded glass from other solid waste. Source separation is generally categorized as a labor-intensive endeavor.

Mechanical separation involves the application of mineral extraction and separation techniques to municipal solid waste to extract glass from mixed refuse. Mechanical systems for glass recovery are at present emerging or experimental, and are usually found as a subsystem and not in an independent mode.

Reuse programs generally involve a tax or deposit on waste containers, which is redeemable upon return. The vast majority of reuse programs disappeared as the market economy favored one-way containers. However, energy and environmental considerations have spurred renewed interest in reuse strategies.

The mechanism of recycling is very similar to virgin material systems. Concentration, purification, and manipulation of material characteristics occur. Once materials are collected, they usually must be aggregated, processed, and otherwise brought up to specification levels acceptable to secondary materials users. Cullet dealers generally represent this portion of the system.

The system is closed with the purchase of cullet by manufacturers, usually glass container industries. Market dynamics, as will be discussed later, appear favorable toward use of glass cullet in secondary products, where specifications are less stringent.

Source Separation

Source separation is basic to the many ecologically motivated community recycling efforts throughout the nation. Source separation actually spans municipal, industrial and commercial recycling. However, it is the difficulty of mechanically extracting saleable material from mixed waste that has sparked renewed interest in source separation.

Source separation is a traditional practice that accounts for nearly all of the glass resource recovery currently conducted. Source separation involving either curbside collection or collection centers has grown over the last decade. Recycling technology is increasing in sophistication, level of efficiency and workability as new equipment, procedures, and processes have been exclusively developed for separate collection and processing. There has been an effort to standardize procedures for such programs that ensure a reliable and quality product from these operations. In part this success is attributable to research funded by the U.S. Environmental Protection Agency (EPA) and other public and private agencies and industry (17).

In the following, discussion will focus on collection centers, cullet dealers and separate collection programs.

Most people are familiar with the community recycling center. There are over 2,000 community recycling centers which have proliferated across the nation, for reasons of community involvement, small capital expense and on the strength of a good core of participants (18). Additionally, most centers accept multimaterials (all grades of paper, metals and glass), and as a result, are better able to weather market fluctuations, an all too common occurrence.

Intermediate glass processors or cullet dealers represent a key link in the effort to recover glass through separation. Industrial, commercial and municipal programs are increasingly dependent on the services that intermediate processors provide. As a secondary materials dealer, they do not produce new glass, but instead act as the purchase agents for a number of glass manufacturers. There are fewer than 20 cullet dealers in the United States. They are located in New England, Florida, California, Missouri, Houston, and the Great Lakes region (10).

By providing storage equipment to large manufacturers, cullet dealers collect scrap glass which might be disposed due to contamination. They remove contamination through their processing system, and then sell it back to glass manufacturers.

By providing storage equipment to local recycling groups, they provide a service in collecting heretofore unreclaimed glass that glass manufacturers will not take, due to certain reasons. Intermediate glass processors will aggregate glass, develop color mixing schemes and provide services by removing contanimants.

Also, cullet dealers are able to collect glass from commercial source generators such as restaurants and bars. Containers may be provided along with employee education programs.

Some intermediate processors may serve as mixed recyclable purchasers for recycling groups. In Los Angeles, California, one cullet dealer is the sole purchaser of recyclable material, including cullet, from the Downey DART source separation program. In that operation, collection vehicles transfer glass cullet and other material collected directly to the glass processor. The cullet dealer separates metals and paper from the scrap glass, and sells all components.

Most of the recent research and successful glass recovery has come from multicategory source separation schemes involving curbside collection. Curbside collection programs generally operate in residential areas. There are approximately 220 such efforts on-line in the nation (19). In a typical program, residents routinely set out for collection using barrels, bags, and boxes, recyclable fraction(s) segregated from refuse. Either separate trucks or integrated collection vehicles collect the recyclables and/or refuse. Material is normally taken to a processing station where, if glass materials are already segregated in glass colors or type, minimal processing is conducted. Where recyclables are mixed, hand or mechanical sorting is required. Long term storage may or may not occur depending on volume.

Source separation programs collecting glass are presented as Table 5. Design variables are indicated.

Mechanical Separation

High technology recovery systems are emerging state-of-the-art for glass recovery. While these systems do recover other materials as well, only the subsystems applicable for glass recovery are addressed in detail. While no subsystem has as yet been proven on more than an experimental or pilot basis, extensive activity continues towards achieving viable and cost-effective mechanical separation.

Froth Flotation for Glass Recovery

Froth flotation is an emerging technique for glass waste recovery. This technique has been extensively tested by the Bureau of Mines, and by the National Center for Resource Recovery (NCRR) at its full-scale operation in New Orleans called Recovery 1. The test results indicate low refractory particle content cullet is recovered (20). It does not, however, meet industry specifications for glass container manufacture (20). Froth flotation is a technique utilizing differences in the chemical properties of fine ground glass and the contaminants to achieve material separation. The glass and contaminants are mixed with a physiochemical reagent, which absorbs preferentially to the surface of the glass. The coated glass attaches to bubbles formed by agitating the mixture by air. This glass-rich froth rises, is swept off the top, and is washed. Commercial glass-sand operations and other reprocessing operations have been using the froth flotation principle for decades to separate silica sand or other ores from unwanted minerals. Normally a series of froth flotation cells are used where progressively more and more of the contaminants in the glass are removed.

Optical Sorting for Glass Recovery

Optical sorting is designed to remove any foreign material from a glass-rich fraction of a waste stream and to separate the glass by color. This method of separation is commonly used in the food processing and other industries and has been modified for the purpose of glass recovery. It is considered a new technology for glass recovery.

Considerable research has been conducted on the propietary Sortex machine. The Sortex machine consists of a series of photocells which separate the opaque particles from the transparent particles by matching the intensity of light transmitted through the particles with a fixed shade background. In the process, glass-rich fragments are charged to a Sortex machine via high speed belts. When the particle does not match the corresponding background, a jet of air is automatically released, and the particle is deflected into the appropriate receiving bins. The transparent particles, comprised of primarily glass particles, are also color sorted in the photocells by the similar mechanism.

This method of separation is most effective when the particle size of the feed stream is larger than 6 mm (1/4 in) since the particles are examined individually as they pass "single file" through the sorter.

TABLE 5. SOURCE SEPARATION PROGRAMS COLLECTING GLASS WITH DESIGN VARIABLES

Site	Collection method[a] R	T	CV	ST	Material contract	Mand. ord.	Scavenging ord.
East Lyme, CT				x		x	
Newington, CT					x		
Waterbury, CT				x	x		
Waltham, MA				x	x		
Andover, MA				x			x
Bedford, MA				x			
Newton, MA			x				x
Somerville, MA			x		x		x
Marblehead, MA			x			x	
Hamilton, MA				x			
Tiverton, RI[b]				x			
Summit, NJ				x	x		x
West Orange, NJ				x		x	x
Bound Brook, NJ				x	x		x
Ithaca, NY				x	x		
Bowil, MD				x			x
Albington, PA				x		x	x
Clifton Heights, PA				x			
Atlanta,		x					
Walbash, IN		x					
Boulder, CO				x			
Downey, CA				x		x	
Fresno-Clovis, CA				x		x	
Davis, CA				x		x	x
San Luis Obispo, CA				x	x		
Modesto, CA				x	x		
El Cerrito, CA				x	x		
Santa Rosa, CA				x	x		

a R = Rack, T = Trailer, both are integrated collection; CV = Compartmentalized vehicle, ST = Separator Truck

b This program is the only one to solely collect glass via curbside collection. Programs generally collect newsprint and metals in varying combinations.

Note: This listing is not inclusive.

A series of tests were conducted by EPA at a resource recovery plant in Franklin, Ohio (21). Initial findings indicated that contamination levels of refractories were excessive. Flint glass averaged six refractories per pound, and the color mixed fraction (green and brown) contained 25 refractories per pound (21).

Systems for Concentrating Glass Wastes

Several other preprocessing methodologies can be used to produce glass-rich fractions from which glass can be separated. These are usually used alone or in conjunction with other units to provide suitable fractions for subsequent froth flotation or optical separation systems. They include:

• Air classification - normally used as a preprocessing step for the complete solid waste recovery systems. There are two basic ways in which air can be injected into the system to achieve the separation of waste materials by weight. The first way of separation involves air flowing horizontally through a falling stream of solid waste material. Heavy fractions including glass of the waste stream are unaffected by the air flow and fall to the bottom of the classifier. In the second method of air classification, shredded solid waste is introduced into the side of a vertical tube with a rising air flow (22). Light particles are carried out the top of the tube by an air stream, while heavy particles settle out at the bottom and are conveyed to subsystems for additional separation.

• Rising current separator - Prior to allowing the material to enter the separator, the incoming refuse is first preprocessed. The particle size of the separator's feed stock is between 0.6 and 5 cm (1/4 inch and 2 inches). In the separator, water is continuously pumped through the system. As a result of the rising water current, light organics remaining in the heavy fractions are carried to the top and removed. Heavy fractions at the bottom of the separator consist of mixtures of glass, rock, aluminum and other nonferrous metals, which can be further processed to obtain individual species (23).

- Heavy media separation - the system is based on different specific gravities of the incoming material. The separator is basically a tank consisting of heavy "liquid" (suspension of a mineral in water) which acts like a single fluid with high density. As the mixture of glass, aluminum and other nonferrous metals is fed to the separator, glass and aluminum (of lower density) float while the other metals sink. The glass and aluminum are skimmed off for further processing.

- Shredders, screeners, and jiggers - often are used to augment the above described components for concentrating glass waste fractions.

Current High Technology Resource Recovery Programs in the United States

Table 6 presents a partial listing of current resource recovery programs that recover glass as one product (24). These resource recovery programs do not now render a saleable glass product.

tainers at the point of consumer purchase. This was the traditional system that was essentially supplanted by the one-way container system. In theory, the consumer returns the container to the retailer to reclaim the deposit. Once returned, the retailer stores the container until it is returned to the bottler. There are bottle deposit systems now in place in several states including Michigan, Vermont, Connecticut, and Oregon.

In response to deposit systems, it is noted here that industry has advocated a litter tax program. Such programs levy manufacturers, retailers, etc. a small annual tax that is collected by state agencies and later parceled out to recyclers through the form of grants or loans. This system has been implemented in California and Washington and has been seemingly successful, both in dampening enthusiasm for bottle bills and in encouraging recycling.

Another form of reuse is characterized by the ENCORE! bottle washing operation which originated in Alameda County in 1975 (25). Recognizing that the 74 million gallons of wine consumed annually in California require over 110 thousand tons of glass "throwaway" bottles, ENCORE! attempted to demonstrate to wineries,

TABLE 6. RESOURCE RECOVERY ACTIVITIES WHICH RECOVER GLASS

Location	Process	Output	TPD Capacity	Capital $mm	Status
Baltimore County, MD	shredding, air classifying	secondary product glass	600-1000	8.4	operational
Bridgeport, CT	froth flotation	glass cullet	1800	5.3	not in operation
Dade County, FL	"hydroposal"	glass cullet	3000	165.	1981 startup
Milwaukee, WI	air classifying	glassy aggregate	1600	18.	in operation
Monroe County, NY	froth flotation	mixed glass	2000	50.4	started up Aug. 1979
New Orleans, LA	froth flotation	glass cullet	700	9.1	operational problems
Hempstead, NY	"hydraposal"/sorter	color sorted glass	2000	73.	shakedown
Wilmington, DE	froth flotation	glass cullet	1000	51.	under construction

<u>Reuse Strategies</u>

There are other methods for recovering glass materials from the waste stream. One of these is deposit legislation. Another is the collection of bottles through buy-back programs for washing and reuse.

In the former, a legal mechanism is initiated which places a deposit on con-

recycling centers, restaurants, stores, concerned groups and individuals that empty wine bottles could be collected, washed, and reused on a large scale.

Used wine bottles are collected and returned to a central sorting warehouse in Berkeley. There, they are washed and sterilized in a hydraulic bottle washer custom-designed for ENCORE! and incorporating special energy saving techniques. Also, ENCORE! is currently heating water by utilizing solar energy. The "revitalized" bottles are then distributed to participating wineries.

ENCORE! maintains the strictest quality control standards and meets all state, local and Federal health regulations. Identification of such areas around the United States where such programs could be implemented has not been conducted. It is also noted here that GPI has not promoted this form of reuse due to the opinion that health and safety risks with reusing the washed bottles outweigh the potential conservation benefits.

Markets and Specifications

The waste glass recovery cycle is closed when materials are ultimately delivered to and utilized by a market. Markets or users of glass derived from post-consumer solid waste, though, are not as well developed as for other recyclable materials such as fibers and metals. Reasons include the extreme nature of specifications, the need to color sort glass and the ready availability of raw resources for container manufacture. There is one geographic region which enjoys an excellent "mixed" cullet market--California, primarily because of the wine bottling industry. New England is the recipient of an excellent cullet market, and there is some movement toward incorporating mixed cullet purchase.

On a national basis, it appears that new secondary product applications such as fiberglass insulation will spark growth in glass recycling over the near and long term. A reason is these products require less stringent specifications on color and contamination.

Specifications

The specifications or standards are dictated by the particular product or application being considered. In the case of containers, the standards are rather well-defined and quite rigid. On the other hand, for the vast majority of other products and potential products which could utilize secondary glass, the standards are either very broad, vague, or essentially nonexistent (10). Glass manufacturers have to keep close control over the batch of raw materials to maintain the quality of the finished product. The cullet extracted from mixed municipal solid waste generally consists of foreign particles and chemical compounds used in coloring container glass. These contaminants must be removed to a level which is acceptable for use in buyers batch recipe, or else masked effectively. Specifications normally concern color and contaminants. Exact specifications are provided in ASTM specification No. C708-79, ASTM Book Part 41, 1980 issue.

Future Trends

Glass recovery from municipal solid waste is limited at present. EPA estimates place recovery at a 4 percent rate (26). There is some impetus being given to increase glass cullet usage through national energy and resource conservation efforts, and stringent air quality control regulations. Stringent specifications, the lack of a national mixed cullet market, manufacturer reluctance to maximize cullet usage in batches, and ready availability of appropriate silica sand deposits tend to mitigate growth trends.

Several trends have been identified from conversations with acknowledged industry experts and current literature. These are listed below:

- trend emerging toward smaller scale operations (economy of scale)
- reduced distribution lines
- more emphasis on fiberglass production, insulation and plastic composites
- effort to increase mixed cullet recycling
- reuse program resurgence
- source separation has emerged as the dominant recovery strategy
- continued inroads by plastics into traditional glass packaging markets will spur glass manufacturers into secondary products and the use of metals and plastics.

ENVIRONMENTAL AND ECONOMIC EVALUATION

In the commercial and manufacturing segments, resource recovery activities have been straightforward. The economics are based on the material being of known composition and quality, and free of contamination. In particular, the economics of the plastics industry is very much dependent on the recycle of scrap (waste) internally or by sale. "Scrap" is usually reintroduced into the production stream either directly or "downstream" of the resin manufacturers. Through the recovery of plastic and glass wastes, adverse environmental and economic impacts are mitigated and beneficial impacts are realized.

In contrast, plastics and glass wastes from municipal sources are mixed with other wastes and are contaminated. They must then be separated from other solid wastes or at least concentrated into suitable fractions, homogenized, and decontaminated prior to any successful utilization. It is apparent that, at the present time, recycling from municipal sources is limited. For both plastic and glass cases, there exists a paucity of environmental and economic information. As a result, environmental and economic impacts are difficult to assess. Moreover, no existing commercial recovery system, other than certain pilot mechanical and source separation systems, recover plastics or glass from MSW as a sole product. Consequently, identification of specific impacts and costs is, at best, a most difficult proposition.

Environmental Impacts of Plastics Waste Recovery

Combustion

The environmental impact of recovering energy values from plastics contained in municipal solid waste is primarily limited to atmospheric emissions. The impact of plastics upon the overall atmospheric emissions from burning refuse is difficult to quantify. Experimental evidence has indicated that burning of the three most widely used plastics -- polyethylene, polystyrene, and polyvinyl chloride -- contributes insignificant emissions under properly maintained combustion conditions (27). Polyethylene melts early in the burning process, is completely consumed in any properly operated plant, and leaves minimal residues. The only byproducts are carbon dioxide and water. Polystyrene emits black smoke particles into the atmosphere when burned in the open air. However, in properly operated incinerators and boilers, this smoke is reduced and any particles would be captured effectively by control devices such as fabric filters, scrubbers, or electrostatic precipitators.

Some concern has risen over potential hydrogen chloride and vinyl chloride emissions from burning waste that contains chlorinated plastics such as polyvinyl chloride (PVC) and vinyl chloride. Both hydrogen chloride and vinyl chloride emissions could be potential health problems. The chloride emissions could also erode the metal surface within the furnace unit. In as much as new installations have not faced serious problems with this pollutant, it can be said that the impact of hydrogen and vinyl chloride emissions is minimal and can be effectively contained through proper equipment design and control systems, i.e. wet scrubbers.

Secondary Products

Of interest here is whether secondary products made from plastic waste represent potential pollutant sources, whether in the process or product. Most of these products, such as fence posts, tiles, plasticizers, paint extenders, etc., are too new to have any definitive data as to their impact. The processes themselves are a different matter. For example, there have been some problems related to workplace hazards and plastics recycling. Especially pyrolysis of polyurethane will yield tolidine diisocyanate (TDI), a deadly toxic substance (28). Literature noted that plastic granulators used to regrind off-spec resin and other scrap have been developed which mount the entire cutting chamber assembly on shock absorbers to isolate the cutting impact from the frame of the machine and decrease noise (7).

Economic Impacts of Plastic Recycling

To ensure that maximum profits can be realized from purchased materials, manufacturers strive to reduce waste to a minimum. Some plastic scrap which is not reprocessed internally by primary polymer producers and fabricators is sold to scrap dealers or processors. The scrap is attractive from an economic viewpoint, since it creates new business opportunities and reduces raw material costs. For example, one company is reported to purchase fairly clean scrap polyethylene film and bags, and rework it. The recovered granulated pellets are added to virgin input in the ratio of five to ten percent scrap. The cost of recovered polyethylene, including the purchase of scrap and processing, is said to be less than 50 percent for the virgin material (29).

While inplant recycling is an established fact, once the plastic waste becomes part of the municipal waste stream, the economic incentives for recovery are generally insufficient to overcome the costs of recovery, except in the case of consistent scrap or PET.

Environmental Impacts of Glass Recovery

Glass waste from the glass manufacturing industry and in many commercial establishments is routinely collected and used in the manufacturing process. Adverse environmental impacts associated with these practices are minimal.

In fact, environmental impacts associated with glass waste recovery from municipal refuse are mostly beneficial. Major impacts are listed below:

- lessened impacts from extractive industry operations
- diverted landfill volume
- reduced air emissions from glass manufacture and the potential offset from cullet reuse
- energy conservation from increased cullet usage in batches

By increasing recyclable volumes into batch processes, a considerable reduction could indirectly occur in environmental emissions. Through virgin materials extraction, and virgin materials processing considerable amounts of energy are expended and environmental degradation occurs (30).

The introduction of an inert material such as glass into landfill systems poses no environmental pollution problem for ground water quality. However, by continuing its introduction into scarce landfill, especially those classified for hazardous waste, glass acts as a potential competitor for limited space.

There have been investigations, according to literature (10), that confirm the relationship between cullet reintroduction into production and lowering of air emissions. Raw virgin materials used in glass manufacture go through complex chemical reactions resulting in the release of gases and particulates. Cullet, having once undergone these reactions, will not add to emissions (31). Also, it has been documented that cullet lowers the melting temperature. By doing so, emissions associated with higher temperatures (such as NO_x) are mitigated. One glass manufacturer in California has reported that increasing cullet usage has allowed his operation to meet air quality regulations.

With regard to energy, cullet introduced into the batch at a controlled rate can reduce [illegible] energy by about 1/4 to 1/3 of a percent per 1 percent of cullet added. This formula is applicable at charges up to 50 percent cullet. Anticipated energy savings could range as high as 11-12 percent per batch (32-35). While detailed energy studies have been conducted for glass container manufacture in Europe, and limited studies in the U.S., no studies have been performed for other glass production sectors.

The EPA in the 5-volume study on the Marblehead and Somerville, Massachusetts source separation programs conducted analysis of energy consumption-savings for three alternative scenarios: landfill, transfer station, and a combination system involving source separation. Of the alternatives, the combined system had the highest energy return (36).

Impacts of reuse systems would appear to be mainly focused in the economic sector, though bottle washing should increase emissions in wastewater (primarily food stuffs and organics), decrease landfill burden, and save energy (37).

Economic Impacts of Glass Recovery

Costs can "center" over specific operational modes. For example, transportation of products to market constitutes one mode. This cost center is slightly different for intermediate processors and community recycling centers. For all programs, though, generalized cost centers include:

- collection
- processing and storage
- transportation
- marketing
- administration

Cost elements involved in these cost centers are factors that change from area to area, and from type of technology to marketing conditions and products. Cost elements include, and are uniform, among all cost centers for specific technologies:

- labor
- utilities and fuel
- capital expense and amortization
- maintenance
- overhead (insurance, etc.)
- building modifications
- publicity

While no specific study has detailed all these centers and elements in a comprehensive economic analysis, there have been individual reports detailing one or more of selected factors.

Representative costs for dropoff system structures were prepared using estimated costs per ton developed on a comparative basis. Using two studies and two estimates, costs were assigned to citizen preparation, public payment, processing equipment, labor, construction, storage, transportation and administration. Costs ranged from $15/ton to $37/ton. The two largest elements were labor and transportation.

A true economic picture of recycling centers is difficult to obtain. "Hidden" costs can include volunteer or low-paid labor (both in source generators and at the centers), free materials, free land, government grants, etc. As noted earlier, some programs have access to CETA employees (38). On the other hand, there are intangible benefits which cannot be included on a ledger including the benefits in education and diverted disposal. Therefore, in an economic study done by EPA, the costs per ton of recycled material varied from $6 per ton after disposal credit to a net $169 per ton excluding landfill credit (39).

In a concurrent analysis of curbside collection programs (40, 41) representative costs were developed based on all recyclables collected. It showed a net gain in the Marblehead, MA program, but a net loss in four other programs. These costs were assigned on the basis of actual processing per ton, disposal savings per ton, and revenue per ton.

In a study performed by EPA of the Franklin, Ohio resource recovery plant, the economics of glass recovery were assessed at the 50 TPD level (21). Projections were then made at the 500 TPD and 1000 TPD levels using 1975 dollars. Cost projection included facility amortization, operating and maintenance costs, and glass, ferrous, and aluminum sales. The study concluded that combined sales held economic viability, but operating the entire subsystem (heavy media separation, electrostatic separation, color sorting, etc.) for glass recovery alone was not feasible. The relative significance of the revenues potentially available are also important in this respect. One-third of the projected revenues would be attributable to glass. Yet over half the costs associated with the plant are associated with glass recovery. This is because color sorting and glass processing is highly capital and energy intensive regardless of whether aluminum/ferrous is recovered. All pre-processing steps are necessary for glass recovery.

A critical assumption of the study was that at larger installations, ceramic contamination could be reduced to meet stringent industry specifications or that the glass industry would accept a higher level of contamination than was accepted at the time. (These specifications have not been relaxed sufficiently. (42))

SPECIFIC ECONOMIC ISSUES

There are a few economic issues important to a full treatment of plastic and glass waste recovery. These include the following:

- employment and other socio-economic impacts
- litter tax and reuse strategies
- obstacles to increased recycling
- economic development
- diversion credits

<u>Employment and Other Socio-Economic Impacts</u>

Recovery of waste materials has positive employment and social impact. In the case of collection centers, such programs directly involve citizens in solid waste management activities. As a result, it can help the public understand the problems of solid waste management and achieve certain levels of conservation and litter abatement (18). An important consideration is that source separation-collection centers are labor-intensive. Many programs are initiated with the goal being to hire the handicapped or difficult to employ person (18). Another aspect is that collection centers assist in raising revenue to undertake community beautification programs (18).

It has been theorized that recycling industries, basically "conservation of energy industries" which also reduce pollutants generation and material's usage, will serve as major foci of investment and urban redevelopment strategies in the near future (13). Not only will employment aspects be served, but additional market capacity will encourage further recovery of waste materials. This has a direct impact on the quantities of materials being landfilled or otherwise disposed.

Litter Tax and Reuse Strategies

In some states, "bottle bill" opponents have supported "litter tax" measures designed to tax litter generators or those who produce items that become litter, a small amount. This levy is then collected and composed into a fund that may be made available to anti-litter programs and "recycling" programs. In California, a "litter tax" program has been in effect for two years at this writing. Over $5 million has been awarded to waste recovery programs for developmental activities. The program will be operational for another 3 years (43). This litter tax program has effectively defused bottle bill proponent efforts.

Waste reduction activities have had a degree of impact on the composition of the waste stream. According to data from Oregon, metal containers have been reduced, and glass has become a larger component of the waste stream. In another study in Michigan, it was found that metal containers were initially reduced, but within a year had increased although not to levels prior to bottle bill enactment (44).

Reuse measures do provide increased recovery opportunities. For example, in Michigan PET 2-liter containers are being returned through the deposit system (44). PET is being recycled because the reuse system ensures a consistent and clean recyclable component. As PET is the only plastic beverage container, there is currently no major problem of compatibility of plastics. The major problems arise with the PET bottle contaminants, e.g., aluminum caps, paper labeling, thermoformed bases, and different colors used (45).

Obstacles to Recycling

Current obstacles exist which inhibit increased glass and plastic recycling. One obstacle is the general price differential between virgin and recycled materials. Virgin materials have been cheaper in the U.S. because natural resources have been plentiful; because public policies favor virgin materials; and because environmental and other social costs (externalities) have been omitted from the price (46).

Federal Land Usage

One obstacle is public policy on Federal land usage. Virgin material extractors, for example, gain competitive advantage from the resources and technical and scientific assistance from a number of supportive Federal agencies (47).

Tax Structures

Tax structures generally favor virgin material processors. Over the years, the Federal government has developed tax policies that favor extractive industries. For example, capital costs incurred in exploring and bringing mineral deposits (glass silica) into production may be deducted as current expenses rather than amortized over the useful life of the property. Also, the costs of development are deductible after a commercial mineral is established. While it is true that at one time it was necessary to quickly and comprehensively exploit our resources, it is not necessarily true today. Incentives to explore and develop virgin materials retard demand for investment in recycling (47).

Railroad Freight Rate Discrimination

Transportation typically accounts for a very large fraction of the delivered cost of materials. Ideally, all materials would be charged costs that relate to the actual cost of hauling. However, in practice, different commodities and shippers are charged rates that differ relative to the required costs incurred by the carrier, a condition referred to by many as freight rate "discrimination" (30). Substantial and systematic rate differentials have been held by Congress, the U.S. EPA, the secondary materials industry and the U.S. Supreme Court to contribute to inefficient relocation of resources and to work against resource conservation. Currently, the Interstate Commerce Commission (ICC) is under litigation to revise their rates relative to scrap materials; to, in effect, equalize freight rates. The ICC recently estimated that glass freight discrimination amounted to $4.70 per ton (30).

Economic Development

Traditionally, the primary use for reclaimed glass is in the manufacture of new containers. However, this is not always feasible or practical especially where extensive mixing of cullet and contaminants occur (necessitating high costs of upgrading) and where transportation costs inhibit purchase of cullet. In all cases, where the cost of the cullet exceeds the cost of virgin materials, the primary markets will utilize virgin materials.

The need for development of secondary product markets independent of, in many cases, artificially low-cost, virgin materials, is becoming increasingly urgent as solid waste management enters an era of large-scale salvage. While many processes are technically feasible, only recently have economics improved to a point where secondary product development provides a competitive return on investment.

Economy of Scale

An area of importance is the apparent reversal of trend from construction of larger, regional-type projects toward smaller, local and community-scaled industries (13). The impetus behind this is partially explained by the following:

- the need to provide local employment
- the ready availability of waste resources for utilization
- with local control of these two aspects, a lessening of impact by macro economic factors (including inflation and recessions)
- less capital is necessary for start-up, research, operation and construction, hence smaller communities and small businesses are able to afford such systems.

GPI evaluated the potential for the commercialization of glass rubble building panels (48). The constructed flat panels produced by vibro-compaction techniques measure up to 10 feet x 4 feet x 4 feet, and weigh up to 1,900 lbs. The finished product would typically be composed of 94 percent ground waste glass, and the remainder a composite of clay and demolition rubble. Various complex sizes and shapes can be made, with ultimate usage as decoration or structural application. The immediate competition is with brick and precase concrete panels for structural application. Decorative panels must compete with rock, marble, mosaic, stucco, and glass-plastic composite panels (48).

Under economic analysis, it was determined that investment and development of these panels as an industry is closely keyed to "carefully defined (geographic) areas at a carefully determined scale of operation." Manufacturing costs range for small-scale operations costs of $1/sq ft to $0.80 for larger operations; both are competitive prices. Wall panels made from "virgin" materials are currently being produced in more than 200 different plants within the U.S., reflecting a strong local nature of the business. Most of the operational and successful plants are located within 70 miles of their immediate market (48).

Under a similar investigation, mineral wool insulation utilizing waste glass was evaluated for technical and economic feasibility (49). Users for up to 50 percent cullet change include insulation batts and blankets, blowing wool, and high temperature felt insulation. Benefits to the manufacturer include:

- permits significant shortcut in manufacturing by bypassing the conversion of silica sand and chemicals to the glass feedstock state.
- useful for up to 1,200 F temperature, which represents a 50 percent increase in use
- costs less to manufacture

However, extensive contamination (stones, etc.) can significantly impair a mineral wool process by plugging the "spinner.

Estimated capital requirements (incorporating a 100 percent inflation factor for 1971 figures) for an 18 ton/day facility is shown in Table 7.

excreta

- economics of manufacturing terrazo with waste glass aggregate
- economics of manufacturing foamed glass construction materials made with waste glass and animal

TABLE 7. ESTIMATED CAPITAL REQUIREMENTS FOR 18 TON/DAY GLASS WOOL PLANT

Category	$
A. Amortized investment	
Engineering, research and development	100,000
Start up	200,000
Subtotal A	300,000
B. Fixed investment	
Structures and improvements	260,000
Machinery and equipment	580,000
Subtotal B	840,000
C. Recoverable investment	
Land	80,000
Working capital	450,000
Total recoverable investment	$ 530,000
Total capital requirement	$1,670,000
D. Capital requirement per ton/day capacity*	$ 92,777

*250 days per year operation

The total manufacturing cost for the 18 ton/day operation is between $187.50 and $300.00 per ton. This range is acceptable within the limits of current glass wool prices (49).

Secondary Materials Development Opportunities

Regardless of the potential for small-scale enterprises, there exists a potential for industrial development utilizing materials derived from municipal waste. GPI has investigated several potential waste utilizing enterprises, however, all have been related to low specification uses which could utilize glass derived from resource recovery enterprises. These enterprises include: (50-53):

- economics of manufacturing ceramic tile with waste glass and animal excreta
- economics of manufacturing slurry seal with waste glass aggregate.

Diverted Disposal Values

Materials diverted by source separation activities have a diverted disposal value. Although not necessarily credited to a center, the value should be considered when assessing program viability.

Savings in diverted solid waste disposal costs are dependent on whether the municipality in which the program is located operates its own facility or franchises out to contractors. In another, secondary sense, the savings value varies with the cost of the disposal method.

Sanitary Landfill

Benefits of source separation on landfill operations include a decrease in the rate of use of remaining landfill space and a decrease in landfill equipment use. Based on operating costs ranging from $1 to $8 per ton, an average of $4 per ton is estimated. Land costs are assumed to represent $0.50 of the total cost based on the disposal of 10,000 tons per acre and a net land cost of $5,000/acre. Therefore, diversion of recyclables can be assumed to potentially save $0.50 per ton in land costs at the landfill and up to $3.50 per ton in operating cost savings (54).

Incineration

The diversion of materials from incineration through source separation activities can be expected to reduce equipment usage and residue disposal requirements. Further, there is a net benefit to energy efficiency when noncombustible recyclables are removed. Incineration costs range from $20 to $30/ton with an average of about $20/ton.

In addition, ash residue must be hauled for final landfill disposal. Residue transport costs vary with many factors, but can be assumed to average $0.50 per ton of residue (54). Total costs can be assumed to be equivalent to the costs in the preceding landfill discussion.

A 95 percent reduction of weight of material can be assumed for paper wastes. No such corresponding weight reduction can be assumed for glass and metals, both noncombustible, if processed through an incinerator. An average of $11 per ton can be assigned to source separation as a result.

STATE-OF-THE-ART PLASTICS AND GLASS WASTES RECOVERY ABROAD

The study of technologies for plastic and glass wastes recovery and recycling in other countries has limited but worthwhile application to the United States. In most foreign countries, capital is scarce and labor usually plentiful. Therefore, emphasis is most often placed on labor-intensive materials extraction rather than energy-capital intensive extraction techniques as used here in the United States. In the industrialized nations of Europe and Japan where the situation is analogous to the United States, maximizing human energy is becoming increasingly important as fossil fuel-derived energy costs soar. It is expected that this will be true, if not already, for the United States.

Materials and energy recovery from solid wastes has traditionally been practiced around the world and in the United States. In some countries, recycling practices have remained relatively static for thousands of years although materials have changed. Some countries are more advanced than others depending on the degree of technological sophistication and industrial-commercial organization. These rely more on state-of-the-art techniques.

In Cairo, Egypt waste materials have been recycled for thousands of years by so-called "refuse people" who live outside Cairo in their own "refuse city." Today they collect and process source separated wastes in much the same manner as in the past: oxen drawn carts are used for collection of refuse. Of course, smelting of aluminum, and plastic reclamation are relatively new (55).

In Japan, plastics reclamation from municipal waste is more widely practiced, especially by technological methods, than elsewhere. A significant reason behind this is that plastics represent a greater percentage of the Japanese waste stream, energy is at high premium, and recycling is highly institutionalized. In fact, Japan passed a law recently mandating nationwide recycling (56).

In Europe, there are found similarities with the United States in issues, objectives, and technologies. Europe is slightly advanced in some areas, especially market development for secondary plastic products.

RESEARCH ON PLASTICS AND GLASS WASTE RECOVERY/REUSE

Plastics Wastes Recovery Research

Basic plastic waste recovery research programs generally focus on the site specific needs of manufacturers. These include: (1) processes for the chemical or mechanical separation of various blends of plastic waste, (2) processes or additives which improve the bonding characteristics of mixed plastic types, (3) development of specifications to both aid consumers in identifying plastics and to enhance recyclability and, (4) processes and systems to upgrade segregated plastic scrap types normally uniformly contaminated (e.g., PVC molded around copper wire).

Less research has been devoted to recycling plastics from mixed municipal refuse due to many factors, including cost-effectiveness, lack of markets, low volume, and lack of demonstrated need. In Europe, the Flakt system concentrates plastic wastes, but this is currently not recovered. Rather, it is removed as a contaminant from paper fibers (57). In the United States, the research efforts focusing on municipal refuse as a source of plastic for recovery are combustion-energy recovery operations, which favor the high Btu content (42 kJ/g (10,000 Btu/lb)) of plastics, selected solvent separation, cryogenics, source separation, air separation, electrodynamics. sink flotation, and research related to PET bottles.

Glass Waste Recovery Research

Research efforts for recovery/reuse have been concerned with mechanical separation, source separation, new secondary products and reuse programs.

Foremost, a market for the recovered glass must exist. Presently there are only limited markets. One area of research that has been promising for glass waste recovery is its use in secondary products. Products such as glasphalt and glass foam insulation demonstrate the technical feasibility of using glass waste for secondary products.

An area of some interest is reuse of products. The ENCORE! system, a wine bottle washing operation, depends on free market forces. It is both profitable and effective. Although there is a question of safety, no serious problems have been encountered to date.

CONCLUSIONS

The following conclusions were developed based on the State of the Art:

Plastics

- Industrial and commercial sources efficiently recycle using simple, proven technology. The main reasons are waste materials are concentrated, relatively uncontaminated and usually of known quality and composition.

- No proven commercial scale recovery system singularly effects recovery of waste. Rather, such materials are recovered as one component of an over-all recovery-collection approach.

- Secondary products, on the whole, have not had specifications developed on product reuse. This has acted as a barrier to increased utilizations since reuse processes have not necessarily been standardized.

- Combustion and energy recovery hold the greatest promise for recovery of the bulk of the plastics fraction of the solid waste stream due to the number of different types of plastics and the differing degrees of degradation of components.

- Source separation from the industrial to the residential levels constitutes the only significant recovery of waste from municipal waste soruces.

- For the immediate future, industrial and commercial sources will comprise the majority of recycling activity. Recovery from post-consumer wastes must overcome significant market, institutional, technical, transportation, and specification barriers in order to compete successfully with virgin products.

Glass

- Glass manufacturers claim that 25 percent of the post-consumer waste stream could be recycled right now. Transportation and collection/delivery problems and contaminant levels mitigate against this.

- Industrial and commercial sources

efficiently recycle using simple, proven technology. The main reasons are waste materials are concentrated, relatively uncontaminated and usually of known quality and composition.

- Municipal sources of wastes are most often mixed with other components of refuse; hence, recovery is difficult with poor economics; also, the ease of obtaining raw materials, prevents a significant recovery incentive.
- No proven commercial scale recovery system singularly effects recovery of glass. Rather, such materials are recovered as one component of an overall recovery-collection approach.
- Source separation often lacks in collection equipment and efficient processing; hence, recovery is inhibited.
- Secondary products, on the whole, have not had specificati s developed on product reuse. This has acted as a barrier to increased utilizations as reuse processes have not necessarily been standardized.
- Mechanical recovery systems for glass wastes have primarily originated from other industries such as mining. They lack proven usage in waste separation where moisture, composition, physical properties, and economics vary widely.
- A national market for mixing color glass cullet could significantly enhance recovery of glass wastes from municipal sources by simplifying collection and processing.
- Source separation from the industrial to the residential levels constitutes the only significant recovery of waste from municipal waste sources.
- For the immediate future, industrial and commercial sources will comprise the majority of recycling activity. Recovery from post-consumer wastes must overcome significant market, institutional, technical, transportation, and specification barriers in order to compete successfully with virgin products.

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FORMALISM VERSUS REALITY IN ECONOMIC FORECASTING

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ABSTRACT

This paper originated in a review of two reports which predicted the composition of future national levels of solid waste. This involves associating technological information with the formalisms of economic analysis. The paper defines this problem in a detailed context.

1. INTRODUCTION

This paper originated in a review of two reports which predicted the composition of future national levels of solid waste. In particular, the assignment was to predict the future volume of sixteen materials in this waste stream.

Predicting the waste stream involves at least implicitely the prediction of the future use of end items in which the materials are embodied. One study used very little technique beyond an exploration and use of available data sources. The other study used an input-output based model to explicitely predict the usage of end items. Neither approach, however, was successful in producing the best estimates that detailed technological analysis, married to prediction of usage on a micro-scale, can come up with in particular cases.

The approach of each study had certain advantages, but each study encountered major difficulties. We found that the two approaches are much more difficult to reconcile than it might appear. Since this difficulty--how to reconcile a knowledge of reality with the current economic models—is a widespread problem, this paper focuses on this point. It defines the problem in precise context of the interface between two professions.

2. TWO REPRESENTATIONS OF AN ECONOMY

The two studies reviewed started by examining production data, and then transformed that information first into final products, and then into a waste stream. In both, the first and key step is to estimate the (potential waste-) material content of articles put into service, i.e., the flow of materials into products. There are two ways of performing this estimation: the input-output method and the flow method.

a. The Input-output Method for Finding Flows.

An input-output table is essentially a doubly balanced accounting model among "industries" and final users. The elements are the purchases by each sector from others, and the sales of each sector to others. There are balancing accounts for such destabilizing factors as inventory changes, depreciation, and profit.

An input-output table can be used to identify material flows. When this is done, the model for many materials is found to have a simple structure in several senses: the largest flows are short, and a few flows account for the preponderant part of output. To illustrate, the three largest flows for aluminum to households are:

Al ⟶ motor vehicles ⟶ 192,000 m. tons
Al ⟶ trailer coaches ⟶ 122,000 m. tons
Al ⟶ metal stampings ⟶ motor vehicles 70,000 m. tons

The quantities represent the amount of aluminum that is used (according to the input-output table.) In two cases, the only multiplication is a single coefficient, aluminum purchased per vehicle times final demand for motor vehicles or trailer coaches. In the other case, two coefficients in the model are multiplied (aluminum per metal stampings times metal stampings per motor vehicle), and the product is multiplied times final demand for motor vehicles.

Each of these lines is called a path (a technical term of the mathematics of directed graphs.) A previous report* studied the paths associated with the 16 materials whose use results in municipal waste. It analyzed the paths that it called "significant," that is, that accounted for 3/4 of the output of each material. For this definition of significance, it was necessary to have 213 paths, an average of 13 1/3 paths per material.

Two aspects of structure are significant: (a) how many parts of the economy affect demand for each material and (b) how indirect is the connection. The number of significant paths for each material ranges from 2 to 35 for various materials. The spread in the lengths of the paths is the following:

Number of paths:	213
Single step	91
Two steps	107
Three or four steps	15

The analysis must be taken further. Each of the paths ends with a final product purchased by consumers. It must be multiplied times demand to obtain the quantity of potential waste. This demand, in turn, depends on aggregate household income which, in long-term economic forecasting, is assumed to depend upon a set of factors (the population, the proportion of population that seeks work, the politically-acceptable unemployment rate, and productivity) which are forecast exogenously. A path, then, is illustrated by the following:

several exogenous forecasts
↓
household income
↓
glass ⟶ soft drinks ⟶ demand for soft drinks ⟶ part of glass in waste stream

What began as a system of simultaneous equations has become reduced to a set of analyses which are not at all formidable computationally.

The simplicity of the structure of an input-output table is a result of the procedures used in tabulating and presenting data. Data are grouped into "industries." An industry may include several steps, e.g., makers of automotive parts are part of the industry "motor vehicles." The data reflect the tendency towards vertical integration in plants, and the large efficiency of combining various steps as in steel mills. It is no surprise that the steps, in a model of such large units, are short.

It should be emphasized that this conversion of part of the matrix into a small number of short flows holds because an input-output model has certain empirical properties. These are reflected in a lack of significant interdependence in the matrix. It does not hold for those parts of an economy where there is substantial interdependence (e.g., transportation, energy), and it does not account for all of the output of materials. (An attempt to account for all flows of a material generally results in an extremely large number of paths.)

* Stedman B. Noble, "Forecasting the Composition and Weight of Household Solid Wastes Using Input-Output Techniques," 2 Vols., 1975. NTIS, PB257 499/4GI; and PB257 500/9GI. Also see Martin Hershkowitz and Stedman B. Noble, "Finding the Inverse and Connections of a Type of Large Sparse Matrix," Naval Research Logistics Quarterly, Vol. 12 (1965), pp. 119-132.

b. Flow Method.

The input-output table represents transactions between sectors of the economy, and can be used to identify material flows into final use. An alternative method is to identify these flows directly. Most of this information is readily available from such sources as

(1) the Census of Manufactures,
(2) other government data such as by Bureau of Mines,
(3) data produced by trade associations and trade press.

Why would an analyst go directly to data when an input-output table is available? Mainly because the table may not satisfy his needs. For example, the composition of solid waste depends upon the weight of the inputs, where an input-output table is given in values. Largely for this reason, each of the studies being reviewed developed historical information on waste by going to published sources. Because they did this, they provide information on the difficulty of a direct method.

Our procedure is the following. Using the 213 flows already defined, we have determined whether the necessary information is or is not available directly in print. Table 1 summarizes this information.

The nonferrous metals pose special problems, so putting them aside, we can focus on steel and nonmetals. For these, almost half of the paths are directly in print. Being "in print" involves two considerations: (a) that the material per end use be published (e.g., plywood purchased by the house trailer industry), and (b) that the proportion selling to final demand can be known. Since quantities on alloction to final demand are not generally published (except in input-output tables), a path is listed in Table 1 as "in print" when sales of its final industry are 85% or more to households. If the information in print is incomplete the input-output furnishes an allocation.

In a further number of paths, the published data can be used because the categories are adequate or even more than adequate for the analysis of solid waste. Textiles provides an example. Here, the input-output model distinguishes knitted goods from woven apparel, a distinction of considerable importance for makers of textile machinery. For the study of solid waste, what is wanted is the composition, by fabric type, of types of apparel, household textiles, etc. This information is available directly in print.*

The direct availability of data in print gives the analyst considerable flexibility in constructing his flows. We have already seen one example where this mattered: the dimensionality of the data. For solid waste, the appropriate dimension is weight. The analyst could obtain this directly, or use an available dimension (e.g., board feet) that is more readily converted than are values. If each user paid the same price per pound, values would be acceptable. Investigations reveal wide divergence in the average price per pound paid by different users.**

There are many other examples where direct use of data affects the way flows are constructed. For example, the largest use of rubber is for tires. An input-output model allocates some tires to new cars, some to households, and some to commercial establishments for replacement. The analyst can afford to ignore this distinction, using the unit all "tires for passenger cars and light trucks," and giving special attention to retreading of tires since this represents a diversion from the waste stream. The distinction between users made in the input-output table is not necessary for analysis of solid waste, and the "retreading" path does not appear in the input-output table.

The most important reason to go directly to the data, however, is the ability to use more detailed information than is available in the input-output table. For example, the input-output table combines lawn mowers with farm machinery whereas the Census of Manufactures identifies the metal purchased by each of these. The Flow Method can readily

* "Textile Organon," Nov. issue each year.

** Stedman B. Noble, op. cit., Vol. I, Table 4.19, p. 111; Vol. II, pp. B-48 ff.

TABLE 1. SIGNIFICANT INFORMATION THAT IS OR IS NOT AVAILABLE IN PRINT.

	Number of significant paths	Paths not directly in print	Categories in print are not acceptable	Involves no aggregation error in input-output model
Lumber	5	1	0	0/0
Paper	14	11	7	0/7
Building paper	7	6	6	5/6
Textiles	22	10	0	0/0
Plastics	35	21	15	6/15
Rubber	4	4	0	0/0
Leather	2	0	-	0/0
Glass	5	2	1	0/1
Steel	14	6	3	3/3
SUBTOTAL	108	61	32	14/32
Copper	20	15	13	3/13
Lead	20	20	18	3/18
Zinc	35	35	14	1/3
Aluminum	19	10	8	0/8
Other metals	12	11	11	1/11
TOTAL	213	152	116	22/116

accommodate the level of detail that is required to trace th actual physical flows. Much of this detail is hidden (aggregated away) in the actual construction of an input-output table, and the structure of an input-output model does not lend itself to putting the detail back in. The significance of this point for two flows is illustrated in Figure 1.

In the first case, data at the 4-digit level in the Census of Manufactures shows that a more restricted path is called for, and that the largest path generated by the input-output model is inaccurate. In the second case, the most detailed information in the Census of Manufactures delimits the flows, but not sufficiently. Going to technological descriptions of the uses of copper*, the special properties of copper are used in furniture hardware, marine hardware and some specialized builder's hardware. Automotive hardware is not mentioned, indicating that the largest path from hardware in the input-output table which is the one that begins "copper hardware", is not valid

* American Society for Metals, Metals Handbook, 9th ed., Vol. 2, pp. 395-439.

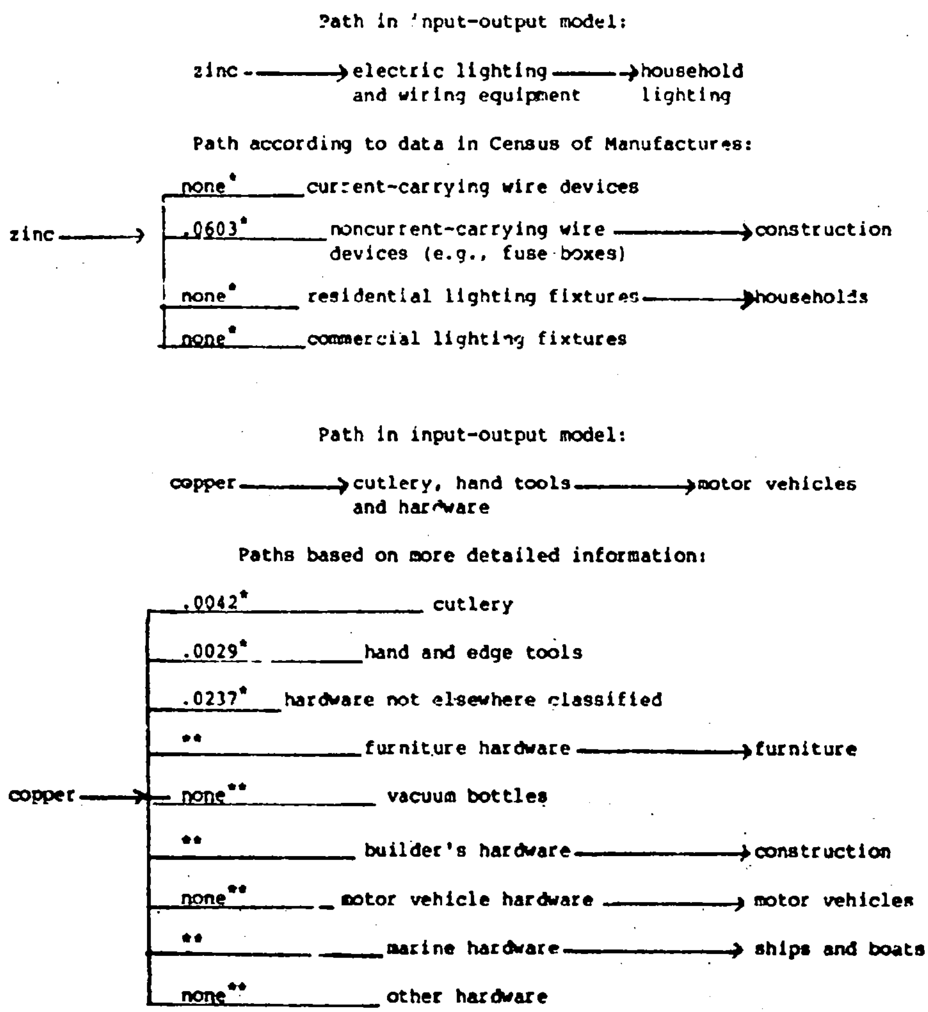

Figure 1. Paths in the input-output model and in reality.

* Allocations using most detailed data in Census of Manufactures. Unit: lbs per $.

** Allocations using technological information on uses of copper. "None" means not mentioned in source.

for copper. Since no data exists at the appropriate level of detail, allocations of copper must be estimated.

For many materials, trade associations provide data that avoid prerating errors. They do this by techniques comparable to those used in Figure 1. To some extent, they tabulate data for individual plants to avoid errors. More generally, they ask their respondents to answer different questions from those asked by the Census of Manufactures which underlies the input-output table. They do not ask Who did you sell to? but rather What was the material ultimately embodied in? The respondents, being familiar with the technology of use and its association with the specific materials being produced, can answer or at least make educated guesses.

How pervasive are aggregation errors? The fourth column of Table 1 enumerates the proportion of paths that were accurate out of those checked. The complement therefore indicates the incidence of serious aggregation errors in the input-output table. A large proportion of the paths are inaccurate for the nonferrous metals. The nonferrous metals also represent most of the long paths, those that involve 3 or 4 steps. The long flows for lead involve its sales to industrial chemicals, resulting in such paths as

lead ⟶ industrial chemicals ⟶ fabrics ⟶ apparel

In fact, lead is used for tetraethyl lead for gasoline and in pigments for paint used in construction. It is not used significantly in the dyes used in fabrics. The long flows of zinc almost always involve sales of zinc to steel, resulting in paths such as

zinc ⟶ steel ⟶ metal stampings ⟶ motor vehicles

In fact, zinc is used to galvanize (coat metal, especially wire) in the steel industry. It is not used for other uses of steel. A matrix connects each input to each output, being unable to recognize the selective uses of these materials. It turns out that the aggregation error resulting from the use of <u>only</u> an input-output table and model to trace flows of waste are both pervasive and large.

It is important to emphasize the formal similarity between the paths constructed freehand and those generated from an input-output model, because this shows that the analysis can be broken into a set of distinct steps:

(a) create coefficients, step-by-step,
(b) study whether the coefficients change over time,
(c) study the demand by households for the end product,
(d) separately forecast total household income.

The difference between the two approches is their use of categories. In an input-output table, the categories are defined in advance. In the flow analysis, the categories emerge during the analysis.

3. THE INPUT-OUTPUT AND FLOW METHODS COMPARED

The preceeding section has already identified some of the relative strengths and weaknesses of the two kinds of model in use for tracing the physical relations between sectors of an economy. In this section, we summarize some of this discussion and appraise the contribution of each approach. The section begins with a short theoretical discussion of the nature of models.

a. <u>Reflections on Models.</u>

The act of modeling is the assertion of a correspondence between features of the economy and certain sets of formal symbols. If in addition we postulate characteristics of the symbols and relationships between them, then the act of modeling asserts that these characteristics and relationships hold "approximately" between the phenomena in the economy which the symbols are supposed to represent.

For example, the rows and columns of an input-output matrix represent sectors of the economy, the coefficients of the matrix represent the ratio of one sector's purchases from another to its total purchases. Using these coefficients implies that what one sector sells another is passed to the

* The data for metals, published by trade associations and Bureau of Mines, are not published in adequate detail for this study. Therefore, Table 1 is not able to treat this as "in print" and is based upon other sources. The available data do demonstrate that these data collectors could provide indirect data at adequate detail if they wished to do so.

second sector's customers in proportion to the values of the second sector's sales.

This therefore assumes that the set of inputs of any industry is strict complements. Viewed as flows, it is assumed that each input is used in the same proportion whatever the pattern of sales of the industry. The example of the uses of lead to industrial chemicals to clothing shows how wrong this interpretation can be.

The correspondence between reality and symbols is called interpretation, and the issue is whether economic models are interpretable, and whether the interpretation is part of the analysis. Interpretation of physical flows depends upon knowledge of technology.

Interpretation becomes particularly important in forecasting future events. The use of computer models in forecasting implicitely assumes a course of future development of the economy. These assumptions may or may not be in accordance with the best technological estimate that can be made at present. Only if these implicit assumptions are made explicit, and checked for their verisimilitude, i.e., only if the operation of the model is interpreted, can the prediction carry sufficient conviction to provide a basis for policy development.

b. Use of the Flow Method.

The strength of the flow method is that it ties directly in the best available technological information. In so far as the method consists of tracing the physical flow of materials via products and on to waste, it is already in physical terms, i.e., interpreted. Furthermore, it can take account of the most current information in the industry.

We have already seen that a flow analysis may introduce new categories such as "retreaded tires" or it may merely replace data., e.g., copper by way of hardware goes to furniture but not to motor vehicles. In the first place, it must develop new forecasts itself for the new categories. In the second place, it can use forecasts that are available for a category such as "furniture." However, the detailed flow alerts the analyst to the dangers of assuming complementation. Copper hardware in furniture does not seem to be inevitably proportionate to sales of furniture. We are reminded of the diversity of furniture, the changing fashions in styles. The analyst must make an estimate whether his detailed component will change more slowly, more quickly, or proportionately than do furniture sales.

c. Uses of the Input-output Method.

The primary use of the input-output table and model provide a bridge between GNP and National Income accounts as shown in the following:

I-O matrix	GNP
NI	

The natural role of this model is to handle problems that focus on the total economy. In macro analysis of an economy, relationships of the following kind are defined: the dependence of household income (a part of National Income) upon various types of aggregate expenditures. This includes any of the elements of GNP: household expenditure, government expenditures (federal, state, local), construction, capital expenditures, exports, imports, and inventory changes. The input-output model disaggregates such equations, defining how industrial composition of income is defined, dependent upon the commodity composition of GNP. The input-output model will therefore translate future GNP into a demand for materials that composes the waste stream. It does this, however, subject to the limitations of interpretation inherent in the model, as well as subject to the limitations in predicting the future.

It has been seen that the principal limitations of the input-output approach for technological analysis are

(1) that is uses fixed categories, and
(2) that it distributes embodied materials among products proportionately to the value of sales between sectors

Limitation (2) leads to extensive false flows.

What the input-output model provides is a coherent framework for GNP calculations and distribution of income over industries. The complementarity assumption however may cause large errors in this distribution of income over industries. The flow method provides the technical insight to identify such errors, but present systems have not developed methods to correct the results.

4. THE TWO STUDIES OF SOLID WASTE

a. The Franklin Study.

Let us now turn to the two studies being reviewed. One of these, the study by Franklin Associates*, is now easily described. It uses the flow method, using data directly in print, rather much as described. No use was made of data from an input-output table.

The Franklin Study had many minor errors, e.g., it did not always use the best available data sources. More relevant, for our purposes, is its prediction method. It obtained data from, or estimated, the material per end use and then extrapolated that. It almost never broke this down into separate steps. The analysis was weakened by not doing this. To illustrate, for household appliances, data were obtained on the total materials composition of a number of specific prototype products, e.g., the total copper, rubber, etc., in a specific dishwasher. The assumption was made that this composition will be constant over time. However, data from the Census of Manufactures shows that the purchase of aluminum in that industry has been growing relative to steel. If coefficients had been identified, and the assumption of constance had been checked, a different forecast of material use would have been seen to be warranted.

Further, the Franklin Study did not review studies of consumer expenditure and use these as part of their projections. Their projections are attached to time series of the use of materials in end products, and are projections for the future use of materials in end products for which no rationale is provided.

b. The IR&T Study.

The approach of the IR&T Study** is almost completely the reverse of the Franklin Study in its heavy reliance upon other studies. The study uses the flow method to develop estimates of potential waste, drawing in part on precursors of the Franklin Study and in part on the input-output model. The use of the input-output model to generate paths without checking the reality of the flow led to errors. For instance, IR&T estimates that municipal waste has twice as much aluminum and over four times as much copper, lead and zinc as is claimed by Franklin. Since nonferrous metals in municipal waste are a major incentive for resource recovery, the difference has important implications.

A comparison with Bureau of Mines, both its data and its ancedotal descriptions of the uses of these metals, does not substantiate IR&T's claims. IR&T provided flow diagrams of this analysis, and these include many paths that are generated by an input-output model but are in fact spurious (e.g., zinc to household lighting, copper to motor vehicles). Apparently, reliance on the input-output model to generate paths led to the error.

For its projections of future waste streams, the IR&T study uses an input-output model. We have seen that this model represents a portion of the National Accounts. If GNP is specified in commodity detail, then the input-output model solves for the production levels of all industries in the economy, taking account of their

* Franklin Associates, Ltd., Post-Consumer Solid Waste and Resource Recovery Baseline, Working Papers, May 16, 1979.

** International Research and Technology Corporation, Forecasts of the Quantity and Composition of Solid Waste, U.S., Environmental Protection Agency, 1979. Also see International Research and Technology Corporation, Impacts of Economic Growth on the Quantity and Composition of Solid Waste, January, 1980.

sales to one another.

Several programs have carried the analyst further by closing the model, that is to also provide equations by which the elements of GNP can be forecast. One such effort, producing forecasts about ten years into the future, and updated every several years, is the Economic Growth Model developed by the Bureau of Labor Statistics. Another system is INFORUM, developed and maintained by Almon*. INFORUM is a computerized system which is kept up to date by continued statistical analysis of time series as updates are published. It is very large: aproximately 2,000 equations generate over 15,000 numbers for each projected year.

One characteristic of INFORUM is that almost any number in it can be "overridden," that is, revised by the user. It is designed for the computation of scenarios. These overrides are also used for updating the model. As new information becomes available, Almon compares it with his projections and tests whether his system accurately predicted the new numbers. When it did not, new relationships can be tried which provide a better fit, and their consequences can be studied. In addition to forecasting elements of GNP, forecasts are also made of each input coefficient based upon past trends, and corrected for the ability of the coefficients in a row to predict production data in each Annual Survey of Manufactures. Since there is always a lag in collecting and producing data—a lag of many years for the best data such as the Census of Manufactures—INFORUM is never entirely up to date.

The use of a computer model developed by one analyst and used by another analyst, and for a different purpose, raises the question of "portability." The IR&T study is really involved in double portability: IR&T used a version of INFORUM that had been transferred to another model—SEAS—where it had been permitted to get out of date. This version retained the override features of INFORUM, but did not have the continual update of the time series that drives the model to be updated.

The real problem of portability is making a fit between technological information and the use of the input-output model, including the processes of "closing" the model. The difficulties are threefold:

(1) Input-output models use a fixed schema for partitioning the economy, with its concommitant assumption of complementarity. Even INFORUM, with all its flexibility, has no built-in procedure for partitioning industries. It has no method to assist in discovering aggregation errors, or for making adjustments if they are discovered.

(2) In general, the updating of the closed models is done by statistical analysis of time series. For instance, Almon updates INFORUM yearly using the newest numbers of consumer expenditure. He found that expenditure on tires was rising faster than his equations suggested. Accepting this as a permanent change in the situation, he corrected his forecasts upward.** The data used were expenditure of households without regard for the number or tires being purchased. The reason for the rise, however, was the increasing acceptance of radial tires which are more expensive per tire. Radial tires last much longer, however, so that there will be a period of increasing acceptance when aggregate expenditure increases. Once ownership is saturated, demand will fall sharply. This illustrates the difficulty. A time series of expenditure may contain the present effect of current technological changes, but seldom contains the information to interpret it.

(3) The models lack adequate "interpretation", that is, they lack a description in technological terms of the numbers and relations embodied in the model. In the example just mentioned, IR&T was not aware that the consumption of tires had been permanently raised. This is unfortunate because IR&T is a firm whose main expertise

* Copper Almon, Jr. and others, 1985: Interindustry Forecasts of the American Economy, 1974.

** Almon, op. cit., p. 34.

is relating technological knowledge to economic data and analysis. Its analysts were familiar with the technological situation in the tire industry. Had there been a warning, they probably would have caught what was happening.

We conclude that the available input-output models are not portable in a technological environment. They are not programmed to accept technological information, nor is the information provided from which the user might see the necessity of transforming technical knowledge into the kind of input the models will accept. IR&T was a victim of this lack of portability; the analysis never really managed to incorporate all the technical information developed by the flow method.

5. CONCLUSION

The review of the two attempts to predict future waste flows has involved an extensive review of two sets of analytical tools: analyses of material flows and input-output models. It must be concluded that it is not at present possible to adopt input-output based models to accommodate detailed technical knowledge on a wide scale.

The reason for this difficulty is that input-output models, in order to model the entire economy which is their rationale, deal with technology schematically and in fixed categories. Technological analysis on the other hand will uncover singularities and change. In principle most of these can be accommodated into an input-output schema by disaggregation. In practice, an input-output model can be manually adjusted to accept a few irregularities. But in present models such manual adjustments do not seem practicable when a large number of interrelated changes are to be made.

The problem is a general one. Two professions have each developed their analytical tools for their own uses, from different points of view. Input-output models contain the reality of fiscal transactions, but physical transactions and technology are only formally embodied in the model. Flow analysis will produce the reality of physical relations. Ex post facto, formalism and reality cannot be meshed.

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