R. J. Ehrig, Editor

Plastics Recycling

Products and Processes

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Preface

The plastics industry has experienced phenomenal growth during the last decade. In 1976, plastics became the most widely used material in the United States, surpassing even steel. Today plastics is a $140-billion-per-year industry—an industry greater than steel and aluminum combined. Plastics are now used in every segment of American business and in the daily life of every one of us. They are found either in the form of the entire product as containers, and fast food packaging or in combination with other materials as parts of transportation vehicles, computers, tools, recreational equipment, etc.

The significant increase in plastics production and product generation has effected a similar significant increase in plastics disposal. Estimated at more than 7% by weight, but possibly twice that by volume, the amount of plastics in the nation's solid waste stream has more than doubled in the last 15 years; a greater percentage rise is expected as more plastic packaging and durable plastic components of automobiles and appliances come to the end of their service life.

Since 73% of all solid waste generated in the U.S. goes to landfill, the amount of plastic in this stream is considered a contributing factor to the nation's increasing solid waste burden and decreasing availability of landfill sites. The Environmental Protection Agency's strategy is to reduce all solid waste by 25% by 1992 and to foster markets for recycled materials. Lawmakers in nine states have passed mandatory plastic beverage bottle recycling bills; eighteen other state legislatures are in various stages of planning or formulating recycling bills; it is expected that all fifty states will have some form of plastics recycling legislation in place by the year 2000.

The plastics industry is responding, but it has a long way to go. Although a high percentage of scrap plastic has been recycled within the industry for many years, the recycling of consumer plastic waste is in an embryonic stage. About 1% of plastics is recovered from the solid-waste stream. Technology for the reclamation of polyethylene terephthalate (PET) bottles has been developed; similar technology exists for reclaiming other plastic bottles; film and molded fabricated parts reclaim technology also exists. Other technology has been developed for commingled plastics. PET is currently the major recyclable plastic material, followed by high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC). Some styrenics, acrylics, polycarbonates, and polyurethanes are reclaimed and recycled. New products and end-use markets are developing rapidly for these materials. Fibers, moldings, construction materials, chemical intermediates, and blending components are just a few.

Organizations, sponsored by many industrial corporations, have been formed to foster plastics recycling through education and research development funding. The same corporations, and others, have become part of the plastic recycling industry by formation of recycling entities within their own organizations and/or through joint ventures. The recycling industry, however, remains primarily an entrepreneurial one.

This book is intended for the plastic or materials engineer, specialist, or entrepreneur in the plastics or recycling industry. It is hoped also that the book will help many environmentalists, organizations, local, state, and federal governmental people who seek information on plastics and plastics recycling. Finally, the editor and authors wish it to be used by researchers, faculty members, and students as a starting point for future technological developments in this very young industry.

I wish to pause here for a moment to express a sincere appreciation and thank you to my "co-editor," Marge Ehrig, for her literary guidance and criticism, for many hours of word processing, proof reading, letter typing, etc., and especially for her patience and understanding.

Many thanks are extended also to the authors and their secretarial staffs, to Peter Prescott, and Marcia Sanders.

R. J. Ehrig

Foreword

Despite the large number of journal articles, technical meetings and general conferences on plastics waste and recycling since 1985, a sound understanding of this extensive and complex subject has been difficult to achieve. *Plastics Recycling* presents the first comprehensive survey of the technical, business and environmental components involved with recovery for reuse of discarded plastics.

The editor, Raymond Ehrig, and his collaborators have undertaken and completed a very demanding task. Their work will provide an important guide to those in the plastics industry, in government, and in other organizations, faced with decisions on the best choices for action.

The publication of *Plastics Recycling* comes at a time of rapid change for this field. Most large plastics producers and users are now heavily involved compared to the smaller companies just five years ago. Progress in the technology for recovery and for new applications has been remarkable.

Recycling of plastics from waste automobiles, appliances and construction is now receiving major attention. The effect of recycling on types and volume of virgin plastics which will be needed in the years ahead is under intensive study.

The Plastics Institute of America is pleased to introduce this volume as an important contribution to this challenging and exciting area for new developments.

William Sacks
Executive Director
Plastics Institute of America, Inc.
Fairfield, New Jersey

Foreword

The Society of Plastics Engineers (SPE) and its recycling division are particularly pleased to sponsor *Plastics Recycling*. It is the first definitive SPE technical volume detailing recycling technology currently available as a means of reducing the burgeoning volume of mankind's solid waste. The editor, Dr. Raymond Ehrig, is a distinguished scientist, ultimately qualified in the techniques of recycling and product applications of reclaimed plastics.

Dr. Ehrig's credentials include service as the co-founder and Chairperson of the Plastics Recycling Division and Chairman of the Plastics Institute of America. In the latter role, he has been involved both as an author and educator in publications, conferences and tutorial seminars on the subject of recycling technology.

SPE, through its Technical Volumes Committee, has long sponsored books on various aspects of plastics. Its involvement has ranged from identification of needed volumes and recruitment of authors to peer review and approval and publication of new books.

Technical competence pervades all SPE activities, not only in the publication of books, but also in other areas such as sponsorship of technical conferences and educational programs. In addition, the Society publishes periodicals, including *Plastics Engineering, Polymer Engineering Science, Polymer Processing and Rheology, Journal of Vinyl Technology,* and *Polymer Composites*, as well as conference proceedings and other publications, all of which are subject to rigorous technical review procedures.

The resource of some 37,000 practicing plastics engineers has made SPE the largest organization of its type worldwide. Further information is available from the Society at 14 Fairfield Drive, Brookfield, Connecticut 06804, U.S.A.

Robert D. Forger
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Plastics Recycling Division

R. J. Ehrig

Plastics Recycling

SPE Books from Hanser Publishers

Ulrich, *Introduction to Industrial Polymers*
Saechtling, *International Plastics Handbook for the Technologist, Engineer and User*
Stoeckhert, *Mold-Making Handbook for the Plastics Engineer*
Bernhardt, *Computer Aided Engineering for Injection Molding*
Michaeli, *Extrusion Dies—Design and Engineering Computations* [out of print]
Rauwendaal, *Polymer Extrusion*
Brostow/Corneliussen, *Failure of Plastics*
Menges/Mohren, *How to Make Injection Molds*
Throne, *Thermoforming*
Manzione, *Applications of Computer Aided Engineering in Injection Molding*
Macosko, *Fundamentals of Reaction Injection Molding*
Tucker, *Fundamentals of Computer Modeling for Polymer Processing*
Charrier, *Polymeric Materials and Processing—Plastics, Elastomers and Composites*
Wright, *Molded Thermosets: A Handbook for Plastics Engineers, Molders and Designers*
Michaeli, *Extrusion Dies for Plastic and Rubber—Design and Engineering Computations*
Ehrig, *Plastics Recycling*

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1 Introduction and History

R. J. Ehrig, M. J. Curry

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This chapter begins with an overview of plastics in municipal solid waste and presents the current status and future role of plastics recycling. Thermoplastics and thermosets are then defined; the terminology, coding and labeling of plastics related to recycling are discussed; organizations involved and current university research programs are introduced. The chapter ends with a brief history of plastics recycling. Some interesting, innovative, entrepreneurial ventures of the past two decades are presented. Research and development efforts to obtain alternate sources of fuel and raw materials for plastics and to use plastics waste as a feedstock source are reviewed. The influence of past work on present developments is noted.

1.1 Introduction

Many parts of the industrial world face serious problems of managing the generation and disposal of municipal solid waste (MSW). In 1989, the European community generated approximately 110 million tons (99.8×10^6 t) of MSW, and Japan's industrial and municipal waste totaled about 330 million tons (299×10^6 t) [1]. The problem is most serious in the United States where the populace generated 180 million tons (163×10^6 t) of MSW in 1989. This amounts to approximately 1400 pounds of discarded solid waste per person for the year. Since 1977, the amount of discards entering the waste stream increased by 35%. It is estimated that 73% of the MSW went to landfill or was otherwise disposed of, 13% was recycled, and 14% incinerated. The disproportionate amount of waste going to landfills, the closing of many of these sites, and the lack of equal numbers of replacement sites is the disposal aspect of the solid waste problem. This has received much attention in the media and is generally known as the "landfill crisis." In the past two decades, the number of active operating landfills has decreased by 75%. Within the next five years, one-third of the landfills currently in operation will be forced to close because of stricter governmental regulations on ground and water contamination and on landfill capacity. Few new sites will be opened since new site selection, preparation, maintenance, and operation also must meet more rigid standards and regulations. This could lead to an approximate shortfall of space for 50 million tons (45×10^6 t) within the next few years. Shortages of landfill space have already occurred in many parts of the northeastern United States. In 1970, New Jersey had 370 operating landfills; by 1989, fewer than eight were accepting more than 90% of the state's MSW [2].

The latest study on the characterization of MSW in the United States estimates that 40% by weight of discarded material is paper, 18% is yard waste, and a 7–9% weight range each for metal, glass, plastics, and food [3]. On a volume basis, the composition of the MSW stream is somewhat different. Paper is still the largest contributor at 34%, while plastic goes from 7% by weight to estimated values of 10% by volume [4] to 20% by volume [5]. Metals are estimated at 12%, yard waste at 10%, glass and food at 2–3%, and all other at 18%. The volume basis of solid waste is an important factor in landfilling. Although the cost of landfilling is done on a weight basis (i.e., tipping fees are determined by weight), the capacity of a landfill is determined by its volume. The relatively large volume that plastics occupy in the MSW stream has caused the plastics industry to come under severe attack in the last few years by environmentalists and solid-waste professionals.

The composition of the MSW stream has also been characterized by product type [6]. Discarded packaging products constitute about 30% by volume; nondurable goods such as newspaper, clothing, single-serve cups, etc., make up another 34%; durable goods such as appliances, furniture, tires, and consumer electronics, 22%; and food, yard, and inorganic wastes make up the remaining 14%. Breaking down the 30% that is packaging products in the MSW, 8% is plastics, 14% is paper, and 8% is metals, glass, etc.

Current recovery rates [7] for all materials in the solid-waste stream with the exception of food wastes exceed that of plastics. Paper is estimated at a 26% recovery rate, aluminum at

32%, and glass at 12%. Plastic is just now reaching an approximate recovery rate of 1%. This low rate has been a major concern to the plastics industry since it reinforces the popular belief that plastics are not recyclable. During the last few years, the plastics industry has been addressing these concerns through the formation and working of various organizations as well as individual companies within the industry. The most notable of these has been The Council for Solid Waste Solutions (CSWS). A discussion of the Council and other organizations concerned with plastics recycling is given in Appendix 3.

Plastics recycling in the United States during the last few years and up to the present time has focused mainly on plastics packaging and primarily on plastic bottles and containers. There are a number of reasons for this. As mentioned above, plastics packaging is considered a significant component of the solid-waste stream at 8% by volume. Packaging has an estimated life cycle of less than one year. As a consequence, plastics packaging continuously enters the solid-waste stream on a short turnaround time. Plastics in packaging has had a sustained growth period and will continue to grow, increasing the volume going to landfill unless increased recycling, as well as source reduction or incineration, is put into effect. In 1990, about 14.8 billion pounds (6.7×10^6 t) of plastics went into packaging applications [8]. This is a 6.5% increase over 1989. Rigid containers consumed 7.5 billion pounds (3.4×10^6 t) of which 4.0 billion pounds (1.8×10^6 t) went into containers and 2.2 billion pounds (1.0×10^6 t) into beverage containers.

Plastics packaging is a very visible part of litter. This, together with its visibility and volume in landfills, has made plastics packaging an easy target for environmentalists, governing bodies, the citizenry, and the media to call for its reduction, removal, or elimination.

In the early eighties, a number of states enacted return bottle bills. This was followed in the late eighties by other states enacting recycling legislation which decreed that local governments establish and provide collection services for the citizens. A growth of curbside collection programs has resulted, and a similar growth in recycling of plastic containers and bottles has occurred when these items are included in the programs. Curbside collection systems allow for easy separation of plastic containers and bottles either by the consumer at curbside or through collection and subsequent separation at municipal recycling facilities (MRFs). This is discussed in the following chapter.

Based on the factors cited above, the primary focus of recycling packaging materials probably will continue for a number of years. This means a continued high level of activity in the technology of recycling of the associated plastics. There are six commodity plastics that constitute 97% of all plastics packaging. These are commonly found in residential household items in the form of rigid bottles and containers or as flexible packaging and wrapping films. A number of chapters are devoted to a discussion of these commodity plastics. Individual chapters review the products and processes of recycling polyethylene terephthalate (PET); the polyolefins, which include the polyethylenes (PE) and polypropylene (PP); polyvinyl chloride (PVC); and polystyrene (PS). Another chapter describes in detail the commingled fraction of these materials after one or more selected resins have been removed (i.e., the mixture of resins after PET and high-density polyethylene (HDPE) containers have been removed).

Packaging items are not the only products of the commodity plastics. Many are used in the fabrication of component parts of durable finished products, such as appliances, furniture, computer housings, and electrical and electronic equipment. Other polymers also used include acrylonitrile-butadiene-styrene (ABS), acrylics, nylon, polycarbonate (PC), phenolic, polyurethanes (PURs), filled and reinforced unsaturated polyesters, etc. As mentioned before, these durable products currently constitute approximately 22 volume % of the MSW stream. Building, construction, and automotive products are the other durables. Building and construction materials are disposed of at sites other than MSW landfills. Automotive waste, such as junked automobiles, are first dismantled, then shredded, ferrous metals removed, and the remainder or automotive shredder residue (ASR) sent to municipal landfills. The recovery of durables from the solid-waste stream has not yet received the focus of attention accorded the nondurables. However, some companies already looking to the future have focused on the recycling of durables. Many companies involved in the manufacture of these polymers and in part fabrication have active programs on recovery processes and new product generation. The remaining chapters of this book review many of these activities—Chapter 7 on engineering resins, Chapter 8 on acrylics, and Chapter 10 on secondary and tertiary recycling (defined in Section 1.3) of phenolics, PURs, and unsaturated polyesters.

1.2 Thermoplastics, Thermosets

The organization of this volume is based on different polymeric material types, the market applications, and current and future recycling of these materials. All the polymers discussed in the ensuing chapters, with the exception of Chapter 10, are thermoplastic.

Historically, polymer materials were classified as thermoplastics or thermosets long before there was a realization of the chemical nature of these materials. The terms are based on the physical changes that occur when the materials are subjected to heating and cooling. Thermoplastics are materials that (1) become soft or "plastic" when heated, (2) are molded or shaped with pressure when in the plastic state, and (3) solidify when cooled to retain the mold or shape. Since this is a physical change with no chemical change occurring, the process is reversible and can be repeated. Such repeating heating cycles will eventually cause decomposition of the polymer. On a molecular level, these thermoplastics are linear or slightly branched polymers.

Thermosets are materials that can be softened, molded, and then hardened or "set" when heated once. The thermosets are infusible solids that decompose on reheating. The hardening or curing process is an irreversible chemical reaction known as cross-linking. On a molecular level, the thermosets are branched polymers that form three-dimensional networks through the cross-linking reaction. Examples from Chapter 10 include the phenolics, epoxies, and PURs.

Thermoplastics have been further subdivided on a cost-property performance basis into commodity and engineering plastics. As new plastics have been developed, further divisions such as advanced polymers, high-heat resistant polymers, etc., have been recognized. Interest here is only on the commodity and engineering plastics. Commodity plastics are less costly and have much greater volume sales than the engineering plastics. The commodity plastics also have lower physical properties and are used in applications with less demanding performance requirements. The engineering plastics possess physical characteristics that allow these materials to be used for structural applications where high strength, impact, chemical, or heat resistance may be required. Some polymeric materials possess characteristics of both commodity and engineering plastics, so the distinction between the two is not always clear. For example, ABS and polymethyl methacrylate (PMMA) may be considered in either category. For this volume, ABS is discussed in the engineering resin chapter.

1.3 Terminology

Through continued use and reference in technical discussions, papers, reports, and at technical conferences, various terms have become a part of the language of plastics recycling. A number of authors [9–11] have defined and refined some of these terms. There are descriptive terms such as reuse, recover, reconstitute; terms that differentiate plastic streams as waste, scrap, nuisance, industrial, and postconsumer; and terms that classify plastics recycling technology. The American Society for Testing and Materials (ASTM) published in September 1990 a standard guide under Designation D-5033-90 [12] that defines many terms and provides information on important factors relevant to the development of standards for the proper use of recycled plastics. Many of the terms defined in the guide are given in Appendix 1. A few terms not included in the guide are redefined here based on earlier definitions of Milgrom [13] and Leidner [14].

1. Waste plastics—that fraction of plastics that enters the solid-waste stream and must be recovered, recycled, incinerated or otherwise disposed of.
2. Scrap plastics—that fraction of plastics generated by various plastic operations that can be recycled into viable commercial products using standard plastic-processing techniques.
3. Nuisance plastics—a byproduct fraction of any plastic operation that cannot be reprocessed into a viable commercial product under existing technical-economic conditions.

Terms also have been developed for classifying plastics recycling into four types of technologies: primary, secondary, tertiary, and quaternary. Milgrom [15] was probably the first to define these terms. He simply defined primary, secondary, and tertiary recycling as scrap plastics reformed into their original form, reprocessed into another form, and converted into energy or another nonplastic form, respectively. Versions of these terms given in this book are based on Leidner's more detailed definitions [16]. ASTM D-5033-90 also defines these terms.

1. Primary recycling—the conversion of scrap plastics by standard processing methods into products having performance characteristics equivalent to the original products made of virgin plastics.
2. Secondary recycling—the conversion of scrap or waste plastics by one or a combination of process operations into products having less demanding performance requirements than the original material.
3. Tertiary recycling—the process technologies of producing chemicals and fuels from scrap or waste plastics.
4. Quaternary recycling—the process technologies of recovering energy from scrap or waste plastics by incineration.

Although this present work is not structured according to the above classification, the process technologies cited are representative of all four types and are easily recognized throughout. Primary recycling is not emphasized since it is not normally a postconsumer plastics recycling technology. The technology is practiced mainly in the manufacturing sector for recycling in-house scrap. Historically, the recycling of in-plant scrap has not been considered part of plastics recycling since such scrap does not normally enter the solid-waste stream. Primary recycling is cited in the historical section of this chapter and when the technology has served as a basis for a secondary recycling process as is given in Chapter 4. Secondary recycling is emphasized throughout the chapters on commodity plastics and also the chapter on commingled plastics. The processes of tertiary recycling are discussed in the acrylic and thermoset chapters and in the history of plastics recycling (Section 1.7). Since quaternary recycling is considered a resource recovery rather than a recycling technology, it has received only minor attention. It is discussed, however, in the PVC chapter. Here, incineration is an important factor.

1.4 Coding and Labeling

In 1988, the Society of the Plastics Industry Inc. (SPI) recognized the need for a simple and easy method to identify the type of plastic used in individual bottles and containers. Recycling of PET beverage bottles had already reached a 20% rate; HDPE milk and water jugs recycling was underway, and many other different plastic bottles and containers were entering the recycling stream. Acting on this need, the SPI developed a simple code system known as the SPI's Voluntary Plastic Container Coding System [17]. Since 1988, the system has gained wide acceptance, and the code also is now imprinted on other forms of packaging, such as supermarket plastic bags, which are intended to be recycled. As of June 1991, 32 states [18] had enacted legislation either accepting or specifying that the SPI plastic identification code system be adopted on bottles of 16 ounces (~0.5 liter) or more in capacity and rigid containers of 8 ounces (~0.25 liter) or more in capacity. Details of the coding system are given in Appendix 2A.

The coding system was developed to help recyclers sort plastic bottles and containers by specific resin and was intended as an interim solution until automatic identification and sorting technology developed. Some of this technology is now in existence. The SPI system should remain, however, since it serves as an excellent means for the consumer to identify the specific plastic items to be separated from other plastics if required as part of a municipal curbside collection program.

Another system for marking plastic products for resin identification was issued as a standard by the ASTM in 1991 under the designation D-1972-91 [19]. The markings are used to assist in product handling, disposal, or recovery. The system is similar to that of the SPI's but broader in scope. Acronyms for 92 plastic family resins and another 37 for commercial plastic blends are listed. Details of the system are given in Appendix 2B.

The Society of Automotive Engineers, Inc., (SAE) also has a system for marking plastic parts to identify the type of material used in the fabrication of the parts [20]. The purpose of the marking is to provide information for recycling as well as repairing or repainting. Standard acronyms for plastics published by the International Organization for Standardization (ISO 1043) and those shown in ASTM D-300[01600] are used. Details of the SAE system are given in Appendix 2C.

Before leaving this subject, some mention should be made about the labeling of products and packages, including plastics, as recyclable, recycled, reusable, etc. It is now accepted by packaging manufacturers that consumers are more environmentally conscious than ever before and will become more so in the years ahead. Manufacturers are reacting by making products and packages more environmentally acceptable and labeling these as recyclable, reusable, recycled, etc. State governments are reacting by introducing or enacting labeling legislation that defines terms and sets requirements for legal use of official labels or emblems. The New York State Department of Environmental Conservation filed for the establishment and use of official emblems in the state. This became effective in December 1990. To use the "recycled" emblem, plastics packaging must contain 30 wt % minimum secondary material and 15 wt % minimum postconsumer material; for plastic products, a 50 wt % secondary material content and a 15 wt % postconsumer material content is required. "Secondary material" or "recovered material" is defined similar to a recovered material as defined in ASTM D-5033-90 (see Appendix 1).

Rhode Island has recycling emblem regulations, and the Indiana State House has proposed legislation providing definitions for environmental labeling terms. Wisconsin and Oregon have bills pending with labeling definitions; Illinois, New Jersey, and California are studying such legislation.

The Northeast Recycling Council, representing ten northeastern state governments, adopted standards to be used by these states as guidelines for the labeling of packages and products in regard to being reusable, recyclable, or having a certain recycled content [21].

Independent certification organizations and associations representing manufacturers also are involved in labeling and submitting guidelines and recommendations.

These diverse labeling measures and recommendations have caused confusion and conflict, prompting industry and consumer groups to call for federal government action to establish uniform labeling standards and guidelines. Further action by state and federal lawmakers on labeling is to be expected.

1.5 Organizations Involved in Plastics Recycling

There are several organizations within the plastics industry involved in plastics recycling education, research, and development. Some of these organizations have been formed in recent years by companies and trade associations with various business interests in the industry (e.g., The Council for Solid Waste Solutions and the Plastics Recycling Foundation). The Polystyrene