LIFE-CYCLE INVENTORY DATA SETS FOR MATERIAL PRODUCTION OF

Aluminum, Glass, Paper, Plastic, and Steel

IN NORTH AMERICA

PREPARED FOR:
U.S. Environmental Protection Agency
Office of Research and Development

PREPARED BY:
RTI International
P.O. Box 12194
Research Triangle Park, NC 27709

RTI INTERNATIONAL

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients. For further information about this study, refer to the project web site at www.rti.org (from the home page, search for life-cycle management of municipal solid waste).

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

EPA REVIEW NOTICE

This report has been peer and administratively reviewed by the U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The information and results from this study are not intended for use in making comparative assertions about the environmental preferability of alternative materials or products.

This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

Abstract

Today's municipal solid waste (MSW) management systems include a variety of alternatives for waste collection, recovery of materials, composting, combustion, and disposal. Communities now must make complex decisions requiring an analysis of both cost and environmental aspects for these integrated systems. To properly account for all of the environmental aspects associated with integrated MSW management systems, planners must have tools that allow them to examine factors outside of the traditional MSW management framework of activities occurring from the point of waste collection to final disposal. This requires an examination of the changes in resource use and environmental releases from raw materials acquisition and manufacturing operations associated with the use of secondary versus primary resources. These environmental changes can be captured by taking a life-cycle approach to MSW management.

The U.S. Environmental Protection Agency's (EPA's) Office of Research and Development, Air Pollution Prevention and Control Division, with co-funding from the U.S. Department of Energy, is leading the development of cutting-edge life-cycle environmental and cost assessment tools into an overall decision-support tool (DST) that provides information for evaluating integrated MSW management systems in the United States. The research team for this project includes life-cycle assessment (LCA) and solid waste management experts from Research Triangle Institute, North Carolina State University, the University of Wisconsin-Madison, Franklin Associates, and Roy F. Weston. Over 80 stakeholders were participants in this research representing state and local government, environmental interest groups, industry, trade associations, and academia. The result is a credible, objective, state-of-the-art tool that provides assistance to MSW practitioners and others to understand environmental and cost aspects of integrated MSW management. The MSW-DST also has the capability, through its optimization module, to identify MSW management strategies that minimize cost and environmental burdens.

This report includes North American life-cycle inventory data sets and supporting documentation that have been developed for use in this overall research project. Industry organizations were intimately involved in developing the data sets and, although shortcomings exist, the data are felt to be the best currently available. The data sets were developed for use in the MSW-DST to estimate the environmental aspects associated with recycling various aluminum, glass, paper, plastic, and steel products from the MSW stream. The data are also available as part of a stand-alone electronic database developed for the overall project.

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List of Acronyms

AF&PA	American Forest and Paper Association
AISI	American Iron and Steel Institute
API	American Petroleum Institute
APME	Association of Plastics Manufacturers in Europe
BHET	Bishydroxyethyl Terephthalate
BOF	Basic Oxygen Furnace
BOM	U.S. Bureau of Mines
BTU	British Thermal Unit
CH_4	Methane
CO_2	Carbon Dioxide
CU FT	Cubic Foot
DIP	Deinked Recovered Pulp
DLK	Double-Lined Kraft
DMT	Dimethyl Terephthalate
DOE	U.S. Department of Energy
DQI	Data Quality Indicator
EAF	Electric Arc Furnace
ECAR	East Central Reliability Coordination Agreement
EDF	Environmental Defense Fund
EIA	Energy Information Agency
EPA	U.S. Environmental Protection Agency
ERCOT	Electric Reliability Council of Texas
ETH	Swiss Federal Institute of Technology
FOEFL	Swiss Federal Office of Environment, Forest, and Landscape
GAL	Gallon
HDPE	High-Density Polyethylene
IISI	International Iron and Steel Institute
ISO	International Standards Organization
KWH	Kilowatt Hour
LB	Pound
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LDPE	Low-Density Polyethylene
LPG	Liquefied Petroleum Gas
LWC	Lightweight Coated Groundwood Paper
MAIN-EM	Mid-American Interconnected Network-East Missouri
MRF	Materials Recovery Facility
MMBTU	Million British Thermal Unit
MSW	Municipal Solid Waste
MSW-DST	Municipal Solid Waste Decision Support Tool

Acronyms (continued)

NAERC	North American Electric Reliability Council
NGL	Natural Gas Liquid
NOx	Nitrogen Oxides
NPCC-NY	Northeast Power Coordination Council-New York Power Pool
NPCC-QUE	Northeast Power Coordination Council-Quebec
NSSC	Neutral Sulfite Pulping Process
OCC	Old Corrugated Containers
PET	Polyethylene Terephthalate
PGW	Pressurized Groundwood Pulp
RMP	Refiner Mechanical Pulp
RTI	Research Triangle Institute
SAEFL	Swiss Agency for the Environment, Forests, and Landscapes
SERC-TVA	Southeastern Electric Reliability Council-Tennessee Valley Authority
SERC-VAC	Southeastern Electric Reliability Council-Virginia and Carolina
SETAC	Society of Environmental Toxicology and Chemistry
SGP	Stone Groundwood Pulp
SPP-WC	Southwest Power Pool-West Central
TPA	Terephthalic Acid
USAMP	U.S. Automotive Material Partnership
WCC-BPA	Western System Coordinating Council-Bonneville Power Administration
WCC-RMP	Western System Coordinating Council-Rocky Mountain Area
WSCC-CAN	Western System Coordinating Council-Canada

Acknowledgments

Through efforts to analyze MSW management systems and their performance, concerns were raised about the lack of environmental data for many management options. For example, although many communities have good information about the cost of recycling efforts, little to no information is available to assess the potential environmental benefit of those efforts. Community representatives and other stakeholders to this project requested assistance from EPA's Office of Research and Development to help develop environmental information for such operations. Through an overall Cooperative Agreement (CR823052) with the Research Triangle Institute and its partners, this was conducted to develop life-cycle inventory type data for the production of commodity materials from primary (virgin) and secondary (recycled) resources. These data would enable solid waste planners to assess the environmental aspects of recycling programs. Through this effort, a review of available data and information was conducted, major data gaps identified and filled, life-cycle inventory profiles constructed, and an overall report prepared and reviewed by project stakeholders and a peer review panel.

We would like to thank all of those who participated in providing data and information contained in this report, and reviewing interim drafts of this report. In particular, we would like to acknowledge the contributions of the following individuals:

Morton Barlaz, North Carolina State University
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Bill Franklin, Franklin Associates
Marge Franklin, Franklin Associates
Melissa Huff, Franklin Associates
Bob Hunt, Franklin Associates
Krishnam Raju, formerly with Roy F. Weston
Sabrina Spatari, Five Winds International
Agis Veroutis, formerly with Roy F. Weston
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1.0 Introduction and Goals

Traditional product life cycle assessments (LCAs) begin with the extraction of raw materials and continue through materials processing, manufacturing, use, and waste management stages. Application of LCA concepts and tools to the management of municipal solid waste (MSW) begins with waste collection and/or dropoff and considers the inputs and effects to all life cycle stages resulting from the management of MSW, as illustrated in Figure 1-1.

MSW is increasingly being managed through integrated management systems consisting of a variety of potential alternatives for waste collection, materials recovery, combustion, composting, and landfilling. The life cycle perspective encourages MSW planners to consider the environmental aspects of the entire MSW management system including activities that occur outside of the traditional framework of activities from the point of waste collection to final disposal. For example, when evaluating options for recycling, it is important to consider the environmental aspects of those options with respect to potential offsets in raw materials extraction, manufacturing, and energy production sectors. To estimate the environmental aspects of recycling, data are needed on the manufacturing of materials from primary and secondary resources. These data were developed for use in evaluating integrated MSW management strategies and are included in an overall decision support tool (MSW-DST) and database. The MSW-DST and database are designed to help local governments and MSW planners.

The material production life cycle inventory (LCI) data sets presented in this report were compiled through a cooperative agreement between the Research Triangle Institute (RTI) and the U.S. Environmental Protection Agency's (EPA's) Office of Research and Development. The data are part of an overall project to evaluate the cost and environmental aspects of integrated MSW management systems in the United States using LCA concepts and tools. RTI's research team for this effort included LCA and solid waste management experts from North Carolina State University, the University of Wisconsin at Madison, Franklin Associates, Roy F. Weston, and Five Winds International. The data in this report were compiled by Franklin Associates, Roy F. Weston, and Five Winds International from primary and secondary sources in North America and Europe. The data are intended to represent the state of practice in LCI for materials production in North America, and industry organizations were intrinsic to their development. Limitations associated with the data are listed in Section 1.4 and conveyed in data quality assessments provided for each material studied. Although shortcomings exist in the data sets, they include the best data available to the research team.

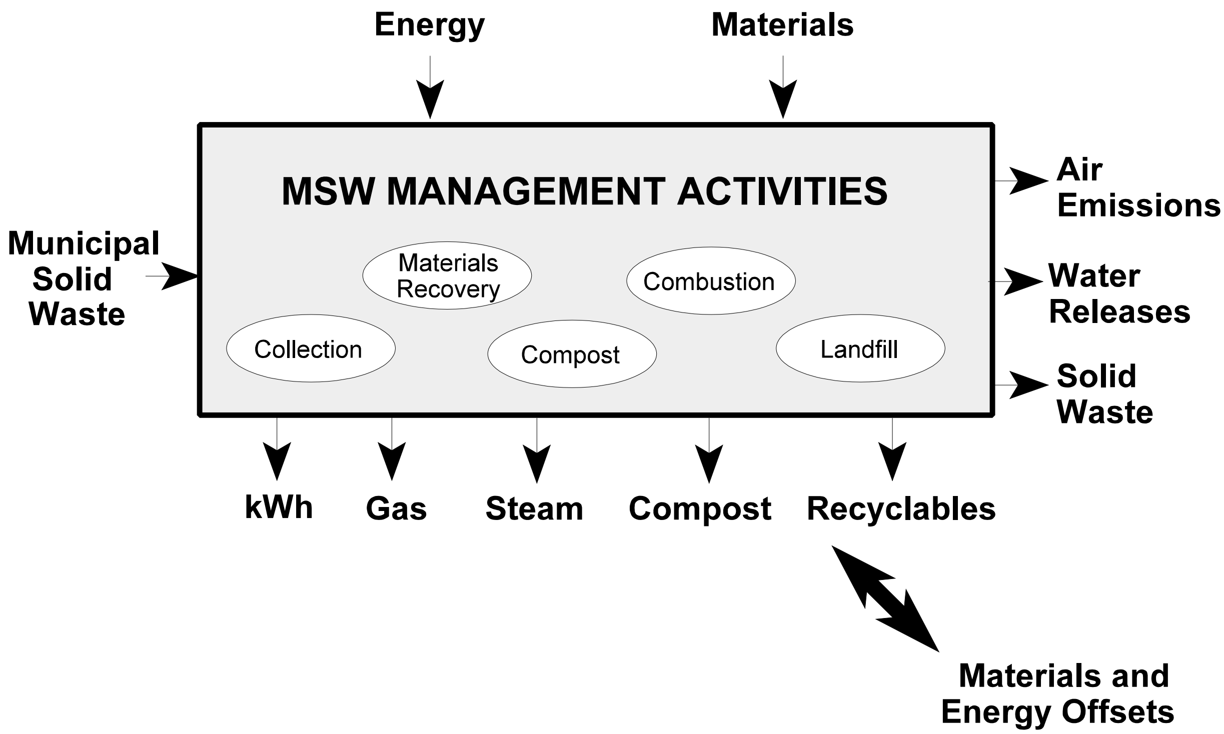


Figure 1-1. Illustration of the municipal solid waste life cycle.

1.1 Goals

The goal of this data collection effort was to develop average "cradle-to-gate" LCI data sets for common recyclable materials, including aluminum, glass, paper, plastic, and steel for North America. These data are used in the MSW-DST to estimate the environmental aspects associated with recycling and are also included in the database. These data can be used, for instance, to estimate the total environmental benefit achieved through a residential curbside recycling program that recovers 25,000 tons of aluminum, glass, newsprint, and polyethylene terephthalate (PET) per year. Alternatively, the data can be used to evaluate how the environmental aspects of an MSW management system change if a specific material, say glass, is added to or removed from a community's recycling program.

1.2 Intended Application of These Data

The data presented in this report were developed for use in evaluating the environmental aspects of MSW management strategies involving recycling. The data are included in the database as raw data as well as a "recycling" module of the MSW-DST. In the MSW-DST, an "offset analysis" is used so that any reductions (or increases) in environmental aspects associated with the use of secondary materials in place of primary materials are included in the overall results. This procedure is summarized below and illustrated in Figure 1-2.

In MSW management strategies where some portion of MSW is recycled, the recyclables will ultimately be delivered to a facility for remanufacturing. Separation will occur during collection, at a materials recovery facility (MRF), or at another waste management facility.

Energy and resources will be expended to deliver the recyclables to a remanufacturing facility. At this facility, additional energy and resources will be expended to convert the recyclables to a new materials. The total amount of energy (or other LCI parameter) required to recover the recyclable from the waste stream and convert it to a new material, termed E_r, will be included in the LCI. In addition, we must include the amount of energy required to produce a similar amount of material from primary resources or E_v. The net amount of energy (E_n) expended (or saved) to recycle a material will then be calculated as the difference between E_r and E_v ($E_n = E_r - E_v$). A similar calculation is performed for all other LCI parameters.

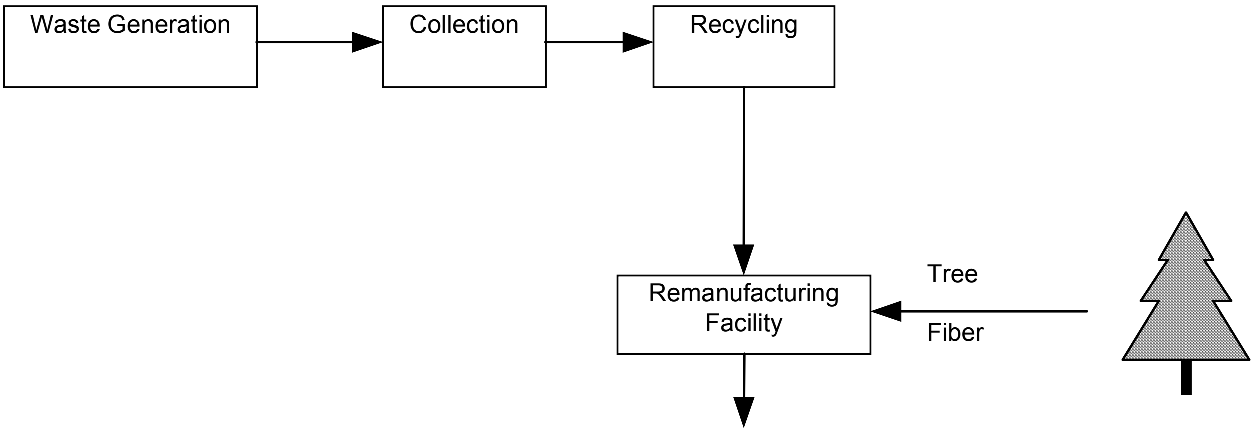
To use this information to calculate the net environmental aspects associated with recycling, two additional factors are needed.

- **Recycled material input ratio:** represents the amount of recovered resources (e.g., old newsprint) required to produce one ton of new material (e.g., new newsprint). This ratio allows the user of the MSW-DST to consider the wide variability in the use of secondary materials. For example, producing a ton of newsprint from secondary resources may require more than one ton of secondary newsprint fiber due to losses in the repulping process. The recycled material input ratio allows the user to tailor the use of secondary resources to match current production practices.

The recycled material input ratios are currently defined as follows in the MSW-DST:

- Aluminum = 1.07 ton recycled/new ton
- Glass = 1.03 ton recycled/new ton
- Corrugated = 1.07 ton recycled/new ton
- Newsprint = 1.06 ton recycled/new ton
- Office Paper = 1.53 ton recycled/new ton
- Textbooks = 1.44 ton recycled/new ton
- Telephone Books = 1.40 ton recycled/new ton
- Magazines/3rd Class Mail = 1.41ton recycled/new ton
- PET = 1.16 ton recycled/new ton
- LDPE = 1.16 ton recycled/new ton
- HDPE = 1.16 ton recycled/new ton
- Steel = 1.19 ton recycled/new ton

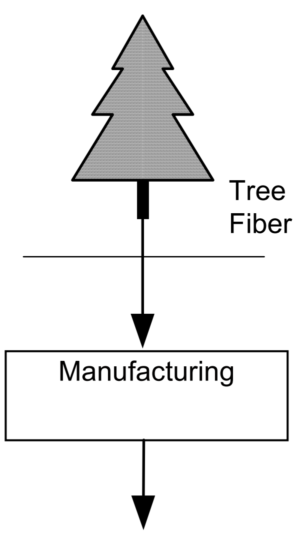
A. Calculation of E_r



1,000 Tons Secondary Newsprint

E_r = Total energy required to produce 1000 tons of newsprint using secondary material, from collection through new material production.

B. Calculation of E_v



E_v = Total energy required to produce 1,000 tons of newsprint from primary material. Includes energy from growth of trees through final production.

1,000 Tons of Primary Newsprint

Figure 1-2. Framework for calculating environmental aspects for recycling newsprint.

These values are implemented as defaults that the user of the MSW-DST may override if better information is available.

- **Materials substitution ratio:** represents the amount of new material (e.g., new newsprint) produced from secondary resources required to produce a product (e.g., newspapers) of equivalent function as a product produced from primary resources. This ratio allows the user of the MSW-DST to consider functional or performance differences between the primary and secondary materials. For example, it may take 1.2 tons of secondary corrugated container linerboard and medium to match the functional equivalence of 1 ton of primary linerboard and medium for a specific application.

All substitution ratios are currently set at one in the MSW-DST. The user may override the default and enter a new substitution ratio if there is appropriate justification.

The recycled material input and substitution ratios are implemented in the remanufacturing module of the MSW-DST and are not discussed further in this report. For additional information, please consult the remanufacturing process model documentation (Dumas, 2000).

Use of this analytical framework requires selection of an intermediate product for which it is possible to compare LCI parameters between the primary and secondary processes. For example, PET beverage bottles may not be recovered and made into new PET beverage bottles. Thus, although the starting material for the remanufacturing process may be a used PET beverage bottle, the end material on which the LCI data is based may be a fiber. In this case, the study should compare LCI parameters between the primary and secondary material production processes for fiber. For this effort, intermediate materials (e.g., aluminum sheet/coil, plastic resin) were used as the endpoints for comparing primary and recycling processes.

Other applications of the data presented in this report may include

- use in other solid waste studies attempting to generate rough estimates of the environmental benefits associated with the recycling of specific materials.

Other applications of the data presented in this report may **not** include

- use as a sole criteria for making decisions regarding recycling of specific materials

- use in studies attempting to compare the life cycle environmental aspects of alternative packaging materials

- use to directly compare “primary” to “secondary” materials (data for materials collection, separation, and transport steps are also required).

1.3 Data Review Process

To ensure the applicability and usefulness of the materials LCI data, we employed an inclusive review process for all data sets and documentation that included

- Internal project team
- Advisors from the U.S. EPA and the U.S. Department of Energy
- Project stakeholders from state and local governments, environmental interest groups, industry, trade associations, academia, and others (listed in Appendix A)
- External project peer review committee (listed in Appendix B).

The high level of involvement by project stakeholders and peer review committee members has contributed greatly to the success of this project and ensures that these data sets are appropriate for supporting the overall effort.

1.4 Key Assumptions and Limitations

Primary and secondary sources of data were used to compile the data sets included in this report. Some of the **key assumptions** of the data include

- Data represent U.S. industry averages and assume an average mixture of U.S. technologies and emissions controls, except for plastics data which are from European sources (see limitations).

- The boundaries for all data sets are "cradle-to-gate." That is, the data incorporate all processes from the extraction of raw materials through materials manufacturing. It is assumed that product manufacturing, distribution, and use stages are identical regardless of whether primary or secondary materials are used.

- Common commodity endpoints (e.g., aluminum sheet) were defined for each material and do not include the manufacture of specific products (e.g., aluminum cans), except for glass (see limitations).

- The data for precombustion (fuels and electrical energy production) are for North America and electrical energy related aspects assume a national electrical energy grid mix. Consistent precombustion data was used from all data sets expect steel (see limitations).

- Data for the production of secondary materials do not include materials collection, separation, and transportation steps. Data for these activities are included in other modules of the MSW-DST and are accounted for in the tool's results.

Although great care was taken to construct the best possible data sets from available sources, there are **limitations** associated with the data

- Since the data sets represent largely U.S. industry averages, there may be variations between the data included in this report for specific materials and data from specific materials production facilities. In addition, the data sets use a U.S. average electricity grid mix to calculate electricity-related resource consumption and emissions, and this may not accurately reflect site-specific electricity grid mixes for individual facilities.

- Data for plastics is from European sources, specifically the Association of Plastics Manufacturers in Europe (APME). Although the manufacturing processes may be quite similar to those in the United States, the electrical energy related data can be much different. Therefore, the electrical energy emissions were backed out of the APME data and the electrical energy information developed for this study were applied to "Americanize" the data.

- Data for glass includes glass container production. Unlike the other materials, which can typically be captured at an intermediate commodity stage, there is no comparable intermediate commodity stage for glass. Also, it was not possible to separate the data for molten glass from container production. Thus, the endpoint for glass is container production.

- Data for steel include the use of the steel industry's electrical energy and precombustion emission factors. These could not be separated from the process data provided by the industry. Comparison of the emission factors used by the industry versus those used in this study showed, what we believe to be, insignificant differences.

- The ability to assess the quality of the data was limited by the extent of data quality assessment and documentation provided by the source of the data. In general, the more recent the source of data, the better the data quality information. This is related to the recent developments in the LCA community to more carefully document data quality.

- The materials data sets are not of equal data quality. The aluminum and steel data are considered to be of excellent quality, glass very good quality, and paper and plastic of average quality. In addition, the paper data sets were developed by two different practitioners and although the data were made as consistent as possible, there may be differences in data sources and methodologies used.

- The aggregated manner in which data are presented limits the ability of reviewers to evaluate the data. For example, reviewers can compare the LCI totals for the manufacture of primary steel presented in this report to those developed for another project, but do not have adequate information to compare process-level (e.g., iron ore mining, coke production) data for the manufacture of that steel. Although the data sets have been reviewed by industry representatives and peer reviewers, their ability to review and comment on the data according to ISO 14040 guidelines was not always possible.

- The approach for calculating the environmental aspects of recycling in the overall MSW-DST using the data sets in this report is simplistic. The quality of recovered materials is dependent of the quality of materials comprising the MSW stream and their management. Contamination and product use can significantly degrade the physical and chemical properties of different materials. It may not be reasonable to assume that the recycled (secondary) materials will always be used in place of primary resources. In addition, the calculation for estimating the environmental aspects of recycling is linear. Thus, the per ton benefit or additional burden is the same regardless of whether 10 tons or 10,000 tons are recycled.

- The assumption that product manufacturing, distribution, and use stages are identical regardless of whether primary or secondary materials are used is not valid in all cases. For example, a plastic bag made from secondary plastic may underperform a comparable bag made from primary plastic. Although a substitution ratio is included in the MSW-DST to address performance aspects between primary and secondary materials, it cannot capture every possible performance issue.

- Actual environmental impacts from the materials data sets would be extremely difficult to estimate due to the aggregated manner in which data are presented. Data for specific process steps was largely unavailable.

1.5 Report Organization

Chapter 2 presents the general scope and boundary conditions followed in generating the data sets and Chapters 3 through 7 provide the material production LCI data sets for aluminum, glass, paper, plastic, and steel.

To the extent possible, ISO 14040 and 14041 guidelines were used to develop and review the LCI data sets included in this report. Although the ISO guidelines could not be reprinted in this report, copies of the guidelines can be obtained by contacting:

American National Standards Institute
11 West 42nd Street
13th floor
New York, NY 10036
Phone: 212-642-4900
Fax: 212-302-1286
E-mail: info@ansi.org
Web: http://www.ansi.org/

1.6 References

Dumas, Robert. 2000. *Life-Cycle Inventory Model for Materials Remanufacturing.* Prepared for RTI by North Carolina State University, Department of Civil Engineering, Raleigh, NC 27695.

2.0 General Scope and Boundary Conditions

A total of 42 MSW components are detailed in the overall project system description document (Barlaz and Weitz, 1996) and include the min categories of aluminum, glass, paper, plastic, and steel. For the MSW components that are recyclable, manufacturing LCI data are needed to evaluate the environmental aspects of recycling. The materials for which cradle-to-gate LCI data were collected and presented in this report include

- Aluminum
- Glass
  - clear
  - brown
  - green
- Paper
  - newsprint
  - corrugated medium and liner
  - office paper
  - textbook
  - telephone book
  - magazines/third class mail
- Plastic
  - low-density polyethylene (LDPE)
  - high-density polyethylene (HDPE)
  - polyethylene terephthalate (PET)
- Steel.

Data for the manufacture of each of these materials from primary and secondary resources is included. Note that although the data sets are titled "primary" and "secondary," few 100 percent primary and secondary material production processes exist. Therefore, the terms primary and secondary should be interpreted as predominantly primary and secondary. Table 2-1 defines the mix of primary and secondary resources used for each material LCI data set.

In addition, for each material, a common manufacturing endpoint had to be defined and applied consistently. For example, the endpoint for aluminum could be an aluminum can or an ingot or sheet. The endpoint for paper could be pulp or paper rolls or final paper products (e.g.,

Table 2-1. Material Definitions

Material	Endpoint	Primary System Content	Secondary System Content	Composite* System Content
Aluminum	sheet (coil)	100% primary	100% secondary	N/A
Glass	container	100% primary	100% secondary	72.5% primary 27.5% secondary
Paper				
corrugated	roll	85.3% primary 14.7% secondary	100% secondary	55% primary 45% secondary
newsprint	roll	100% primary	100% secondary	62% primary 38% secondary
office paper	roll	100% primary	100% secondary	N/A
text book	roll	100% primary	100% secondary	N/A
telephone book	roll	100% primary	100% secondary	N/A
magazines/3rd class mail	roll	100% primary	100% secondary	N/A
Plastic				
HDPE	resin/flake	100% primary	100% secondary	N/A
LDPE	resin/flake	100% primary	100% secondary	N/A
PET	resin/flake	100% primary content	100% secondary	N/A
Steel	sheet (coil) or bar	100% primary (sheet)	100% secondary (bar)	N/A

*Although data for composite materials are included in this report and the project database, only data for the primary and secondary systems are used in the decision support tool to calculate the environmental aspects of recycling.

corrugated boxes). The endpoints defined for all of the products included in this data collection effort are listed in Table 2-1. The overall goal was to select endpoints at the commodity level. Therefore, the endpoint for aluminum was defined to be aluminum sheet/coil because, after that point, any other product manufacturing process is assumed to be identical regardless of whether the sheet/coil is made from primary or secondary resources. The one exception to this boundary condition is glass because glass is typically produced in the form of a container (or other product) and lacks an intermediate “commodity” stage. Thus, for glass, the endpoint was defined as a glass container.

2.1 General Boundary Conditions

The scope and boundaries for each set of LCI data presented in the specific materials LCI summaries are partially depicted by the accompanying process flow diagrams. Each process flow diagram for the primary materials production shows the major process steps that occur in acquiring and processing the basic raw materials needed in the life cycle of the material being manufactured. For example, the flow diagram for manufacturing aluminum sheet from primary materials shows that bauxite ore is mined and is used to make alumina, which in turn is used to make aluminum. Also, salt is mined to make caustic soda (sodium hydroxide), which is used in the manufacture of alumina.

Data for each process step shown in the flow diagram are included in the results presented in the accompanying tables. The quantities of each raw material and intermediate material used to make 1 ton of the material are shown on the material flow diagrams where possible. Therefore, the materials flow diagrams show the basic system boundaries and scope for each option represented by the LCI results in the accompanying table. Transportation steps are shown by the arrows between each major process step.

As is shown by the process flow diagrams, the systems for which data are presented are not fully complete "cradle-to-grave" systems. This is because the data presented in this report are supplemental to data included in other modules of the MSW-DST or that cover converting steps (e.g., production of newspapers), which are assumed to be common to both the primary and secondary material. Only after all of the pieces of LCI data are assembled, can a full LCI for each material be completed.

For the primary material production systems, the LCI data are “cradle-to-gate.” This means that the data include the steps from raw materials extraction to production of a commodity material. The fabrication of a consumer product, such as aluminum or steel cans, is not included. Also, the use and disposal steps are not included for any of the products. The use step is assumed to be identical regardless of whether the product is made from virgin or recycled materials. The disposal step is accounted for in separate modules of the MSW-DST.

For the recycled product systems, both the beginning steps and the ending steps of the LCI are excluded from the LCI data sets. Collection of post-consumer materials and transportation to the reprocessing facility are not included, nor are the use or disposal steps for any of the materials. Again, this is because the disposal step (including waste collection and sorting at an MRF) and transportation are captured by separate modules of the MSW-DST.

There is one section of the system for each material that is not shown on the process flow diagrams. This is the section that includes the processes for acquiring energy resources and processing these resources into usable fuels (termed “precombustion”). These components of the life cycle **are** included in the LCI results presented in each of the LCI tables in the specific material summaries. For example, the use of electricity to convert alumina to aluminum means that coal (and other energy resources) must be mined and processed to a usable form. This activity uses energy and creates environmental emissions.

If marketable coproducts or byproducts are produced in any process step in the system, adjustments have been made in the materials balance and energy requirements and process emissions to reflect only the portion of each process step that is attributable to the material being considered. This is done based on the mass of each coproduct. Coproducts of any process step are not shown on the process flow diagrams.

2.2 Data Tables

The LCI data for each material are presented in a common table format, as shown in Table 2-2. The sections of the data tables are described in this section. Note that there are exceptions to this format due to the manner in which some of the data were originally aggregated by the source and specific data reporting requirements specified by the source.

2.2.1 Energy Usage Section

The first column in each data table shows the units of each fuel that are consumed in the aggregated process steps and aggregated transportation steps in the life cycle of the product. In the second column, these fuel units are converted to British thermal unit (Btu) values. The third column shows the conversion factors used to convert from units of fuel to Btu. These factors represent the higher heating values of the fuels.

For electricity, calculations are made converting delivered kilowatt-hours (kWh) of electricity shown in the first column to Btu of fuel used to generate and deliver the electricity in the second column. These calculations account for the average efficiency of conversion of fuel to electricity and for transmission losses in power lines. Therefore, the kWh value shown on the tables is the aggregated amount of electricity used by the system, as delivered to the manufacturing facilities. The Btu value shown in the second column accounts for the average mix of fuels used by utilities to produce electricity in the United States in 1992.

Note: The U.S. average fuel grid for utilities is **not** used to represent electricity used by several of the process steps for aluminum manufacture. Instead, different combinations of country- and region-specific fuels are used. These processes are different from other manufacturing processes because a large portion of the raw materials is obtained from other countries and the electricity-intensive process of aluminum uses a dedicated utility or provides a baseload for a specific public utility. The specific fuels used to generate electricity for aluminum processes are discussed in more detail in Section 3.

The data tables for each material system report (where available) energy data in the categories of energy of material resource, combustion process energy, precombustion process energy, combustion transportation energy, and precombustion transportation energy.

Energy of material resource is the fuel value (higher heating value) of any fossil energy resources (fossil fuel reserves—petroleum, natural gas, and coal) used as raw materials in any of the processing steps. For example, petroleum and coal are used to produce coke or pitch, which are raw materials for the aluminum smelting process. In the case of aluminum, these raw materials are consumed in the smelting operation. For other materials, such as plastics, the raw materials petroleum and/or natural gas liquids become a part of the final product.

Table 2-2. Sample Data Table Format

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Energy of Material Resource				
Combustion Process Energy				
Electricity	kWh			
Coal	lb			
Diesel	gal			
Distillate Oil	gal			
Gasoline	gal			
LPG	gal			
Natural Gas	cu ft			
Residual Oil	gal			
Precombustion Process Energy				
Coal	lb			
Distillate oil	gal			
Gasoline	gal			
Hydropower	Btu			
LPG	gal			
Natural Gas	cu ft			
Nuclear	lb U238			
Residual Oil	gal			
Other	Btu			
Combustion Transportation Energy				
Combination Truck	ton-miles			
Diesel	gal			
Rail	ton-miles			
Diesel	gal			
Barge	ton-miles			
Diesel	gal			
Residual Oil	gal			
Ocean Freighter	ton-miles			
Diesel	gal			
Residual	gal			
Pipeline-Petroleum Products	ton-miles			
Electricity	kWh			
Precombustion Transportation Energy				
Coal	lb			
Distillate Oil	gal			

(continued)

Table 2-2. (continued)

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Gasoline	gal			
Hydropower	Btu			
LPG	gal			
Natural Gas	cu ft			
Nuclear	lb U238			
Residual Oil	gal			
Other	Btu			

Environmental Emissions	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb			
Aldehydes	lb			
Ammonia	lb			
Antimony	lb			
Arsenic	lb			
Benzene	lb			
Beryllium	lb			
Cadmium	lb			
Carbon Monoxide	lb			
Carbon Tetrachloride	lb			
CFC/HCFC	lb			
Chlorine	lb			
Chromium	lb			
Cobalt	lb			
COS	lb			
Dioxins	lb			
Fluorine	lb			
Formaldehyde	lb			
Fossil Carbon Dioxide	lb			
Hydrocarbons	lb			
Hydrochloric Acid	lb			
Hydrogen Cyanide	lb			
Hydrogen Fluoride	lb			
Kerosene	lb			
Lead	lb			
Manganese	lb			

(continued)

Table 2-2. (continued)

Environmental Emissions	Units	Total	Process	Fuel Related
Mercury	lb			
Metals	lb			
Methane	lb			
Methylene Chloride	lb			
Naphthalene	lb			
Nickel	lb			
Nitrogen Oxides	lb			
Nitrous Oxide	lb			
N-Nitrosodimethylamine	lb			
Other Organics	lb			
PAH	lb			
Particulates	lb			
Perchloroethylene	lb			
PFC	lb			
Phenols	lb			
Radionuclides	Ci			
Selenium	lb			
Sulfur Oxides	lb			
Sulfuric Acid	lb			
Trichloroethylene	lb			
Solid Wastes				
Ash	lb			
Environmental Abatement	lb			
Municipal	lb			
Process	lb			
Waterborne Wastes				
Acid	lb			
Ammonia	lb			
Ammonium Ion	lb			
BOD	lb			
Boron	lb			
Cadmium	lb			
Calcium	lb			
Calcium Ion	lb			
Chloride	lb			
Chloride Ion	lb			
Chromates	lb			
Chromium	lb			

(continued)

Table 2-2. (concluded)

Environmental Emissions	Units	Total	Process	Fuel Related
COD	lb			
Cyanide	lb			
Detergent	lb			
Dissolved Chlorine	lb			
Dissolved Organics	lb			
Dissolved Solids	lb			
Fluorides	lb			
Hydrocarbons	lb			
Iron	lb			
Lead	lb			
Magnesium Ion	lb			
Manganese	lb			
Mercury	lb			
Metal Ion	lb			
Nickel	lb			
Nitrates	lb			
Nitrogen	lb			
Oil	lb			
Other Organics	lb			
Phenol	lb			
Phosphates	lb			
Sulfate Ion	lb			
Sulfates	lb			
Sulfides	lb			
Sulfur	lb			
Sulfuric Acid	lb			
Sodium	lb			
Sodium Ion	lb			
Suspended Solids	lb			
Vinyl Chloride Monomer	lb			
Zinc	lb			

Renewable fuels such as wood are not considered a primary energy resource in the United States and are not included as energy of material resource. In the overall decision support tool, the combustion of MSW with energy recovery is given a credit to the extent that it displaces baseload power generation by the utility sector. Although a boundary decision was made to not include renewable fuels as energy of material resource, the results of any MSW-DST run will not favor one material over another because energy of material resource is not tracked in the tool. Other users of these material data sets should carefully consider this boundary decision when conducting their studies.

Combustion process energy is the energy consumed in the various processes used to produce a material. The energy to extract, transport, and process these fuels into a usable form is labeled **precombustion process energy**.

Combustion transportation energy describes the energy or fuels needed to transport the materials and components to the site of the next processing step. Transportation energy is calculated, where possible, by using the distance of transport (miles), mode of transport (truck, rail, barge, ship), and information included in the transportation process model developed for use in the overall project. The distance and mode of transportation are usually provided by specific companies or facilities from which materials are shipped. The transportation database expresses fuel usage per ton-mile of goods transported by specific modes of transportation. The energy to extract, transport, and process the fuels used for transportation is labeled **precombustion transportation energy**. All of the transportation steps included in each LCI are presented as aggregated data.

Note: For some paper and plastic materials, transportation was already included in an aggregate form and could not be broken out into separate sections. In these cases, the transportation energy is included in the energy totals reported in the LCI, and no section for combustion transportation energy is provided.

2.2.2 Environmental Emissions Section

Environmental emissions include air pollutants, solid wastes, and waterborne wastes. Environmental emissions are also labeled as process- or fuel-related. **Process emissions** are those emitted during a processing step, but not as a result of fuel combustion. For example, the calcining of limestone to produce lime emits carbon dioxide (CO_2). The quantity of CO_2 emitted from this process would be listed under process air emissions. **Fuel-related emissions** are those emissions that result from the combustion of fuels. For example, the combustion of wood by-products in a paper mill produces a fuel-related solid waste, ash. The emissions reported on the data tables in the product summaries are the quantities reaching the environment (air, water, and land) after pollution control measures have been taken.

2.2.2.1 <u>Air and Waterborne Releases</u>. Atmospheric emissions include all substances released to the air that are regulated or classified as pollutants. Emissions are reported as pounds of pollutant per ton of final product, as shown in the table headings. Atmospheric emissions also include CO_2 releases, which are calculated from fuel combustion data or process chemistry. CO_2 emissions are not regulated, but they are reported in this study because of the growing concern about global warming. CO_2 emissions are labeled as being from either fossil or nonfossil fuels.

CO_2 released from combustion of fossil carbon sources (coal, natural gas, or petroleum) or released during the reaction of chemicals derived from these materials is classified as **fossil carbon dioxide**. CO_2 released from mineral sources (e.g., the calcining of limestone to lime), is also classified as fossil CO_2. CO_2 from sources other than fossil carbon sources (i.e., from biomass) is classified as **nonfossil carbon dioxide**. Nonfossil CO_2 includes CO_2 released from the combustion of plant or animal material or released during the reaction of chemicals derived from these materials. This labeling of the CO_2 releases as either fossil or nonfossil is done to aid in the interpretation of the LCI data. The source of CO_2 releases is an important issue in the context of natural carbon cycle and global warming.

As with atmospheric emissions, waterborne wastes include all substances classified as pollutants. Waterborne wastes are reported as pounds of pollutant per ton of product, as shown in the data table headings. The values reported are the average quantity of pollutants still present in the wastewater stream after wastewater treatment and represent discharges into receiving waters.

Air or waterborne emissions that are not regulated or reported to regulatory agencies are not reported in the LCI results presented in the material summaries. Reliable data for any such emissions would be difficult to obtain except for a site-specific study where additional testing were authorized. Conversely, some air and waterborne emissions data that are regulated and reported may not have been included in the LCI results. The data used represent the best available from existing sources.

The air and waterborne emissions data reported in the LCI tables are aggregated across the life cycle of the product being studied. They represent a mixture of measured data from actual manufacturing sites, calculated data from actual manufacturing sites, and estimates based on regulatory emissions standards. Actual environmental impacts from these aggregated emissions would be extremely difficult to estimate.

2.2.2.2 Solid Wastes. Process solid wastes include mineral processing wastes (such as red mud from alumina manufacturing), wastewater treatment sludge, solids collected in air pollution control devices, trim or waste materials from manufacturing operations that are not recycled, and packaging materials from material suppliers. Fuel-related solid wastes are fuel combustion residues such as the ash generated by burning coal or wood.

2.3 General Boundary Decisions

Some general decisions and assumptions have been made in assembling the LCI results presented. These assumptions are discussed below.

2.3.1 Geographic Scope

With the exception of overseas transportation of crude oil, bauxite, and alumina to the U.S., all data are for the U.S.

The acquisition and processing data (precombustion energy and emissions) for fuels used to generate electricity for bauxite and alumina processing in other countries are the same for each fuel, as if the fuels were produced in the U.S.

2.3.2 Carbon Sequestration

To account for carbon sequestration by forest systems, the paper data sets incorporate a carbon sequestration credit of 2.2 pounds of CO_2 per pound of wood consumed (Kramer and Kozlowski, 1979). This credit is estimated by multiplying the pounds of wood consumed in the material LCI by the 2.2 pounds of CO_2 per pound of wood factor. The resulting value for CO_2

sequestered is netted out of the nonfossil CO_2 air emission value in the LCI results. As an example, if 1000 pounds of wood are consumed to manufacture a paper product, then 2200 pounds of CO_2 are assumed to be sequestered in the generation of that wood. This amount is included as a negative value in the nonfossil CO_2 air emission value. The implications of this carbon sequestration credit are that any nonfossil CO_2 emissions that occur through the combustion or degradation of wood will offset by the amount of the credit. Because biogenic CO_2 has a zero weighting factor in greenhouse gas calculations, this credit does not affect climate change implications.

Note that the carbon sequestration credit only applies to wood consumed. EPA's Office of Solid Waste used a different methodology in a report on greenhouse gas emission from solid waste management (EPA, 1998). Among other aspects, this methodology tracks carbon storage related to changes in forest carbon stocks due to paper recycling. The basic assumption used is that increases in paper recycling result in a lower demand for wood and thus an increase in mature trees left standing in forests that store carbon. At this time, consensus has not been reached on how to make the carbon sequestration approaches consistent. Future updates to the paper LCI data sets will likely include a modification to the carbon sequestration methodology.

2.3.3 Self-Generated Electricity

Where self-generated electricity (electricity generated onsite at a manufacturing facility) is reported, this use of electricity is not shown in the LCI results as kilowatt-hours of electricity. Instead, the fuels used at the facility to produce self-generated electricity are shown. This avoids representing self-generated electricity with the fuels for the U.S. average grid. Many of the primary materials production systems use some self-generated electricity. In the case of aluminum, some companies own dedicated generating plants. In the case of paper products, wood byproducts and other purchased fuels are often used to cogenerate steam and electricity onsite.

2.3.4 Recycling

Because this report presents LCI results for secondary materials production only, a direct analysis of recycling systems cannot be made. The LCI results presented in the data summaries represent the partial recycling systems shown in the materials flow diagrams. No data were included for the collection, processing, or transport of any product to be recycled. These data are included in separate modules of the MSW-DST and are incorporated into any MSW management strategy using recycling.

There are different ways to model recycling systems within the LCI framework. Two basic concepts for modeling recycling systems are open-loop recycling and closed-loop recycling. Limited recycling, such as the recycling of a newspaper into a folding carton, which is not recycled, is referred to as “open-loop” recycling. Repeated recycling, such as the recycling of an aluminum can back into another aluminum can, is called “closed-loop” recycling. Theoretically, closed-loop recycling can occur an infinite number of times because the aluminum does not degrade with repeated recycling steps. The type of recycling model that is appropriate for a material depends not only on infrastructure for collecting and transporting post-consumer materials, but also on the physical properties of the material being recycled.

In an open-loop system, the energy requirements, environmental emissions, and raw materials for primary material acquisition/processing and disposal are generally allocated equally among the products produced; i.e, the primary raw material energy requirements for the initial product are divided by the total number of product sets produced. For folding boxes made from old newspaper, half the raw material energy, emissions, and materials are allocated to the primary material and half to the secondary material. Likewise, half of the energy, emissions, and materials for reprocessing are allocated to the primary material and half to the secondary material. This, in effect, links the primary and secondary material production systems and shows the overall LCI results for the combined system.

In a closed-loop system, recycling of the same material occurs over and over, theoretically permanently diverting it from disposal. At the ideal 100 percent recycling rate, the energy requirements and environmental emissions for primary raw material acquisition and processing become negligible. Then, only the data for collecting post-consumer material and reprocessing it into a secondary material is considered.

A closed-loop recycling system is assumed for all materials included in the overall project.

2.4 Components Not Included

There are a number of items that have been excluded from the LCIs because they are typically found to be negligible in terms of the LCI totals. These items are described below.

2.4.1 Capital Equipment

The energy associated with the manufacture of capital equipment is not included in the energy profiles. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. The energy associated with such capital equipment generally, for a ton of materials, becomes negligible when averaged over the millions of tons of product that the capital equipment manufactures.

2.4.2 Space Conditioning

The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations. For most industries, space conditioning energy is quite low compared to process energy. Energy consumed for space conditioning is usually less than 1 percent of the total energy consumption for the manufacturing process.

2.4.3 Support Personnel Requirements

The energy associated with research and development, sales, and administrative personnel or related activities have not been included in this analysis.

2.4.4 Miscellaneous Materials and Additives

For each system evaluated, there are small amounts of miscellaneous materials associated with the manufacturing processes that are not included in the LCI results. Generally these materials make up less than 1 percent of the mass of raw materials for the system. For example, the use of biocides and other conditioning chemicals for cooling water are not documented and included in the LCI results except to the extent that these materials contribute to waterborne emissions from the facilities.

2.5 Data Sources and Quality

Data sources are identified and a data quality assessment performed to the extent possible in each of the specific material LCI profiles. The data presented are from a variety of sources, as summarized in Table 2-3. Much of these data have been independently reviewed and verified for other LCI projects as well as this project. Based on the project team's evaluation of data quality for each of these sources, a qualitative data quality rating is provided (see Table 2-3). The details of the data quality evaluation are provided in each of the materials chapters. The individual data quality indicators used in the evaluation are described in the following sections.

2.5.1 Geographic Coverage

Geographic coverage refers to the geographical area from which data for the unit processes or system under study were collected. For example, the plastics data may have been collected to represent average plastics manufacturing in Europe.

2.5.2 Time-Related Coverage

Time-related coverage provides an indicator of the age of the data and the period over which data were collected.

2.5.3 Technological Coverage

Technological coverage is an indicator of the practices and technologies represented by the data collected. For example, data may be collected to represent an average mix North American technology for steel production.

2.5.4 Precision

Precision is a measure of variability of individual data values from the mean of the data set. In studies that measure precision for each data category within each unit process, the mean and the standard deviation of the reported values are calculated. The precision measure provides an understanding of the variability of unit process performance.

2.5.5 Completeness

Completeness is the measure of primary data values used in the analysis divided by the number of possible data points for each data category within the sample domain. For example, if

Table 2-3. Summary of Data Sources Used in LCI Profiles

Material	Primary Data Source	Data Quality Rating
Aluminum	Life Cycle Inventory Report for the North American Aluminum Industry, published by The Aluminum Association (1998).	Excellent
Glass	Franklin Associates, Ltd. in-house data (2000).	Very Good
Paper		
corrugated	Franklin Associates, Ltd. in-house data (2000).	Very Good
newsprint	Franklin Associates, Ltd. in-house data (2000).	Average
office paper	Paper Task Force White Papers 3, 5, and 10A, published by the Environmental Defense Fund (1995a, b, c).	Average
text book	Paper Task Force White Papers 3, 5, and 10A, published by the Environmental Defense Fund (1995a, b, c).	Average
telephone book	Paper Task Force White Papers 3, 5, and 10A, published by the Environmental Defense Fund (1995a, b, c).	Average
magazines/3rd class mail	Paper Task Force White Papers 3, 5, and 10A, published by the Environmental Defense Fund (1995a, b, c).	Average
Plastic		
LDPE	Reports 3, 8, and 10, published by the Association of Plastics Manufacturers in Europe (1993, 1995, 1997); and Swiss Eco-Profiles of Packaging Materials, published by SFAEFL (1996).	Average
HDPE	Reports 3, 8, and 10, published by the Association of Plastics Manufacturers in Europe (1993, 1995, 1997); and Swiss Eco-Profiles of Packaging Materials, published by SFAEFL (1996).	Average
PET	Reports 3, 8, and 10, published by the Association of Plastics Manufacturers in Europe (1993, 1995, 1997); and Swiss Eco-Profiles of Packaging Materials, published by SFAEFL (1996).	Average
Steel	Life Cycle Inventory of Steel, prepared by the American Iron and Steel Institute (1999).	Excellent

a data collection questionnaire was sent to 10 bauxite mining operations and 8 of them returned the questionnaires completed, then the completeness for this unit process would be 80 percent.

2.5.6 Consistency

Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study. The consistency measure is one of the most important in the LCI data development process. To ensure consistency, it is crucial to have a clear communication and understanding of what data is needed, how it is measured, how it is reported, and how it is to be used.

2.5.7 Representativeness

Representativeness is an indicator measures the degree to which the data values used in the analysis present a true and accurate measurement of the average processes that the study is examining. The degree of representativeness is normally judged by the comparison of values determined in the study with existing reported values in other analyses or published data sources dealing with the subject matter. Any major variances identified should be examined and explained.

2.5.8 Reproducibility

Reproducibility is an indicator of whether or not sufficient information, both methodological and data values, exist to permit someone to independently carry out the calculations and reproduce the results reported in the study.

2.5.9 Uncertainty/Limitations

Uncertainty and limitations is a qualitative indicator that was included to capture any data quality aspects that were not addressed by the other data quality indicators.

2.6 References

Aluminum Association, Inc. 1998. *Life Cycle Inventory Report for the North American Aluminum Industry*. Prepared by Roy F. Weston, Inc. Boston, MA. November.

American Iron and Steel Institute (AISI). 1999. *Life Cycle Inventory of Steel.* Developed for Research Triangle Institute, Research Triangle Park, NC.

Association of Plastics Manufacturers of Europe (APME). 1993. *I. Boustead, Eco-profiles of the European Plastics Industry*; *Report 3: Polyethylene and Polypropylene*. Association of Plastic Manufacturers in Europe. Brussels, Belgium.

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Association of Plastics Manufacturers of Europe (APME). 1997. *I. Boustead, Eco-profiles of the European Plastics Industry, Report 10: Polymer Conversion*. Brussels, Belgium.

Barlaz, Morton and Keith Weitz. 1996. *Life Cycle Management of Municipal Solid Waste: System Description*. Research Triangle Institute, Research Triangle Park, NC 27709.

Environmental Defense Fund (EDF). 1995a. *White Paper No. 3, Environmental Comparison - Manufacturing Technologies for Virgin and Recycled-content Printing and Writing Paper*. New York, NY.

Environmental Defense Fund (EDF). 1995b. *White Paper No. 5, Environmental Comparison of Bleached Kraft Pulp Manufacturing Technologies*. New York, NY.

Environmental Defense Fund (EDF). 1995c. *White Paper No. 10A, Environmental Comparison - Manufacturing Technologies for Virgin and Recycled-content Printing and Writing Paper*. New York, NY. December 1995.

Franklin Associates, Ltd. 2000. *A Life Cycle Inventory of Linerboard & Medium Rolls, Newsprint Rolls, Aluminum Sheet, and Glass Containers*. Prepared for Research Triangle Institute, Research Triangle Park, NC. January.

Kramer, P.J. and T.T. Kozlowski. 1979. *Physiology of Woody Plants*. Orlando, FL: Academic Press.

Swiss Federal Agency for the Environment, Forests and Landscape (SFAEFL). 1996. *Life Cycle Inventories for Packaging.* Environmental Series No. 250/11, Waste. Swiss Agency for the Environment, Forests and Landscape. Bern, Switzerland.

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3.0 Summary LCI of Aluminum Sheet/Coil

3.1 Introduction

This chapter contains "cradle-to-gate" LCI data for the production of primary and secondary aluminum sheet/coil. Process flow diagrams for primary and secondary aluminum sheet/coil are presented, as well as process descriptions for the production of aluminum sheet/coil. Also included are the LCI data tables for producing 1 ton of primary and secondary aluminum sheet/coil. These data are a mixture of data obtained from the aluminum industry (The Aluminum Association, 1998) and data collected by Franklin Associates. Data sources are listed at the end of the chapter in Section 3.3.

3.2 Aluminum Sheet/Coil Production

The following sections describe the steps for the production of primary aluminum from raw materials extracted from the earth and the production of secondary aluminum from recycled aluminum containers. The process of producing molten aluminum from recycled containers is much simpler than the process of producing it from primary raw materials.

The following steps in the production of aluminum sheet/coil are discussed in this section:

- Limestone mining
- Lime production
- Salt mining
- Caustic soda and chlorine production
- Bauxite mining
- Alumina production
- Crude oil production
- Petroleum coke production
- Coal mining
- Metallurgical coke production
- Anode production
- Aluminum smelting
- Ingot casting
- Hot/cold rolling
- Aluminum can recovery and processing
- Used container melting and ingot casting.

Figure 3-1 shows the flow diagram for producing 1 ton of primary aluminum sheet/coil. The flow diagram for producing 1 ton of 100 percent secondary aluminum sheet/coil is presented in Figure 3-2. The energy and emissions data for producing 1 ton of primary aluminum sheet/coil are shown in Table 3-1. Table 3-2 presents equivalent data for producing 100 percent secondary aluminum sheet/coil. Although for calculation purposes the secondary module used in this study is for 100 percent recycled aluminum, the recycling percentage when post-consumer aluminum is used is generally less because the variety of alloys found in recovered aluminum prohibits 100 percent recycling.

3.2.1 Limestone Mining

Limestone is quarried primarily from open pits. In the central and eastern U.S., underground mining is becoming more common (U.S. Bureau of Mines, 1993). The energy data (and fuel-related pollutants) used in this analysis represent a combination of open pit and underground mining (split unknown). The process emissions data are based solely on open pit techniques. The most economical method of recovering the limestone has been through drilling, blasting, mechanical crushing, conveying, and screening (U.S. Bureau of Mines, 1993 and 1984). Airborne particulates are generated in the form of limestone dust throughout many of the operations. A conceptual flow diagram for open pit mining is shown in Figure 3-3.

3.2.2 Lime Production

Lime is never found in a natural state but is manufactured by calcining (burning) high-purity calcitic or dolomitic limestone at high temperatures. The calcination process drives off the CO_2, forming calcium oxide (quicklime). The subsequent addition of water creates calcium hydroxide (hydrated or slaked lime). The term *lime* is a general term that includes the various chemical and physical forms of quicklime and hydrated lime. Most of the lime produced in the United States in 1994 was quicklime (85 percent), with hydrated lime (13 percent) and dead-burned dolomite (2 percent) accounting for the rest. The data in this section are for the production of quicklime (EPA, 1994; USGS, 1995).

Solid wastes generated during the manufacture of lime include impurities removed from the limestone, tailings collected in the lime production process, and lime kiln dust collected from particulate control devices on the lime kilns. Based on lengthy discussions with a representative of the National Lime Association and a confidential lime industry expert, it was assumed that all collected lime dust and tailings from lime production are sold for various useful purposes, injected back into mines, replaced in quarries, or land-applied onsite (personal communication, Franklin Associates, with Eric Malias, National Lime Association, January 1998, and confidential industry sources, January 1998). This may not be true of a few smaller companies that are not close to their source of limestone. The solid waste numbers reported in the data table are an estimate from a representative of the lime industry and include packaging and other industrial wastes that may be disposed of in a municipal landfill (personal communication, Franklin Associates and confidential industry sources, January 1998).

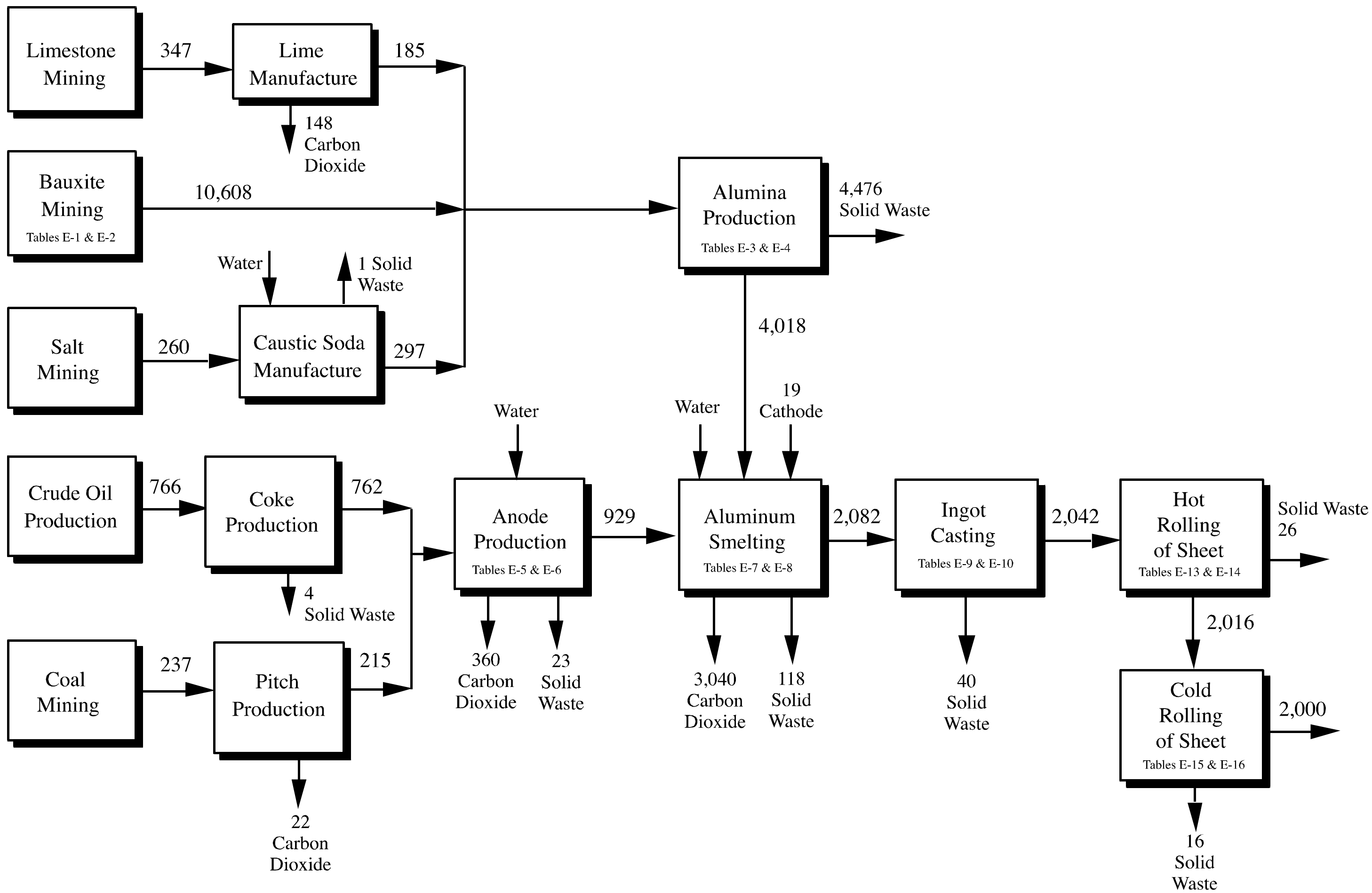

Figure 3-1.Flow diagram for manufacturing 1 ton of primary aluminum sheet/coil. Flow diagram does not include alloys, lacquers, etc. Arrows indicate conveyance to the next process, including possible transportation. The numbers on the arrows represent pounds of material. Datasets from the Aluminum Association report (1998) are designated by the table number from that report.

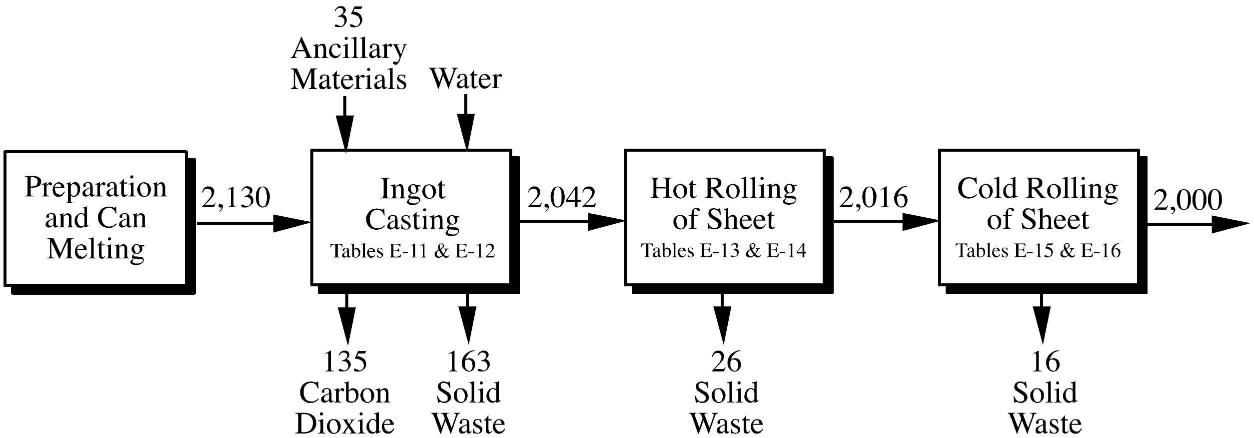

Figure 3-2. Flow diagram for manufacturing 1 ton of secondary aluminum sheet/coil. Flow diagram does not include alloys, lacquers, etc. Arrows indicate conveyance to the next process, including possible transportation. The numbers on the arrows represent pounds of material. Datasets from the Aluminum Association report (1998) are designated by the table number from that report.

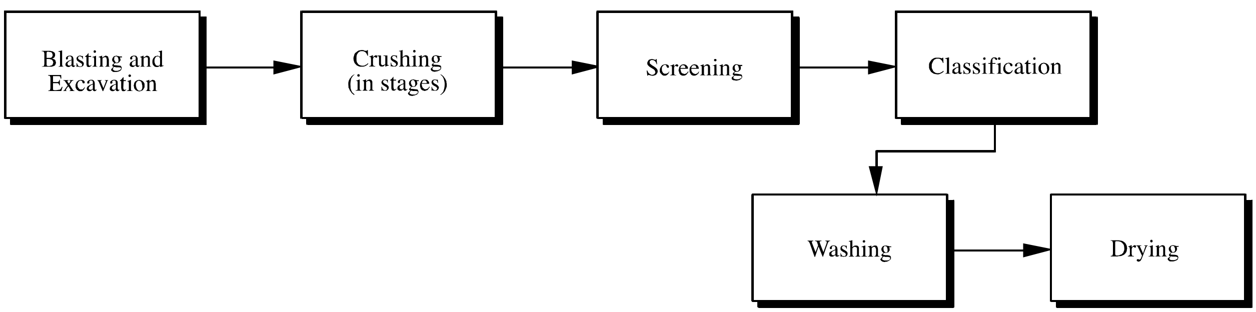

Figure 3-3. Process diagram for open pit limestone mining.

3.2.3 Salt Mining

For the most part, salt-based chlorine and caustic facilities use captive salt from another process or use salt recovered from underground deposits in the form of brine. In solution mining, an injection well is drilled and pressurized fresh water is introduced to the bedded salt (U.S. Bureau of Mines, 1989). The brine is then pumped to the surface for treatment. Salt mines are widely distributed throughout the United States.

Table 3-1. Data for Production of 1 Ton of Primary Aluminum Sheet/Coil

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Energy of Material Resource				
Coal	lb	2.65E+02	3.17E+00	1.20E-02
Petroleum	lb	7.92E+02	1.53E+01	1.94E-02
Combustion Process Energy				
Electricity	kWh	1.58E+04	1.01E+02	*
Coal	lb	7.57E+01	8.40E-01	1.12E-02
Diesel	gal	7.39E+00	1.03E+00	1.39E-01
Distillate Oil	gal	6.56E+00	9.10E-01	1.39E-01
Gasoline	gal	5.50E-01	6.90E-03	1.25E-01
LPG	gal	1.90E-01	1.80E-02	9.55E-02
Natural Gas	cu ft	2.16E+04	2.22E+01	1.03E-03
Residual Oil	gal	5.14E+01	7.69E+00	1.50E-01
Precombustion Process Energy				
Coal	lb	8.84E+01	9.20E-01	1.04E-02
Distillate Oil	gal	5.67E+00	7.90E-01	1.39E-01
Gasoline	gal	2.08E+00	2.60E-01	1.25E-01
Hydropower	Btu	5.56E+04	5.60E-02	1.00E-06
LPG	gal	1.10E-01	1.10E-02	9.55E-02
Natural Gas	cu ft	4.67E+03	4.82E+00	1.03E-03
Nuclear	lb U238	3.50E-04	3.40E-01	9.85E+02
Residual Oil	gal	4.35E+00	6.50E-01	1.50E-01
Other	Btu	4.93E+04	4.90E-02	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	2.69E+01		
Diesel	gal	2.50E-01	3.50E-02	1.39E-01
Rail	ton-miles	1.55E+03		
Diesel	gal	3.72E+00	5.20E-01	1.39E-01
Barge	ton-miles	9.20E+00		
Diesel	gal	1.80E-02	2.60E-03	1.39E-01
Residual Oil	gal	7.40E-03	1.10E-03	1.50E-01
Ocean Freighter	ton-miles	2.11E+04		
Diesel	gal	2.11E+00	2.90E-01	1.39E-01
Residual	gal	3.80E+01	5.69E+00	1.50E-01
Pipeline-Petroleum Products	ton-miles	1.09E+02		
Electricity	kWh	2.40E+00	2.70E-02	1.11E-02
Precombustion Transportation Energy				
Coal	lb	6.90E+00	6.90E-02	1.12E-02
Distillate Oil	gal	2.10E-01	3.00E-02	1.39E-01
Gasoline	gal	6.10E-02	7.70E-03	1.25E-01

(continued)

Table 3-1. (continued)

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Hydropower	Btu	4.00E+03	4.00E-03	1.00E-06
LPG	gal	6.20E-02	5.90E-03	9.55E-02
Natural Gas	cu ft	4.81E+02	5.00E-01	1.03E-03
Nuclear	lb U238	2.50E-05	2.60E-02	1.03E+03
Residual Oil	gal	1.88E+00	2.80E-01	1.50E-01
Other	Btu	3.55E+03	3.60E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	1.80E-04		1.80E-04
Aldehydes	lb	4.30E-01	4.00E-02	3.90E-01
Ammonia	lb	7.80E-02	2.10E-02	5.70E-02
Antimony	lb	2.20E-04		2.20E-04
Arsenic	lb	7.20E-04		7.20E-04
Benzene	lb	1.90E-04		1.90E-04
Beryllium	lb	7.10E-05		7.10E-05
Cadmium	lb	5.40E-04		5.40E-04
Carbon Dioxide-fossil	lb	2.27E+04	3.76E+03	1.89E+04
Carbon Monoxide	lb	1.59E+02	1.42E+02	1.71E+01
Carbon Tetrachloride	lb	2.40E-04		2.40E-04
CFC/HCFC	lb	2.50E-01	2.50E-01	
Chlorine	lb	9.46E-01	3.60E-02	9.10E-01
Chromium	lb	9.70E-04		9.70E-04
Cobalt	lb	6.00E-04		6.00E-04
COS	lb	2.33E+00	2.33E+00	
Dioxins	lb	9.70E-10		9.70E-10
Fluorine	lb	3.90E-02	3.90E-02	
Formaldehyde	lb	8.00E-04		8.00E-04
Hydrocarbons	lb	3.55E+01	8.65E+00	2.68E+01
Hydrochloric Acid	lb	4.80E+00	1.10E-01	4.69E+00
Hydrogen Cyanide	lb	7.70E-02	7.70E-02	
Hydrogen Fluoride	lb	1.45E+00	1.32E+00	1.30E-01
Kerosene	lb	2.60E-03		2.60E-03
Lead	lb	4.20E-04	4.20E-04	1.1.0E-03
Manganese	lb	1.60E-03		1.60E-03
Mercury	lb	5.70E-04	1.60E-04	4.10E-04
Metals	lb	6.12E-01	6.10E-01	1.90E-03
Methane	lb	3.91E+01	1.23E+00	3.79E+01
Methylene Chloride	lb	7.40E-04		7.40E-04
Naphthalene	lb	1.20E-05		1.20E-05
Nickel	lb	7.90E-03		7.90E-03
Nitrogen Oxides	lb	1.02E+02	3.27E+01	6.94E+01
Nitrous Oxide	lb	1.04E-01	4.40E-03	1.00E-01
N-Nitrosodimethylamine	lb	3.80E-05		3.80E-05
Other Organics	lb	1.16E+00	7.20E-01	4.40E-01

(continued)

Table 3-1. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
PAH	lb	4.30E-01	4.30E-01	
Particulate	lb	6.58E+01	4.83E+01	1.75E+01
Perchloroethylene	lb	1.70E-04		1.70E-04
PFC	lb	8.00E-01	8.00E-01	
Phenols	lb	4.50E-04		4.50E-04
Radionuclides	Ci	3.00E-03		3.00E-03
Selenium	lb	1.40E-03		1.40E-03
Sulfur Oxides	lb	2.00E+02	3.95E+01	1.60E+02
Sulfuric Acid	lb	4.50E-03	4.50E-03	
Trichloroethylene	lb	1.70E-04		1.70E-04
Solid Wastes				
Ash	lb	2.43E+03		2.43E+03
Environmental Abatement	lb	7.07E+02	7.07E+02	
Municipal	lb	3.89E+02	3.89E+02	
Unspecified	lb	5.53E+03	5.53E+03	
Waterborne Wastes				
Acid	lb	2.50E-01	2.50E-01	1.10E-06
Ammonia	lb	9.80E-03	2.10E-03	7.70E-03
Ammonium Ion	lb	2.10E-03	2.10E-03	
BOD	lb	2.90E-01	1.70E-01	1.20E-01
Boron	lb	5.20E-01		5.20E-01
Cadmium	lb	5.10E-03		5.10E-03
Calcium	lb	2.20E-03		2.20E-03
Calcium Ion	lb	2.30E-02	2.30E-02	
Chloride	lb	5.17E+00		5.17E+00
Chloride Ion	lb	8.90E-02	8.90E-02	
Chromates	lb	1.28E-03	8.30E-04	4.50E-04
Chromium	lb	5.10E-03	3.40E-06	5.10E-03
COD	lb	2.70E+00	1.08E+00	1.62E+00
Cyanide	lb	1.21E-03	1.20E-03	7.50E-06
Detergent	lb	1.30E-03	1.30E-03	
Dissolved Chlorine	lb	4.40E-04	4.40E-04	
Dissolved Organics	lb	5.60E-02	5.60E-02	
Dissolved Solids	lb	1.15E+02	2.07E+00	1.13E+02
Fluorides	lb	1.40E-01	1.30E-01	1.00E-02
Hydrocarbons	lb	3.20E-05	3.20E-05	
Iron	lb	6.95E-01	3.50E-02	6.60E-01
Lead	lb	7.29E-05	7.10E-05	1.90E-06
Magnesium Ion	lb	4.40E-03	4.40E-03	
Manganese	lb	4.00E-01		4.00E-01
Mercury	lb	6.29E-06	5.90E-06	3.90E-07
Metal Ion	lb	4.23E-01	4.00E-01	2.30E-02
Nickel	lb	1.50E-07	1.50E-07	
Nitrates	lb	4.37E-03	3.40E-03	9.70E-04
Nitrogen	lb	6.50E-03	6.50E-03	
Oil	lb	2.15E+00	1.40E-01	2.01E+00
Other Organics	lb	4.20E-01		4.20E-01

(continued)

Table 3-1. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Phenol	lb	8.74E-04	8.00E-04	7.40E-05
Phosphates	lb	6.60E-02	2.70E-05	6.60E-02
Sodium	lb	4.10E-03		4.10E-03
Sodium Ion	lb	7.89E+00	7.89E+00	
Sulfate Ion	lb	7.08E+00	7.08E+00	
Sulfates	lb	5.23E+00		5.23E+00
Sulfides	lb	2.00E-05	2.00E-05	
Sulfur	lb	1.20E-03	1.20E-03	
Sulfuric Acid	lb	1.30E-01		1.30E-01
Suspended Solids	lb	1.08E+01	8.80E-01	9.92E+00
Vinyl Chloride Monomer	lb	6.00E-08	6.00E-08	
Zinc	lb	1.82E-03	2.30E-05	1.80E-03

* The electricity for bauxite mining, alumina production, aluminum smelting, and ingot casting use special electricity grids, and therefore, this conversion factor varies. See text for more information.

Source: Franklin Associates. 2000.

Table 3-2. Data for Production of 1 Ton of Secondary Aluminum Sheet/Coil

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	9.03E+02	1.98E+00	*
Natural Gas	cu ft	3.57E+03	3.68E+00	1.03E-03
Distillate Oil	gal	4.91E+00	6.80E-01	1.39E-01
Gasoline	gal	3.70E-02	4.60E-03	1.25E-01
Diesel	gal	5.60E-01	7.80E-02	1.39E-01
Precombustion Process Energy				
Natural Gas	cu ft	6.13E+02	6.30E-01	1.03E-03
Residual Oil	gal	4.40E-01	6.70E-02	1.50E-01
Distillate oil	gal	5.70E-01	7.90E-01	1.39E-01
Gasoline	gal	2.80E-01	3.50E-02	1.25E-01
LPG	gal	1.06E-02	1.00E-03	9.55E-02
Coal	lb	1.08E+01	1.20E-01	1.12E-02
Nuclear	lb U238	4.30E-05	4.40E-02	1.03E+03
Hydropower	Btu	6.82E+03	6.80E-03	1.00E-06
Other	Btu	6.05E+03	6.00E-03	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	2.11E+02		
Diesel	gal	2.49E+00	3.50E-01	1.39E-01
Rail	ton-miles	2.34E+01		
Diesel	gal	7.30E-02	1.00E-02	1.39E-01

(continued)

Table 3-2. (continued)

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Precombustion Transportation Energy				
Natural Gas	cu ft	2.06E+01	2.10E-02	1.03E-03
Residual Oil	gal	8.10E-02	1.20E-02	1.50E-01
Distillate Oil	gal	9.10E-03	1.30E-03	1.39E-01
Gasoline	gal	2.60E-03	3.30E-04	1.25E-01
LPG	gal	2.60E-03	2.50E-04	9.55E-02
Coal	lb	2.60E-01	2.90E-03	1.12E-02
Nuclear	lb U238	1.10E-06	1.10E-03	1.03E+03
Hydropower	Btu	1.70E+02	1.70E-04	1.00E-03
Other	Btu	1.50E+02	1.50E-04	1.00E-03

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	1.70E-05		1.70E-05
Aldehydes	lb	9.10E-03	9.10E-03	
Ammonia	lb	7.50E-03		7.50E-03
Antimony	lb	8.00E-06		8.00E-06
Arsenic	lb	4.00E-05		4.00E-05
Benzene	lb	1.60E-05		1.60E-05
Beryllium	lb	5.40E-06		5.40E-06
Cadmium	lb	9.90E-06		9.90E-06
Carbon Dioxide-fossil	lb	2.13E+03	1.82E+02	1.94E+03
Carbon Monoxide	lb	5.05E+01	4.81E+01	2.42E+00
Carbon Tetrachloride	lb	2.90E-05		2.90E-05
CFC/HCFC	lb	7.80E-08	7.80E-08	
Chlorine	lb	1.30E-01	1.30E-01	1.80E-05
Chromium	lb	7.00E-05		7.00E-05
Cobalt	lb	2.50E-05		2.50E-05
Dioxins	lb	9.60E-11		9.60E-11
Formaldehyde	lb	8.50E-05		8.50E-05
Hydrocarbons	lb	4.53E+00	1.19E+00	3.34E+00
Hydrochloric Acid	lb	4.38E-01	3.50E-01	8.80E-02
Hydrofluoric Acid	lb	1.20E-02		1.20E-02
Hydrogen Cyanide	lb	1.50E-05	1.50E-05	
Hydrogen Fluoride	lb	2.20E-02	2.20E-02	
Kerosene	lb	4.00E-04		4.00E-04
Lead	lb	8.71E-04	8.10E-04	6.10E-05
Manganese	lb	1.30E-04		1.30E-04
Mercury	lb	3.40E-05		3.40E-05
Metals	lb	6.00E-01	6.00E-01	2.30E-04
Methane	lb	4.20E+00		4.20E+00
Methylene Chloride	lb	7.60E-05		7.60E-05
Naphthalene	lb	1.40E-06		1.40E-06

(continued)

Table 3-2. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Nickel	lb	2.50E-04		2.50E-04
Nitrogen Oxides	lb	3.93E+01	3.21E+01	7.20E+00
Nitrous Oxide	lb	9.90E-03		9.90E-03
N-Nitrosodimethlyamine	lb	3.70E-06		3.70E-06
Other Aldehydes	lb	2.60E-02		2.60E-02
Other Organics	lb	1.02E+00	7.30E-01	2.90E-01
Particulate	lb	2.46E+00	8.50E-01	1.61E+00
Perchloroethylene	lb	1.70E-05		1.70E-05
Phenols	lb	4.90E-05		4.90E-05
Radionuclides	Ci	3.60E-04		3.60E-04
Selenium	lb	1.20E-04		1.20E-04
Sulfur Oxides	lb	1.75E+01	3.00E-02	1.75E+01
Sulfuric Acid	lb	4.40E-04	4.40E-04	
Trichloroethylene	lb	1.60E-05		1.60E-05
Solid Wastes				
Ash	lb	2.43E+02	2.43E+02	
Environmental Abatement	lb	3.23E+00	3.23E+00	
Municipal	lb	1.25E+01	1.25E+01	
Unspecified	lb	2.03E+02	2.03E+02	
Waterborne Wastes				
Acid	lb	8.60E-08	8.60E-08	
Ammonia	lb	1.00E-03	1.00E-03	
Ammonium Ion	lb	2.90E-05	2.90E-05	
BOD	lb	2.80E-01	1.20E-01	1.60E-01
Boron	lb	4.50E-02	4.50E-02	
Cadmium	lb	7.10E-04	7.10E-04	
Calcium	lb	3.50E-04	3.50E-04	
Chloride	lb	7.20E-01	7.20E-01	
Chloride Ion	lb	2.50E-02	2.50E-02	
Chromates	lb	8.45E-04	8.30E-04	1.50E-05
Chromium	lb	7.10E-04	7.10E-04	
COD	lb	3.70E-01	1.50E-01	2.20E-01
Cyanide	lb	7.70E-06	6.70E-06	1.00E-06
Detergent	lb	2.40E-05	2.40E-05	
Dissolved Organics	lb	7.40E-04	7.40E-04	
Dissolved Solids	lb	1.58E+01	7.60E-02	1.57E+01
Fluorides	lb	1.60E-03	1.60E-03	
Hydrocarbons	lb	9.50E-04	9.50E-04	
Iron	lb	6.60E-02	4.50E-05	6.60E-02
Lead	lb	5.02E-05	5.00E-05	1.50E-07
Manganese	lb	3.80E-02	3.80E-02	
Mercury	lb	5.50E-08	5.50E-08	
Metal Ion	lb	6.20E-03	4.40E-03	1.80E-03
Nitrates	lb	5.80E-04	4.30E-04	1.50E-04

(continued)

Table 3-2. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Nitrogen	lb	6.80E-03	6.80E-03	
Oil	lb	3.56E-01	7.60E-02	2.80E-01
Other Organics	lb	5.30E-02	5.30E-02	
Phenol	lb	4.39E-05	3.80E-05	5.90E-06
Phosphates	lb	5.60E-03	5.60E-03	
Sodium	lb	6.40E-04	6.40E-04	
Sulfate Ion	lb	2.50E-02	2.50E-02	
Sulfates	lb	7.50E-01	7.50E-01	
Sulfuric Acid	lb	1.10E-02	1.10E-02	
Suspended Solids	lb	1.11E+00	9.00E-02	1.02E+00
Vinyl Chloride Monomer	lb	6.00E-08	6.00E-08	
Zinc	lb	2.40E-04	2.40E-04	

* The electricity for bauxite mining, alumina production, aluminum smelting, and ingot casting use special electricity grids, and therefore, this conversion factor varies. See text for more information.

**Materials collection, separation, and transport to a remanufacturing facility are handled by the collection, materials recovery facility, and transportation process models, respectively, of the decision support tool.

Source: Franklin Associates. 2000.

3.2.4 Caustic Soda and Chlorine Production

Caustic soda (sodium hydroxide) and chlorine are produced from salt by an electrolytic process. The aqueous sodium chloride solution is electrolyzed to produce caustic soda, chlorine, and hydrogen gas. For this analysis, resource requirements and environmental emission coproduct credits are allocated on a weight basis to each of the materials produced in the cell. Coproduct credit is given on a weight basis because it is not possible, using the electrolytic cell, to get chlorine from salt without also producing sodium hydroxide and hydrogen, both of which have commercial value as useful coproducts. Likewise, sodium hydroxide cannot be obtained without producing the valuable coproducts chlorine and hydrogen. Furthermore, it is not possible to control the cell to increase or decrease the amount of chlorine or caustic soda resulting from a given input of salt. This is determined by the stoichiometry of the reaction. The electrolytic cell is perceived as a “black box” with an input of salt and electricity and an output of chlorine, sodium hydroxide, and hydrogen.

The electrolysis of sodium chloride is performed by one of two processes: the mercury cathode cell process or the diaphragm cell process. About 83 percent of electrolyzed chlorine and caustic soda production comes from the diaphragm process, with the remainder coming from the mercury cell process (Chlorine Institute, 1989). The data for caustic soda incorporated into Table 3-1 represents this weighted average.

The diaphragm cell uses graphite anodes and steel cathodes. Brine solution is passed through the anode compartment of the cell, where the salt is decomposed into chlorine gas and sodium ions. The gas is removed through a pipe at the top of the cell. The sodium ions pass through a cation-selective diaphragm. The depleted brine is either resaturated with salt or concentrated by evaporation and recycled to the cell. The sodium ions transferred across the diaphragm react at the cathode to produce hydrogen and sodium hydroxide. Diffusion of the cathode products back into the brine solution is prevented by the diaphragm.

The mercury cathode cell process is described by:

$$NaCl + xHg \rightarrow \frac{1}{2} Cl_2 + Na(Hg)x$$

and

$$Na(Hg)x + H_2O \rightarrow NaOH + \frac{1}{2} H_2 + xHg.$$

Chlorine gas collects at graphite anodes. The chlorine gas from the anode compartment is cooled and dried in a sulfuric acid scrubber. The gas is then cooled further to a liquid for shipment, generally by rail and barge. Metallic sodium reacts with the mercury cathode to produce an amalgam, which is sent to another compartment of the cell and reacted with water to produce hydrogen and high-purity sodium hydroxide. Mercury loss is a disadvantage of the mercury cathode cell process. Some of the routes by which mercury can escape are in the hydrogen gas stream, in cell room ventilation air and washing water, through purging of the brine loop and disposal of brine sludges, and through end box fumes.

3.2.5 Bauxite Mining

Aluminum is the most widely distributed metal in the earth's crust, with only the nonmetallic elements oxygen and silicon surpassing it in abundance. However, bauxite ore is, at present, the only commercially exploited source of aluminum. Although other types of earth, including ordinary clay, contain aluminum, economics favors the use of bauxite.

Bauxite is formed by the action of rain and erosion on materials containing aluminum oxide (alumina). The heavy rainfall and warm temperatures of the tropics provide nearly ideal conditions for this process, and most of the world's bauxite is mined in these regions. Australia is the leading producer of bauxite, followed by Guinea, Jamaica, Brazil, and Guyana (American Metals Market, 1997). Although a number of other countries also produce and export bauxite to the U.S., more than 98 percent of the total is supplied by Guinea, Jamaica, Brazil, and Guyana. For this analysis, only these countries are considered as the suppliers of bauxite to the U.S.

To calculate the fuels used to generate electricity for bauxite production, it is necessary to determine the percentage of bauxite produced in each of the aforementioned countries. This quantity is calculated from the amount exported to the U.S. as bauxite ore and the amount used within each country to produce alumina, which is then exported to the U.S. About 53 percent of the alumina used in U.S. smelters is produced domestically, mainly from imported bauxite (U.S. Bureau of Mines, 1996). The remaining 47 percent is imported as alumina.

Australia, Jamaica, and Suriname supply about 90 percent of the alumina imported into the United States. For this study, these three countries are assumed to supply all of the imported alumina. It is assumed that bauxite produced in these countries is used to produce the alumina that is exported. (It is assumed that approximately 2.5 pounds of bauxite are required to produce 1 pound of alumina.) Total bauxite production figures based on these assumptions are as follows: Australia, 35.1 percent; Jamaica, 26 percent; Guinea, 19.2 percent; Brazil, 11.7 percent; Suriname, 4.2 percent; and Guyana, 3.9 percent.

Table 3-3 lists the fuels used to produce electricity in each of these countries and the weighted average fuel used to generate electricity for bauxite mining based on the above bauxite production percentages.

Table 3-3. Fuel Used to Produce Electricity for Bauxite Production

	Country (Percent of production) percent of electricity from each source						
Fuel Source	Australia (35.1)	Jamaica (26.0)	Guinea (19.2)	Brazil (11.7)	Suriname (4.2)	Guyana (3.9)	Weighted Average
Coal	79.0	4.8		3.9			29.4
Nuclear							
Hydro	10.0	2.1	35.1	93.5	84.9	2.2	25.4
Fuel Oil	2.2	93.0	64.9		15.1	97.8	41.9
Natural Gas	8.9						3.9
Other				2.6			0.3
Total	100	100	100	100	100	100	100

Sources: U.S. Bureau of Mines (BOM). 1996; U.S. Department of Energy (DOE),1997a; U.S. Department of Energy (DOE),1997b; and Franklin Associates, Confidential.

3.2.6 Alumina Production

Before it can be used in the manufacture of metallic aluminum, bauxite ore must be refined to nearly pure aluminum oxide, usually called alumina. This is accomplished using a process called the Bayer process almost exclusively. Bauxite is crushed and dissolved in digesters using strong caustic soda and lime solution. The undissolved residue, known as red mud, is filtered out. Sodium aluminate remains in solution, where it is hydrolyzed and precipitated as aluminum hydroxide, which is then calcined to alumina, generally in a rotary or fluid bed kiln (The Aluminum Association, 1998).

Red mud filtered from the digester liquid is considered solid waste in this analysis. Red mud production rates vary depending on the quality of the ore and the level of alumina recovery.

It is assumed that the energy requirements for foreign-produced alumina are approximately the same as for domestically refined alumina (U.S. Bureau of Mines, 1989). Primary fuels used to generate electricity for producing alumina that is imported into the U.S. (47 percent of the total alumina used) are calculated according to the countries producing the alumina. As mentioned, Australia, Jamaica, and Suriname produce the majority of the alumina imported into the U.S. For this analysis, it is assumed that about 38 percent of alumina used in the U.S. comes from Australia, about 4 percent comes from Jamaica, and about 5 percent comes from Suriname.

Primary fuels used to generate electricity for alumina production facilities in the United States (53 percent of the total alumina used) are calculated from the fuel mix for the North American Electricity Reliability Council (NAERC) regional electricity grid in which the plants are located. About 67 percent of the U.S. alumina production capacity is in the Electric Reliability Council of Texas (ERCOT), and the remaining 33 percent is in the Southwest Power Pool (SPP) (U.S. Bureau of Mines, 1996). Therefore, about 36 percent of the total alumina used is produced in the ERCOT and about 17 percent is produced in the SPP.

Table 3-4 presents the fuel mix for these countries and NAERC regions and the average fuel mix for electricity used for alumina production.

Table 3-4. Fuels Used to Produce Electricity For Alumina Production

Fuel Source	Country or NAERC Region (percentage of production) (percentage of electricity from each source					Weighted Average
	Australia (38)	Jamaica (4.3)	Suriname (4.7)	ERCOT (36)	SPP (17)	
Coal	79.0	4.8		41.3	54.1	54.5
Nuclear				12.8	16.2	7.4
Hydro	10.0	2.1	84.9	0.30	2.60	8.5
Fuel Oil	2.20	93.0	15.1	0.20	0.500	5.7
Natural Gas	8.9			35.8	24.7	20.5
Other				9.60	1.9	3.8
Total	100	100	100	100	100	100

Sources: U.S. Bureau of Mines (BOM). 1996; U.S. Department of Energy (DOE). 1997a; Department of Energy (DOE). 1997b; CRC, 1994; and Franklin Associates, confidential.

3.2.7 Crude Oil Production

Oil is produced by drilling into porous rock structures generally located several thousand feet underground. Once an oil deposit is located, numerous holes are drilled and lined with steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although most oil requires some energy to drive pumps that lift oil to the surface. Once oil is on the surface, it is stored in tanks to await transportation to a refinery. In some cases, it is immediately transferred to a pipeline, which transports the oil to a larger terminal.

There are two primary sources of waste from crude oil production. The first source is the "oil field brine," or water that is extracted with the oil. The brine goes through a separator at or near the well head to remove the oil from the water. These separators are very efficient and leave minimal oil in the water.

The American Petroleum Institute (API) estimates that 21 billion barrels of brine water were produced from crude oil production in 1985 (API, 1987). This quantity of water equates to a ratio of 5.4 barrels of water per barrel of oil. The majority of this water (85 percent) is injected into separate wells specifically designed to accept production-related waters. This represents all waters produced by onshore oil production facilities, which are not permitted to discharge "oil field brine" to surface waters (personal communication, Franklin Associates and L. Gibson, U.S. EPA, NPDES Permits Branch, Dallas, TX). The remainder of the produced water is from offshore oil production facilities and is assumed to be discharged to the ocean. Therefore, the waterborne wastes represent the brine wastes present in this 15 percent of brine water (DOE, 1994). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (API, 1987).

The second source of waste is the gas produced from oil wells. While most of this is recovered for sale, some is not. Atmospheric emissions from crude oil production are primarily hydrocarbons. They are attributed to the natural gas produced from combination wells and relate to line or transmission losses and unflared venting.

The transportation data assume a mix of foreign and domestically produced crude oil. According to the Petroleum Supply Annual (EIA, 1994), 49 percent of the crude oil used in the U.S. is imported.

3.2.8 Petroleum Coke Production

Petroleum coke is used in the manufacture of carbon electrodes, which are used in the electrolytic reduction of alumina to aluminum. Coking is an extreme form of thermal cracking that uses high temperatures and a long residence time to break down heavy crude residues to get lighter liquids (Kent, 1992). Coking takes place in a series of ovens in the absence of oxygen. After a typical coking time of 12 to 20 hours, most of the volatile matter is driven from the crude residue and the coke is formed. The desired products of the coking process are actually the volatile products. The petroleum coke itself is considered a byproduct. The coke is collected in a coke drum, while the lighter products go overhead as vapors.

The energy requirements and environmental emissions for crude oil desalting and atmospheric and vacuum distillation to produce heavy crude residues are included in data on production of petroleum coke.

3.2.9 Coal Mining

Coal may be obtained by surface mining of outcrops or seams that are near the earth's surface or by underground mining of deposits. In strip mining, the overburden is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. Generally, the overburden is eventually returned to the mine and is not considered as a solid waste in this analysis.

After the coal is mined, it goes through various preparation processes before it is used. These processes vary depending on the quality of the coal and the use for which it is intended. Coal preparation usually involves some type of size reduction and partial removal of ash-forming materials.

3.2.10 Metallurgical Coke Production

The two proven processes for manufacturing metallurgical coke are known as the beehive process and the byproduct process (U.S. Steel Corporation, 1985). The primary method for manufacturing coke is the byproduct method, which accounts for more than 98 percent of U.S. coke production (U.S. EPA, 1995). For this analysis, it is assumed that all metallurgical coke is produced in the byproduct oven.

In the byproduct method, air is excluded from the coking chambers, and the necessary heat for distillation is supplied from external combustion of some of the gas recovered from the coking process (U.S. Steel Corporation, 1985). Coking 1,000 pounds of coal in the byproduct oven is assumed to produce the following: coke, 774 pounds; tar, 37 pounds; water, 32 pounds; benzene, 11 pounds; and coke oven gas, 147 pounds (Loison, 1989). Coproduct credit is given on a weight basis to all of the byproducts from the oven, except water. It is assumed that about 40 percent of the coke oven gas (59 pounds) is used as a fuel for underfiring the coke oven (U.S. Steel Corporation, 1985). Therefore, coproduct credit is given for the remaining 88 lb of coke oven gas. The energy content of the coke oven gas is accounted for in the energy of material resource for the coal used as a feedstock for the coke oven. While it is recognized that the gas is actually used as a fuel in the coke oven, the methodology used in this study accounts for the energy derived from materials used as feedstocks on the basis of the energy content of the material that is extracted from the ground to produce the raw material.

3.2.11 Anode Production

Depending on which type of smelting technology is used, either briquettes or prebake blocks are used for the anodes. The process for making the aggregate for these is the same. Coke is calcined, ground and blended with pitch to form a paste that is extruded into blocks or briquettes and allowed to cool (The Aluminum Association, 1998). The briquettes are sent to the pots (reduction cell for the Soderberg design) for consumption. The blocks are sent to a separate baking furnace.

3.2.12 Aluminum Smelting

Smelting is the reduction of refined alumina to metallic aluminum by the electrolytic separation of aluminum from its oxide. The process is carried out in a long series of electrolytic cells carrying direct current. The alumina is dissolved in a molten bath of cryolite, which increases the conductivity of the electrolyte. These chemicals are assumed to be recovered with little or no loss, and therefore negligible inputs of these materials are assumed for this LCI. Carbon anodes carry the current to the solution and on to the next cell. The anodes are consumed during the reaction at a rate of approximately 500 pounds of material per 1,000 pounds of aluminum produced. The principal products of the reaction are carbon dioxide, which is evolved as a gas, and elemental aluminum, which settles to the bottom of the cell and is periodically drained off.

Aluminum smelting is based on an electrolytic process (Hall-Heroult); therefore, a relatively large quantity of electricity is used to produce primary aluminum. Although the quantity of electricity (kilowatt-hours) required to smelt aluminum can be assessed from industrial and literature sources, the calculation of energy used to generate this electricity is somewhat more arbitrary. This estimate has a pronounced effect on the quantity of energy (in million Btu) used by the process because different efficiencies are experienced for each power source. For example, coal-fired power plants use about 1 pound of coal per kilowatt-hour of electricity generated (U.S. Department of Commerce, 1990). At an energy content of 9,975 Btu per pound of coal (U.S. Department of Commerce, 1990), this equates to approximately 9,975 Btu per kWh. Assuming the standard conversion is 3,412 Btu per kWh (*CRC Handbook of Chemistry and Physics*, 1994), this equates to a thermal efficiency of about 34 percent. On the other hand, the quantity of "fuel" consumed and thermal efficiency are not considerations when producing electricity from hydropower. Therefore, the energy to produce electricity from hydropower is determined using the standard conversion of 3,412 Btu/kWh. If electricity for aluminum smelting is assumed to come from coal, the energy used for smelting will be about three times higher than if all electricity is assumed to come from hydropower.

According to statistics published by the International Primary Aluminum Institute (IPAI) for 1993, about 31 percent of the electricity used for primary aluminum production in North America (Canada and the U.S.) was self-generated and the remaining 69 percent was purchased (IPAI, 1993). Although the fuel mix for self-generated electricity in North America was not released for reasons of confidentiality, the international percentage breakdown is reported. This breakdown is assumed to be representative of North America for this analysis. The following self-generated electricity fuel mix is reported by the IPAI: hydro, 62 percent; coal, 23 percent; and natural gas, 15 percent (IPAI, 1993).

The fuel mix for purchased electricity is estimated according to the quantity of primary aluminum produced in each NERC region and subregion in the U.S. and Canada, with one exception. The electricity supplied from the Northwest Power Pool is assumed to come exclusively from the Bonneville Power Administrations portion of the regional grid.

The grid includes both the U.S. and Canada because aluminum ingots are a commodity made and traded extensively in and between these countries. Table 3-5 presents this breakdown.

Table 3-5. Aluminum Production According to NAERC Regions and Subregions

NAERC Region/Subregion	Percent of Production
United States	
East Central Reliability Coordination Agreement (ECAR)	16.8
Electric Reliability Council of Texas (ERCOT)	3.5
Mid-American Interconnected Network/East Missouri (MAIN-EM)	3.0
Northeast Power Coordination Council/New York Power Pool (NPCC-NY)	3.5
Southwest Power Pool/West Central (SPP-WC)	3.8
Southeastern Electric Reliability Council/Tennessee Valley Authority (SERC-TVA)	2.6
Southeastern Electric Reliability Council/Virginia-Carolina (SERC-VAC)	4.1
Western System Coordinating Council/Bonneville Power Administration (WCC-BPA)*	20.5
Western System Coordinating Council/Rocky Mountain Power Area (WCC-RMP)	2.9
Subtotal—United States	60.7
Canada	
Northeast Power Coordination Council/Quebec (NPCC-QUE)	35.0
Western System Coordinating Council/Canada (WSCC-CAN)	4.3
Subtotal—Canada	39.3
Grand Total	100

*BPA is an administration within the NWPP that supplies most of the electricity to the aluminum smelters in the Northwest.
References: American Metals Market. 1997; North American Electric Reliability Council, 1994.

The fuel mix used in each of the regions and subregions is weighted according to production percentages to obtain the average fuel mix for purchased electricity.

Table 3-6 presents the weighted fuel mix, along with the previously discussed mix for self-generated electricity. The overall average mix for aluminum smelting in the U.S. and Canada is also presented in Table 3-6.

3.2.13 Ingot Casting

Molten aluminum is discharged from a smelter into the holding and ingot casting facility. In the holding furnace, the composition is adjusted to the specific alloy wanted. The melt is then fluxed to remove impurities and reduce gas content (The Aluminum Association, 1998). A melt loss occurs when these impurities, called dross, are skimmed off the molten aluminum.

Electricity for ingot casting is assumed to be produced by the same fuel mix used for aluminum smelting because smelting and ingot casting usually occur in the same facility.

3.2.14 Hot/Cold Rolling

According to an aluminum industry expert, most aluminum sheet used for packaging purposes is taken through both the hot and cold rolling processes. The ingot is taken through the

Table 3-6. Fuel Mix for Electricity Production by NAERC Region/Subregion and Average Mix for Aluminum Smelting.

	NAERC Region/Subregion (Percent of total generation)												
Fuel	ECAR (11.6)	ERCOT (2.4)	MAIN-EM (2.1)	NPCC-NY (2.4)	SERC-TVA (1.8)	SERC-VAC (2.9)	SPP-WC (3.6)	WSCC-BPA (14.1)	WSCC-RMP (2.0)	NPCC-QUE (24.2)	WSCC-CAN (3.0)	**Self Generated Electricity**	**Weighted Average**
Coal	88.8	41.3	64.4	19.7	67.6	45.6	61.5	2.5	78.1	0.0	42.0	23	27.9
Nuclear	7.7	12.8	29.6	21.2	14.4	43.5	0.0	7.49	0.0	4.0	0.0		5.9
Hydro	0.56	0.30	5.3	18.9	17.8	2.7	7.2	89.6	15.2	95.3	48.4	62	57.3
Fuel Oil	0.14	0.19	0.22	7.9	0.10	1.0	0.0	0.0	0.01	0.28	0.0		0.3
Nat. Gas	0.26	35.8	0.48	13.1	0.08	1.1	27.3	0.27	0.88	0.0	6.6	15	7.0
Other	2.5	9.6	0.0	19.2	0.06	6.1	4.0	0.13	4.6	0.42	2.9		1.6
Total	100	100	100	100	100	100	100	100	99.9	100	99.9	100	100

Sources: American Metals Market, 1997; U.S. Department of Energy, 1994; International Primary Aluminum Institute, 1993; North American Electric Reliability Council, 1994.

hot rolling mill first. The ingots are preheated to about 1,000 ˚F. They can then be scalped on their rolling surfaces or directly fed to a reversing hot mill (The Aluminum Association, 1998). The ingot then passes between the rollers, so that the thickness is reduced to between 1 to 2 inches. They are then fed to a continuous hot mill so the thickness can be further reduced to less than one-quarter of an inch.

The coils may then be annealed to give the metal workability (The Aluminum Association, 1998). They are then passed through a cold mill to reduce the thickness to the customer's requirements and may also go through leveling, heat treating, slitting, cutting to length, and coating processes.

3.2.15 Aluminum Recovery and Processing

Widespread aluminum can recovery is observed through voluntary collection centers, curbside collection programs, and mandatory beverage container deposit laws. The high scrap value and easily identified containers are two reasons for the high recovery rate experienced with aluminum. In the 1980s, collection centers could commonly be found in shopping centers and other retail store locations. At present, the recovery of aluminum creates little environmental disruption and requires energy only to the extent that fuel is required to transport aluminum to the collection center.

Once the aluminum is collected, it must be densified in some fashion and shipped. Aluminum is commonly flattened or shredded at recycling centers. The processed scrap is usually blown into tractor-trailer vehicles for shipment to an aluminum recycling plant. The scrap can also be densified in balers at the recycling center, an MRF, or in special units that produce smaller bales called briquettes.

Data for the collection and transportation of postconsumer aluminum are **not included** in Table 3-2. These data are captured in other modules of the decision support tool and included in waste management strategies including recycling.

3.2.16 Secondary Ingot Casting

Once aluminum is recovered in a reasonably pure form and prepared for melting, it can be placed in a secondary furnace. The main difference between primary and secondary ingot casting is the melting technology (The Aluminum Association, 1998). Types of melting furnaces include top-loaded closed melters, rotary melters, and sidewall feeding melters.

3.2.17 Data Quality

Table 3-7 summarizes data quality information for aluminum.

Table 3-7. Data Quality Information for Aluminum

Data Quality Indicator	Primary and Secondary Aluminum Sheet/Coil
Geographical coverage	U.S. and Canadian facilities with exceptions for countries producing bauxite and alumina.
Time-related coverage	Primary data from 1995 with the exception of one bauxite plant (1992-1993).
Technological coverage	The full range of technological differences in the various unit processes included.
Precision	The mean and standard deviation were calculated for each unit process included.
Completeness	Excellent at 93 percent for the total unit processes.
Consistency	Excellent.
Representativeness	Data quality rankings were given for each data point in the unit process tables of the source.
Reproducibility	If a company has data, it should be able to reproduce numbers close to the results using the flow diagrams and methodological section. However, the data are not transparent.
Uncertainty/limitations	Data were collected from a large number of actual manufacturers and were scrutinized by members of The Aluminum Association. Additional information about uncertainty and limitations is provided in *Life Cycle Inventory Report for the North American Aluminum Industry* (The Aluminum Association, 1998).
Data Quality Rating	The aluminum data are considered to be of excellent quality.

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4.0 Summary LCI of Glass Containers

4.1 Introduction

This summary presents “cradle-to-gate” LCI results for glass container production scenarios: primary, secondary, and composite primary/secondary. The data include energy and emissions from raw materials extraction through production of the final product but does not include the use or disposal portions of a traditional LCI. In addition, data for the collection, processing, and transportation of recovery cullet to a reprocessing facility are not included in the data sets for the secondary and composite systems. These data are included in other modules of the MSW-DST.

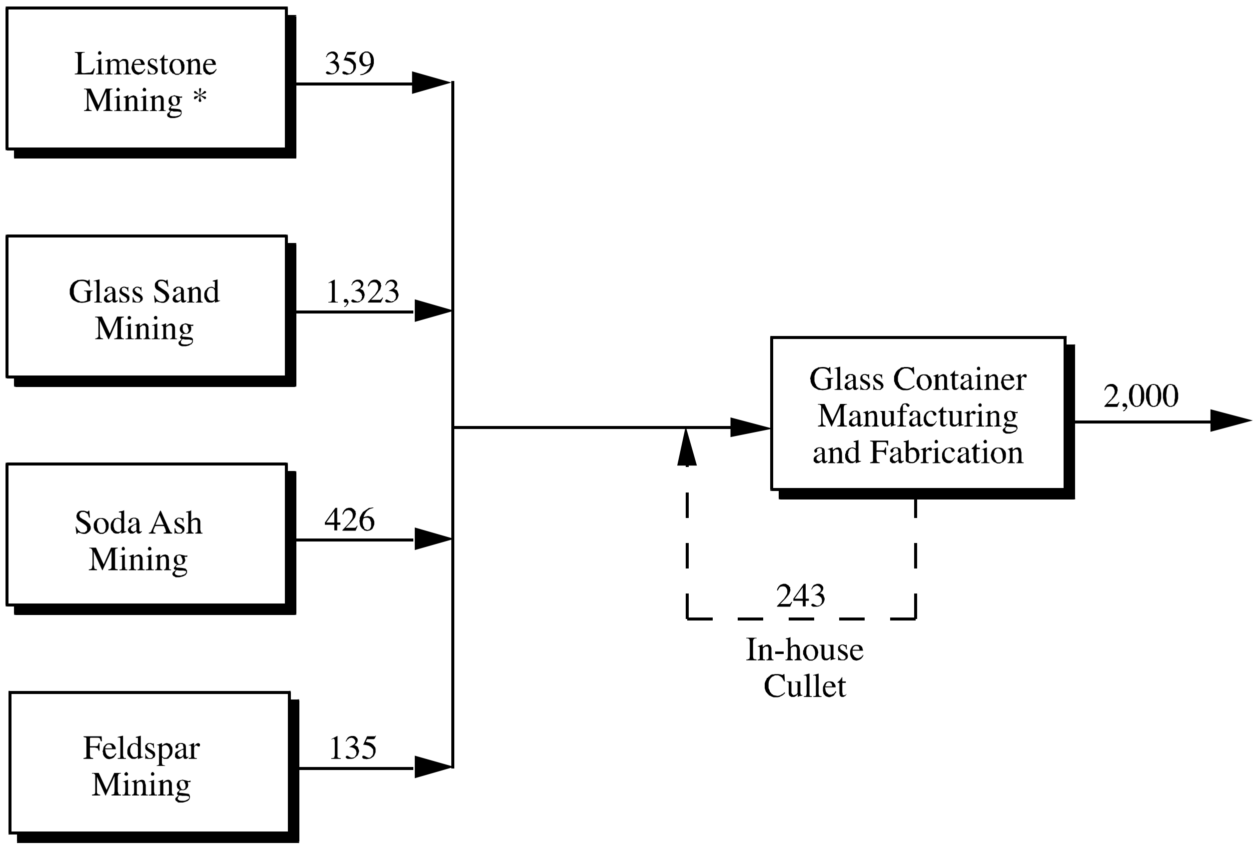
Materials flow diagrams for the production scenarios are presented and LCI data for 1 ton of each type of glass container system are presented. Data sources are provided in Section 4.3.

4.2 Overview

The following sections describe the manufacture of glass from raw materials extracted from the earth and from recycled glass containers. This analysis identifies the primary components for the glass container. The following steps for the production of glass containers are discussed.

- glass sand mining
- feldspar mining
- cullet (in-house)
- cullet (postconsumer)
- glass container manufacture.

Limestone mining is discussed in Section 3.0 and soda ash is discussed in Section 6.0. Materials flow diagrams and tables for glass container manufacturing are presented in Figures 4-1 through 4-3 and Tables 4-1 through 4-3. Table 4-1 provides the cradle-to-gate data for producing 1 ton of primary glass. The cradle-to-gate data for the production of 1 ton of 100 percent postconsumer secondary glass is are presented in Table 4-2. Table 4-3 presents the cradle-to-gate data for the production of 1 ton of composite 27.5 percent postconsumer/72.5 percent primary glass. Conceptual flow diagrams for mining and processing each of the raw materials are provided in Figures 4-4 through 4-7. The 100 percent cullet scenario was calculated to show the most extreme recycled content scenario. The calculations are done on the basis of closed-loop recycling in which post consumer glass is recovered and recycled back into secondary glass containers. However, it is not a realistic scenario for glass container manufacturing since 100 percent cullet is not typically used. This is because much of the recovered cullet is mixed-color and otherwise contaminated and is not suitable for recycling back into containers. Other applications are being developed for this cullet.



* Includes categories of slag, dolomite, and others.

Figure 4-1. Flow diagram for generating 1 ton of primary glass containers. (Numbers represent pounds of material.)

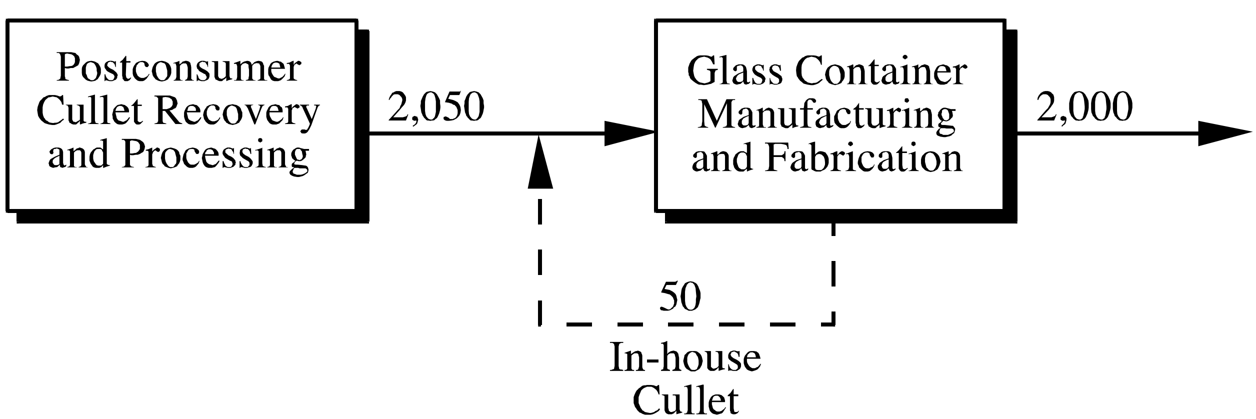
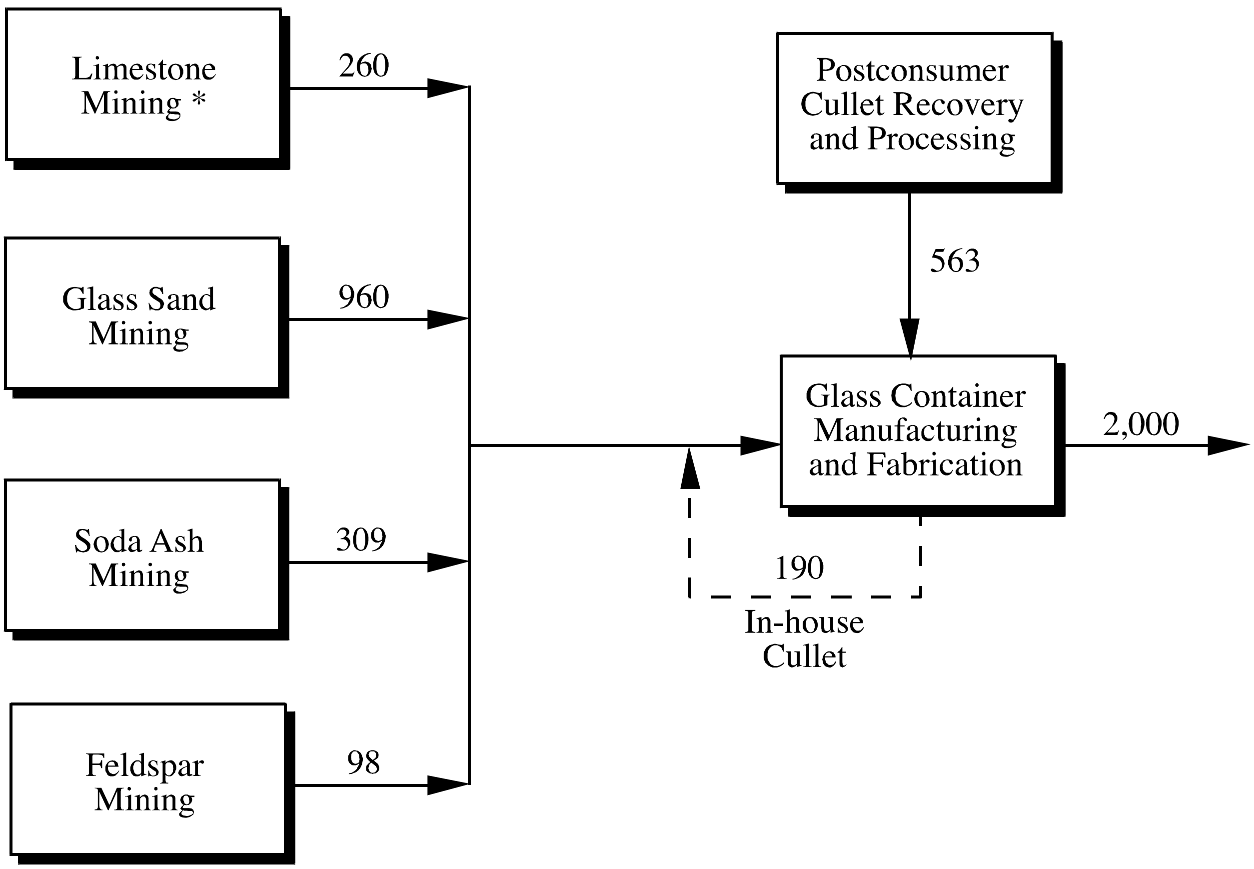


Figure 4-2. Flow diagram for generating 1 ton of 100 percent secondary glass containers. (Numbers represent pounds of material).



*Include categories of slag, dolomite, and others.

Figure 4-3. Flow diagram for generating 1 ton of composite glass containers containing 27.5 percent postconsumer cullet and 72.5 percent primary materials. (Numbers represent pounds of material.)

Table 4-1. Data for Production of 1 Ton of Primary Glass Containers

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	6.27E+01	7.00E-01	1.10E-02
Natural Gas	cu ft	4.58E+03	4.73E+00	1.00E-03
Coal	lb	4.12E+01	4.60E-01	1.10E-02
Distillate Oil	gal	4.50E-01	6.20E-02	1.40E-01
Residual Oil	gal	8.30E-02	1.20E-02	1.50E-01
Gasoline	gal	3.60E-02	4.50E-03	1.30E-01
Precombustion Process Energy				
Natural Gas	cu ft	4.97E+02	5.10E-01	1.00E-03
LPG	gal	1.70E-03	1.60E-04	9.60E-02
Coal	lb	3.64E+00	3.80E-02	1.00E-02
Distillate Oil	gal	2.30E-01	3.10E-02	1.40E-01
Residual Oil	gal	1.20E-01	1.80E-02	1.50E-01
Gasoline	gal	2.50E-01	3.10E-02	1.30E-01
Nuclear	lb U238	1.50E-05	1.50E-02	9.85E+02
Hydropower	Btu	1.81E+03	1.80E-03	1.00E-06
Other	Btu	1.31E+03	1.30E-03	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	2.57E+02		
Diesel	gal	3.03E+00	4.20E-01	1.40E-01
Rail	ton-miles	2.23E+02		
Diesel	gal	6.90E-01	9.60E-02	1.40E-01
Barge	ton-miles	4.67E+00		
Diesel	gal	9.30E-03	1.30E-03	1.40E-01
Residual Oil	gal	2.80E-03	4.20E-04	1.50E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	3.71E+01	3.80E-02	1.00E-03
LPG	gal	4.80E-03	4.60E-04	9.60E-02
Coal	lb	5.00E-01	5.20E-03	1.00E-02
Distillate Oil	gal	1.70E-02	2.40E-03	1.40E-01
Residual Oil	gal	1.00E-01	1.50E-02	1.50E-01
Gasoline	gal	4.70E-03	5.90E-04	1.30E-01
Nuclear	lb U238	2.10E-06	2.00E-03	9.85E+02
Hydropower	Btu	2.50E+02	2.50E-04	1.00E-06
Other	Btu	1.80E+02	1.80E-04	1.00E-06
Atmospheric Emissions				
Aldehydes	lb	2.50E-02		2.50E-02
Ammonia	lb	5.00E-04		5.00E-04
Antimony	lb	1.30E-06		1.30E-06
Arsenic	lb	7.40E-05		7.40E-05
Benzene	lb	1.60E-05		1.60E-05
Beryllium	lb	8.70E-06		8.70E-06
Cadmium	lb	2.70E-05		2.70E-05

(continued)

Table 4-1. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Carbon Dioxide-fossil	lb	1.27E+03	3.56E+02	9.18E+02
Carbon Dioxide-nonfossil	lb	1.30E-01		1.30E-01
Carbon Monoxide	lb	2.29E+00		2.29E+00
Carbon Tetrachloride	lb	3.20E-06		3.20E-06
Chlorine	lb	7.90E-06		7.90E-06
Chromium	lb	1.50E-04		1.50E-04
Cobalt	lb	3.70E-06		3.70E-06
Extractable Organic Matter	lb	2.90E-03		2.90E-03
Hydrocarbons	lb	2.95E+00		2.95E+00
Hydrochloric Acid	lb	5.50E-06		5.50E-06
Kerosene	lb	3.70E-05		3.70E-05
Lead	lb	1.00E-05		1.00E-05
Manganese	lb	2.40E-04		2.40E-04
Mercury	lb	2.60E-06		2.60E-06
Metals	lb	5.20E-05		5.20E-05
Methane	lb	1.84E+01		1.84E+01
Methylene Chloride	lb	5.90E-06		5.90E-06
Naphthalene	lb	1.40E-07		1.40E-07
Nickel	lb	1.40E-04		1.40E-04
Nitrogen Oxides	lb	3.46E+00		3.46E+00
Nitrous Oxide	lb	2.50E-03		2.50E-03
Other Organics	lb	3.60E-01		3.60E-01
Particulate	lb	7.45E+00	6.99E+00	4.60E-01
Perchloroethylene	lb	1.40E-06		1.40E-06
Phenols	lb	2.40E-06		2.40E-06
Selenium	lb	8.00E-03	8.00E-03	1.40E-06
Sulfur Oxides	lb	1.22E+01	1.00E+00	1.12E+01
Trichloroethylene	lb	1.40E-06		1.40E-06
Solid Wastes				
Ash	lb	6.26E+01		6.26E+01
Unspecified	lb	7.07E+01	7.07E+01	
Waterborne Wastes				
Acid	lb	4.10E-08		4.10E-08
Ammonia	lb	3.90E-04		3.90E-04
BOD	lb	1.50E-02		1.50E-02
Boron	lb	7.80E-03		7.80E-03
Cadmium	lb	6.60E-04		6.60E-04
Calcium	lb	3.20E-05		3.20E-05
Chloride	lb	6.60E-01		6.60E-01
Chromates	lb	3.40E-06		3.40E-06
Chromium	lb	6.60E-04		6.60E-04
COD	lb	2.00E-01		2.00E-01
Cyanide	lb	9.70E-07		9.70E-07
Dissolved Solids	lb	1.45E+01		1.45E+01
Fluorides	lb	1.50E-04		1.50E-04
Iron	lb	1.10E-02		1.10E-02
Lead	lb	7.20E-08		7.20E-08

(continued)

Table 4-1. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Manganese	lb	3.40E-05		3.40E-05
Mercury	lb	5.10E-08		5.10E-08
Metal Ion	lb	8.60E-04		8.60E-04
Nitrates	lb	1.40E-05		1.40E-05
Oil	lb	2.50E-01		2.50E-01
Other Organics	lb	4.30E-02		4.30E-02
Phenol	lb	2.80E-06		2.80E-06
Phosphates	lb	9.80E-04		9.80E-04
Sodium	lb	5.90E-05		5.90E-05
Sulfates	lb	5.30E-01		5.30E-01
Sulfuric Acid	lb	2.00E-03		2.00E-03
Suspended Solids	lb	1.59E+00	1.32E+00	2.70E-01
Zinc	lb	2.20E-04		2.20E-04

Source: Franklin Associates. 2000.

Table 4-2. Data for Production of 1 Ton of Secondary Glass Containers

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	2.10E+01	2.40E-01	1.10E-02
Natural Gas	cu ft	3.55E+03	3.66E+00	1.00E-03
Precombustion Process Energy				
Natural Gas	cu ft	3.73E+02	3.80E-01	1.00E-03
LPG	gal	5.90E-04	5.70E-05	9.60E-02
Coal	lb	2.24E+00	2.30E-02	1.00E-02
Distillate Oil	gal	1.20E-01	1.70E-02	1.40E-01
Residual Oil	gal	7.50E-02	1.10E-02	1.50E-01
Gasoline	gal	1.90E-01	2.40E-02	1.30E-01
Nuclear	lb U238	9.10E-06	9.00E-03	9.85E+02
Hydropower	Btu	1.12E+03	1.10E-03	1.00E-06
Other	Btu	8.10E+02	8.10E-04	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	1.80E+02		
Diesel	gal	2.12E+00	2.90E-01	1.40E-01
Rail	ton-miles	2.00E+01		
Diesel	gal	6.20E-02	8.60E-03	1.40E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	2.17E+01	2.20E-02	1.00E-03
LPG	gal	2.80E-03	2.70E-04	9.60E-02
Coal	lb	2.90E-01	3.10E-03	1.00E-02

(continued)

Table 4-2. (continued)

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Distillate Oil	gal	1.00E-02	1.40E-03	1.40E-01
Residual Oil	gal	5.90E-02	8.80E-03	1.50E-01
Gasoline	gal	2.70E-03	3.04E-02	1.30E-01
Nuclear	lb U238	1.20E-06	1.20E-03	9.85E+02
Hydropower	Btu	1.50E+02	1.50E-04	1.00E-06
Other	Btu	1.10E+02	1.10E-04	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions	lb			
Aldehydes	lb	1.40E-02		1.40E-02
Ammonia	lb	2.10E-04		2.10E-04
Antimony	lb	5.50E-07		5.50E-07
Arsenic	lb	1.40E-05		1.40E-05
Benzene	lb	6.20E-07		6.20E-07
Beryllium	lb	1.60E-06		1.60E-06
Cadmium	lb	5.90E-06		5.90E-06
Carbon Dioxide-fossil	lb	5.63E+02		5.63E+02
Carbon Dioxide-nonfossil	lb	7.90E-02		7.90E-02
Carbon Monoxide	lb	1.50E+00		1.50E+00
Carbon Tetrachloride	lb	1.30E-06		1.30E-06
Chlorine	lb	4.10E-06		4.10E-06
Chromium	lb	2.80E-05		2.80E-05
Cobalt	lb	1.60E-06		1.60E-06
Extractable Organic Matter	lb	7.30E-04		7.30E-04
Hydrocarbons	lb	2.14E+00		2.14E+00
Hydrochloric Acid	lb	2.90E-06		2.90E-06
Kerosene	lb	1.30E-05		1.30E-05
Lead	lb	2.30E-06		2.30E-06
Manganese	lb	4.50E-05		4.50E-05
Mercury	lb	6.00E-07		6.00E-07
Metals	lb	3.20E-05		3.20E-05
Methane	lb	1.38E+01		1.38E+01
Methylene Chloride	lb	2.10E-06		2.10E-06
Naphthalene	lb	8.80E-08		8.80E-08
Nickel	lb	4.00E-05		4.00E-05
Nitrogen Oxides	lb	2.13E+00		2.13E+00
Nitrous Oxide	lb	3.10E-04		3.10E-04
Other Organics	lb	2.50E-01		2.50E-01
Particulate	lb	3.60E-01	2.00E-01	1.60E-01
Perchloroethylene	lb	5.20E-07		5.20E-07
Phenols	lb	1.50E-06		1.50E-06
Selenium	lb	8.00E-03	8.00E-03	6.00E-07
Sulfur Oxides	lb	8.69E+00	1.00E+00	7.69E+00
Trichloroethylene	lb	5.10E-07		5.10E-07

(continued)

Table 4-2. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Solid Wastes				
Ash	lb	2.65E+01		2.65E+01
Unspecified	lb	4.51E+01	4.51E+01	
Waterborne Wastes				
Acid	lb	2.10E-08		2.10E-08
Ammonia	lb	2.60E-04		2.60E-04
BOD	lb	1.10E-02		1.10E-02
Boron	lb	1.60E-03		1.60E-03
Cadmium	lb	5.10E-04		5.10E-04
Calcium	lb	1.20E-05		1.20E-05
Chloride	lb	5.00E-01		5.00E-01
Chromates	lb	1.40E-06		1.40E-06
Chromium	lb	5.00E-04		5.00E-04
COD	lb	1.50E-01		1.50E-01
Cyanide	lb	7.40E-07		7.40E-07
Dissolved Solids	lb	1.11E+01		1.11E+01
Fluorides	lb	5.40E-05		5.40E-05
Iron	lb	2.00E-03		2.00E-03
Lead	lb	3.80E-08		3.80E-08
Manganese	lb	1.20E-05		1.20E-05
Mercury	lb	3.90E-08		3.90E-08
Metal Ion	lb	4.50E-04		4.50E-04
Nitrates	lb	5.10E-06		5.10E-06
Oil	lb	1.90E-01		1.90E-01
Other Organics	lb	3.20E-02		3.20E-02
Phenol	lb	1.50E-06		1.50E-06
Phosphates	lb	1.90E-04		1.90E-04
Sodium	lb	2.10E-05		2.10E-05
Sulfates	lb	3.90E-01		3.90E-01
Sulfuric Acid	lb	3.90E-04		3.90E-04
Suspended Solids	lb	2.00E-01		2.00E-01
Zinc	lb	1.70E-04		1.70E-04

Note: Materials collection, separation, and transport to a remanufacturing facility are handled by the collection, materials recovery facility, and transportation process models, respectively, of the decision support tool.

Source: Franklin Associates, 2000.

Table 4-3. Data for Production of 1 Ton of Composite (27.5 Percent Secondary/72.5 Percent Primary) Glass Containers

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	5.13E+01	5.70E-01	1.10E-02
Natural Gas	cu ft	4.30E+03	4.43E+00	1.00E-03
Coal	lb	2.99E+01	3.30E-01	1.10E-02
Distillate Oil	gal	3.30E-01	4.50E-02	1.40E-01
Residual Oil	gal	6.00E-02	9.00E-03	1.50E-01
Gasoline	gal	2.60E-02	3.30E-03	1.30E-01
Precombustion Process Energy				
Natural Gas	cu ft	4.63E+02	4.80E-01	1.00E-03
LPG	gal	1.40E-03	1.30E-04	9.60E-02
Coal	lb	3.25E+00	3.40E-02	1.00E-02
Distillate Oil	gal	2.00E-01	2.70E-02	1.40E-01
Residual Oil	gal	1.10E-01	1.60E-02	1.50E-01
Gasoline	gal	2.30E-01	2.90E-02	1.30E-01
Nuclear	lb U238	1.30E-05	1.30E-02	9.85E+02
Hydropower	Btu	1.62E+03	1.60E-03	1.00E-06
Other	Btu	1.18E+03	1.20E-03	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	2.36E+02		
Diesel	gal	2.78E+00	3.90E-01	1.40E-01
Rail	ton-miles	1.67E+02		
Diesel	gal	5.20E-01	7.20E-02	1.40E-01
Barge	ton-miles	3.38E+00		
Diesel	gal	6.80E-03	9.40E-04	1.40E-01
Residual Oil	gal	2.00E-03	3.00E-04	1.50E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	3.29E+01	3.40E-02	1.00E-03
LPG	gal	4.20E-03	4.00E-04	9.60E-02
Coal	lb	4.40E-01	4.60E-03	1.00E-02
Distillate Oil	gal	1.50E-02	2.10E-03	1.40E-01
Residual Oil	gal	8.90E-02	1.30E-02	1.50E-01
Gasoline	gal	4.20E-03	5.20E-04	1.30E-01
Nuclear	lb U238	1.80E-06	1.80E-03	9.85E+02
Hydropower	Btu	2.20E+02	2.20E-04	1.00E-06
Other	Btu	1.60E+02	1.60E-04	1.00E-06

(continued)

Table 4-3. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Aldehydes	lb	2.20E-02		2.20E-02
Ammonia	lb	4.20E-04		4.20E-04
Antimony	lb	1.10E-06		1.10E-06
Arsenic	lb	5.80E-05		5.80E-05
Benzene	lb	1.20E-05		1.20E-05
Beryllium	lb	6.70E-06		6.70E-06
Cadmium	lb	2.10E-05		2.10E-05
Carbon Dioxide-fossil	lb	1.08E+03	2.58E+02	8.21E+02
Carbon Dioxide-nonfossil	lb	1.10E-01		1.10E-01
Carbon Monoxide	lb	2.07E+00		2.07E+00
Carbon Tetrachloride	lb	2.60E-06		2.60E-06
Chlorine	lb	6.80E-06		6.80E-06
Chromium	lb	1.20E-04		1.20E-04
Cobalt	lb	3.10E-06		3.10E-06
Extractable Organic Matter	lb	2.30E-03		2.30E-03
Hydrocarbons	lb	2.73E+00		2.73E+00
Hydrochloric Acid	lb	4.80E-06		4.80E-06
Kerosene	lb	3.10E-05		3.10E-05
Lead	lb	8.00E-06		8.00E-06
Manganese	lb	1.90E-04		1.90E-04
Mercury	lb	2.00E-06		2.00E-06
Metals	lb	4.70E-05		4.70E-05
Methane	lb	1.71E+01		1.71E+01
Methylene Chloride	lb	4.80E-06		4.80E-06
Naphthalene	lb	1.30E-07		1.30E-07
Nickel	lb	1.10E-04		1.10E-04
Nitrogen Oxides	lb	3.09E+00		3.09E+00
Nitrous Oxide	lb	1.90E-03		1.90E-03
Other Organics	lb	3.30E-01		3.30E-01
Particulate	lb	5.50E+00	5.13E+00	3.70E-01
Perchloroethylene	lb	1.20E-06		1.20E-06
Phenols	lb	2.10E-06		2.10E-06
Selenium	lb	8.00E-03	8.00E-03	1.20E-06
Sulfur Oxides	lb	1.12E+01	1.00E+00	1.02E+01
Trichloroethylene	lb	1.10E-06		1.10E-06
Solid Wastes				
Unspecified	lb	6.37E+01	6.37E+01	
Ash	lb	5.27E+01		5.27E+01
Waterborne Wastes				
Acid	lb	3.50E-08		3.50E-08
Ammonia	lb	3.60E-04		3.60E-04
BOD	lb	1.40E-02		1.40E-02
Calcium	lb	2.60E-05		2.60E-05
Chloride	lb	6.20E-01		6.20E-01
Chromium	lb	6.20E-04		6.20E-04
COD	lb	1.90E-01		1.90E-01
Dissolved Solids	lb	1.35E+01		1.35E+01

(continued)

Table 4-3. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	1.20E-04		1.20E-04
Iron	lb	8.20E-03		8.20E-03
Lead	lb	6.30E-08		6.30E-08
Manganese	lb	2.80E-05		2.80E-05
Metal Ion	lb	7.50E-04		7.50E-04
Oil	lb	2.40E-01		2.40E-01
Phenol	lb	2.40E-06		2.40E-06
Sodium	lb	4.80E-05		4.80E-05
Sulfates	lb	4.90E-01		4.90E-01
Sulfuric Acid	lb	1.50E-03		1.50E-03
Suspended Solids	lb	1.21E+00	9.60E-01	2.50E-01
Zinc	lb	2.10E-04		2.10E-04

Note: Materials collection, separation, and transport to a remanufacturing facility are handled by the collection, materials recovery facility, and transportation process models, respectively, of the decision support tool.

Source: Franklin Associates, 2000

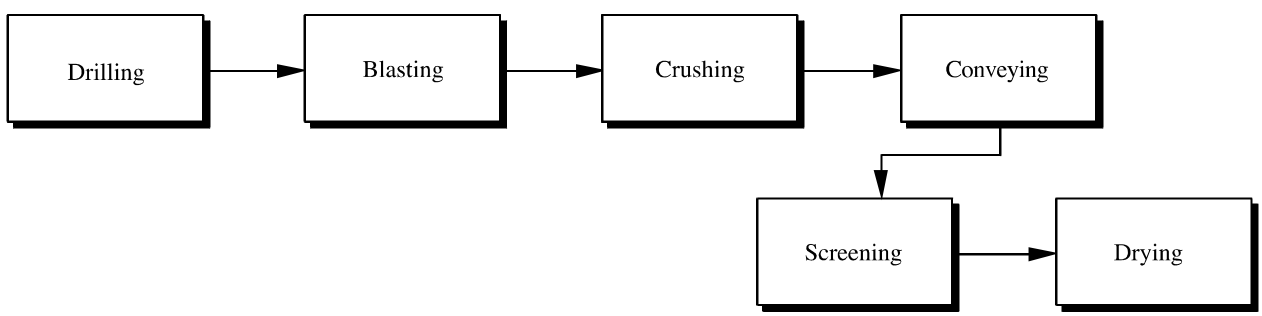


Figure 4-4. Process diagram for open pit limestone mining.

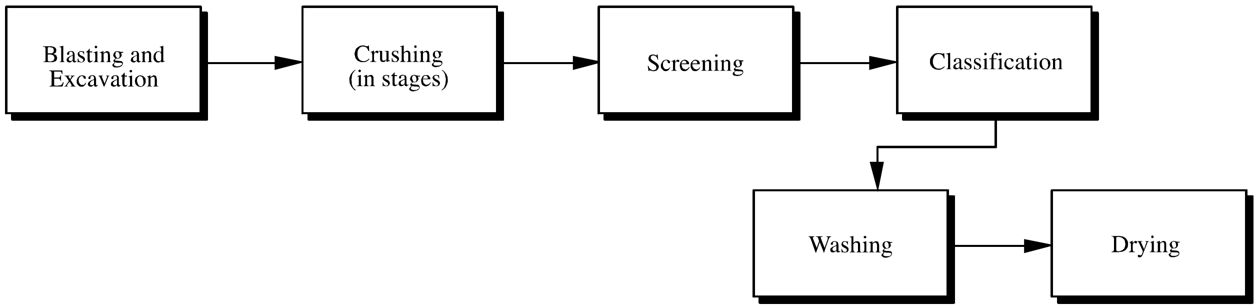


Figure 4-5. Process diagram for open pit sand mining.

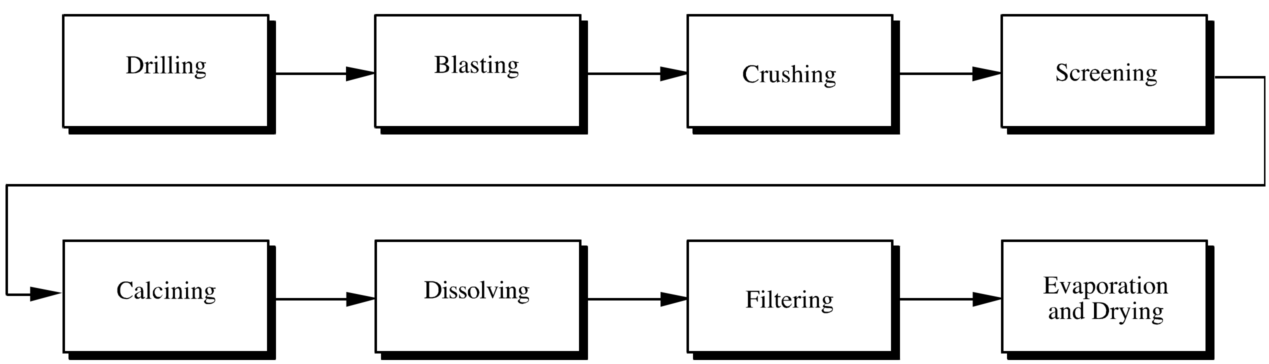


Figure 4-6. Process diagram for underground trona mining to produce soda ash.

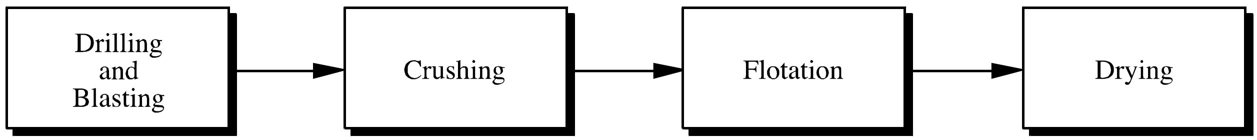


Figure 4-7. Process diagram for open pit mining and purifying of feldspar.

4.2.1 Glass Sand Mining

Glass sand, the predominant raw material for glass manufacture, is the source of almost all of the silicon dioxide present in the finished glass. Silicon dioxide accounts for approximately 70 percent by weight of finished glass.

Glass sand is a high-purity quartz sand with high silica content and typically less than 1 percent of iron oxide, chromium compounds, and alumina, calcium, or magnesium oxides. In general, U.S. consumption of glass sand is met by U.S. production, but some high-purity glass sand is imported. Glass sand deposits exist in New Jersey in the form of unconsolidated sand banks and as sandstone found in the Alleghenies and the Mississippi Valley. The east-west belt of states running from Pennsylvania to Illinois has rich resources of glass sand.

Mining operations vary depending on the nature of the deposit at each location. Open pit excavation and dredging are the two basic mining methods, each requiring a combination of many types of equipment including crushers, screens, washers, classifiers, and grinding mills. The LCI data used for this step are based on open pit (dry) excavation. Particulates are generated, especially during drying and packaging operations (U.S. Bureau of Mines, 1993). Waterborne suspended solids from clay are generated during washing operations (National Stone Association, 1991). A flow diagram is shown in Figure 4-5.

4.2.2 Feldspar Mining

Feldspar is an aluminum silicate mineral that is used in glass manufacture to obtain aluminum oxide. This oxide improves the stability and durability of the glass microstructure.

Feldspar is mined in seven states, but North Carolina produces the majority of the nation's total. It is mined primarily by open pit quarry techniques. The data in this report for feldspar mining are based on open pit mining. The deposit material is removed from the quarry and crushed. The crushed material is then sent through flotation processes to remove minerals, to lower the iron content, and to purify the feldspar to glass-grade products. A conceptual flow diagram is shown in Figure 4-7. The feldspar is used in the manufacture of glass in the form of a silica mixture or as a quartz.

The majority of the nonfeldspar material recovered with this mineral is sold as a coproduct. The remainder of the material is placed in settling ponds and used for land cover. Therefore, no solid waste is associated with the mining and processing of feldspar (personal communications, with Richard Phillips, N.C. Geological Survey Division of Natural Resources, February 1993, and R. Lee Astin, State of Georgia, February 1993). The air pollution generated is primarily particulates produced during the mining and crude ore processing.

4.2.3 Cullet (In-house)

In-house cullet is melted in a glass furnace in a manner similar to the handling of virgin inputs to a conventional batch operation. It is widely recognized that cullet melts at a lower temperature than virgin glass materials. Because the glass furnace accounts for a large portion of the manufacturing energy for the container, any energy savings in the furnace can significantly affect the total energy demand. Cullet generated in-house is returned to the furnace and accounts for approximately 8 percent of the total raw material requirements with an estimated 10 percent loss of material (Fredonia Group, Inc., 1990).

4.2.4 Cullet (Postconsumer)

Although in-house scrap has been the major source of cullet for many plants, mandatory deposit conditions and more active collection programs have increased the amount of postconsumer cullet recovered. Postconsumer cullet must be recovered, sorted, and crushed before it is added to the primary material. The data for these steps are **not included** in the tables since these steps are included as separate modules of the decision support tool. We do not have individual data for making glass with cullet versus primary materials; however, an industry source estimates that, for every 1 percent of cullet added to primary glass, there is a 0.4 percent reduction in energy requirements. This rule-of-thumb is considered true up to 50 percent cullet, then the energy reduction per 1 percent becomes 0.2 percent (personal communication, with Robert Towles, Owens-Illinois, Glass Manufacturing Division, September 1997.). All other parameters (transportation, emissions, etc.) are assumed to remain unchanged with the use of secondary material.

4.2.5 Glass Container Manufacture

Glass is manufactured by mixing glass sand, limestone, soda ash, feldspar, small amounts of other minerals, and cullet into a homogenous mixture, which is then fed to the melting furnace. This is typically a natural gas-fired, continuous melting, regenerative furnace. Fuel is conserved by using brick checkers to collect furnace exhaust gas heat, then using the hot checkers to preheat the furnace combustion air. The molten glass is directed to forming machines where it is cut into sections called gobs and shaped into containers. The container is finished, annealed, inspected, and then prepared for shipment.

The melting furnace contributes over 99 percent of the total air emissions from a glass plant, including particulates, sulfur oxides, and nitrogen oxides. Particulates and selenium, resulting from the volatilization of materials during the melting operation, combine with gases to form condensates. Sulfur oxides are produced from the decomposition of the sulfates in the feed and sulfur in the fuel. Nitrogen oxides form when nitrogen and oxygen react in the scrubbers. High-energy venturi scrubbers, baghouses, and electrostatic precipitators have been used to collect the particulates and sulfur oxides.

Most of the water used in glass manufacturing is used in coolers and boilers and is, therefore, not in direct contact with the glass. Water used in washing and quenching of the glass does come into direct contact and is sometimes contaminated with oil and grease from the forming machine lubricant; however, at this time, the cooling water is recirculated and not released to the environment. The suspended solids in this water are collected as solid waste.

4.2.6 Data Quality

This report provides cradle-to-gate LCI data for primary glass containers, 100 percent secondary glass containers, and 1996 average composite primary/secondary content glass containers. The data presented were calculated using Franklin Associates standard LCI methodology, which follows that of the Society of Environmental Toxicology and Chemistry (SETAC) and the ISO 14040 Standards. Table 4-4 summarizes data quality information for glass containers. The overall data quality for the glass systems is considered to be very good.

Table 4-4. Data Quality Information on Glass Containers

Data Quality Indicator	Primary, Secondary, and Composite Glass Containers
Geographical coverage	Unknown geography of plants surveyed
Time-related coverage	1996
Technological coverage	Average of a number of unknown types of furnaces at various stages in their lifetime
Precision	Exact precision of all furnaces is unknown as the data were averaged by the industry source
Completeness	Small number of data points compared to U.S. total
Consistency	Excellent
Representativeness	Average data set (unknown geographical and technological constraints)
Reproducibility	If a company has data, they should be able to reproduce numbers close to the results using the flow diagrams and methodological section. However, the data are not transparent.
Uncertainty/Limitations	Although Franklin Associates depended on an industry source for the data, it was reviewed by members of the Glass Packaging Institute and no adverse comments were made.
Data Quality Rating	The glass data are considered to be of very good quality.

4.3 References

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5.0 Summary LCI of Paper Products

5.1 Introduction

This chapter presents cradle-to-gate LCI data for the production of rolls of primary and secondary paper for the following paper categories.

- corrugated linerboard and medium
- newsprint
- office paper
- textbook paper
- magazine/third-class mail paper
- telephone book paper.

The LCI results include energy and emissions from raw materials extraction through production of 1 ton of paper rolls but do not include the production of specific paper products (e.g., corrugated boxes), use, or disposal portions of a traditional LCI. For each profile, process flow diagrams and information on production processes are provided, LCI results are presented, and data quality is discussed. Also, the secondary data sets do not include data for the collection, baling, and transport of discarded paper. Data for these activities is included in separate modules of the MSW-DST and are captured in any waste management strategy using recycling.

Data from Franklin Associates, Ltd. in-house data base were used to represent the LCI profiles for corrugated linerboard and medium and newsprint. Data from Environmental Defense Fund's (EDF) White Paper 10A (EDF, 1995c) were used to represent the LCI profiles for office, textbook, and magazine paper. Data from EDF White Paper 3 were used to model the LCI profile for telephone book paper (EDF, 1995a). Because different data sources were used, there may be methodological differences between the practitioners that limit the comparability of the data sets.

All EDF data were modified to include Franklin Associates' data on precombustion energy and related emissions for fuels and electricity used at the paper mills, as specified in the EDF report (1995b). The model for precombustion fuel energy and their environmental releases was developed by Franklin Associates (1998). The allocation procedures employed are specified by EDF (1995c); however, White Paper 10A did not address the allocation procedure used. All material and water consumption, as well as environmental emissions, are presented as mass in pounds (lb), volume in U.S. gallons (gal), gaseous volume in cubic feet (ft^3), and energy in British thermal units (Btu).

5.2 Rolls of Linerboard and Medium for Corrugated Containers

5.2.1 Introduction

This section contains LCI profiles for three different scenarios for producing rolls of linerboard and medium for corrugated containers: primary, composite, and secondary. Process descriptions for the production of rolls of linerboard and medium to be used as corrugated containers (boxes) are provided. Also included are energy and environmental data tables for 1 ton of primary, composite, and secondary linerboard and medium rolls. Data quality information is provided in Section 5.2.11.

5.2.2 Linerboard and Medium Rolls Production

Corrugated containers are made by combining three paperboard layers—a kraft or secondary paperboard inner liner and outer liner and a semichemical or secondary fluted paperboard medium—using a starch-based adhesive to adhere all three layers. The resulting containerboard is then cut, scored, and possibly printed to form the finished box. The starch adhesive and finished box are not included in this profile.

The following sections describe the steps for the manufacture of primary linerboard and medium for corrugated containers from raw materials extracted from the earth and from old corrugated containers (OCC). The actual manufacture of corrugated boxes and the starch adhesive used is not included in any data in this report. A primary corrugated box actually contains a minimum of 14.7 percent total secondary fiber content. Six percent of total secondary fiber content is from OCC, which requires a recovery rate of 11 percent to have enough secondary fiber, due losses during processing. This minimum recycled content is the total amount of OCC in the semichemical medium multiplied by the percent of that medium in the container. Primary linerboard is used in this scenario. The semichemical medium almost always has some OCC content in it, which is why there is some secondary content in the primary corrugated system.

A composite corrugated box contains 45 percent total secondary fiber content and 39 percent OCC content and has a recovery rate of 67 percent of the finished boxes (Franklin Associates, 1998). The total secondary content is the total amount of OCC and kraft clippings in the medium and liner multiplied by the percent of that medium or linerboard in the container. A 100 percent secondary corrugated box contains 100 percent secondary fiber content and has a recovery rate of 100 percent. We have assumed a maximum of 100 percent OCC only for the 100 percent secondary corrugated box as it is the best case scenario. It is possible for the box to contain a percentage of double-lined kraft (DLK) in the semichemical medium and secondary medium and linerboard.

The following steps in the production of linerboard and medium for corrugated boxes are discussed.

- roundwood harvesting
- wood residues production

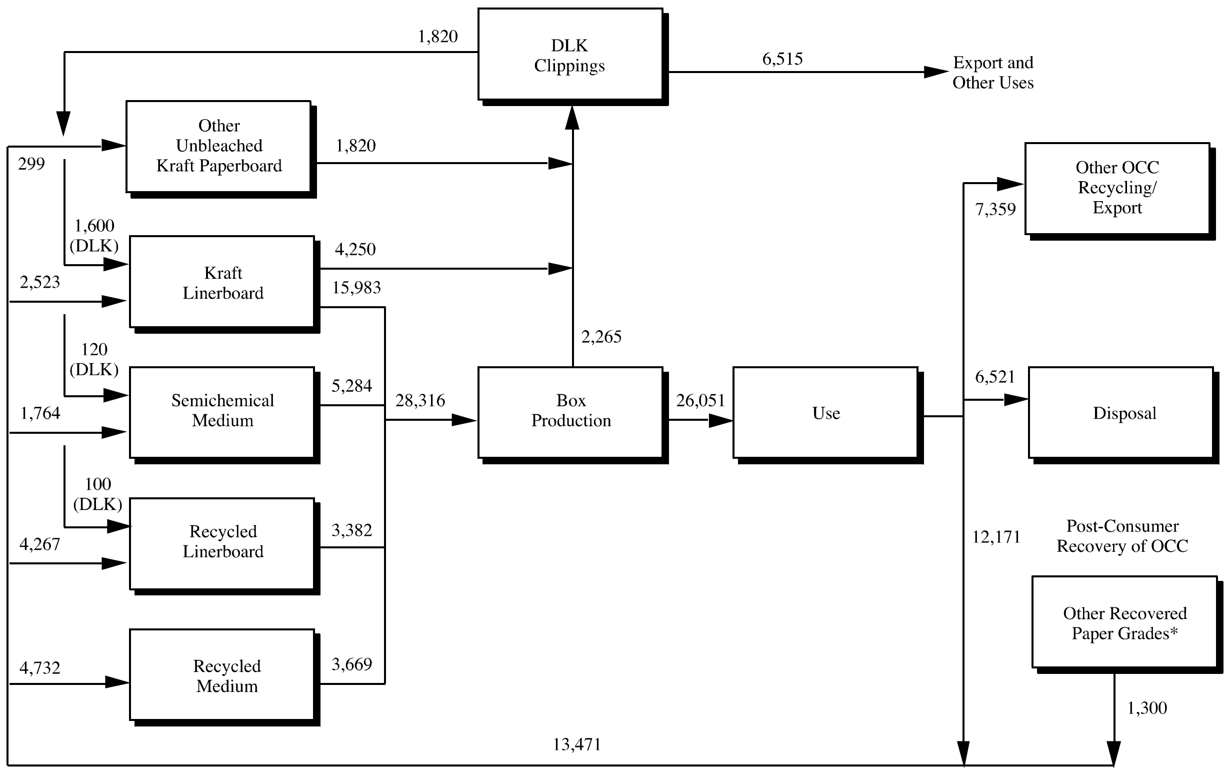
- sodium sulfate mining and processing
- soda ash production
- corn starch manufacture
- primary unbleached kraft paperboard production (linerboard)
- semichemical paperboard production (medium)
- secondary paperboard production (linerboard and medium).

Limestone mining and lime production data are presented in Section 3.0 and are not repeated here. Sulfur mining and production, sulfuric acid production, salt mining, and sodium hydroxide production are less than 1 percent of the system and have been omitted in this study.

For this profile, 1996 U.S. statistical data on linerboard and medium consumption at box plants and recovered paper consumption are used to construct a composite corrugated container (not including the container production). Specific corrugated containers will contain varying amounts of secondary fiber content (DLK and OCC).

Figure 5.2-1 shows the 1996 U.S. raw material and product flows of corrugated (AF&PA, 1997a, 1997b, 1997c, 1998; personal communication, Franklin Associates with paper industry sources; Fibre Box Association, 1997). The figure highlights industrial scrap, which are DLK clippings from converting operations, and postconsumer fiber flows into the four categories of paperboard used in making containerboard—kraft linerboard, semichemical medium, secondary linerboard, and secondary medium. The production amounts of the various paperboard categories have been adjusted from those reported by the paper industry to account for a small difference between the reported **production** of those paperboard categories and the **consumption** of paperboard at facilities making corrugated containers reported by another source. The box plant consumption amount is from the Fibre Box Association Annual Report, but production statistics for the containerboard are from Paper, Paperboard, and Wood Pulp by the American Forest and Paper Association (AF&PA). These numbers were different, so the difference between the consumption and production was split (using a straight average) between each type of linerboard and medium so that the production amount now equals the consumption amount.

The relevant characteristics of 1996 U.S. containerboard derived from Figure 5.2-1 are summarized in Table 5.2-1. Figure 5.2-2 is a flow diagram for producing 1 ton of primary fiber linerboard and medium for corrugated boxes. The flow diagram for producing 1 ton of composite linerboard and medium for corrugated boxes is presented in Figure 5.2-3. Figure 5.2-4 shows the flow diagram for producing 1 ton of secondary corrugated boxes. Table 5.2-2 presents the energy and emissions data for producing 1 ton of primary linerboard and medium for corrugated boxes. The data **exclude** OCC collection, baling, and transportation steps because these are included in separate modules of the MSW-DST. The energy and emissions data for producing 1 ton of secondary linerboard and medium for corrugated boxes are shown in Table 5.2-3. The energy and emissions data for producing 1 ton of composite linerboard and medium for corrugated boxes are shown in Table 5.2-4. Tables 5.2-2 through 5.2-4 include a CO_2 credit for the sequestration of CO_2 within the product and for the wood used as fuel. The wood used as fuel was calculated from the mass balance—input wood minus output product. The carbon content of wood is 86 percent. This credit in netted out of the nonfossil CO_2 value.



* Includes both pre/postconsumer fibers, but is predominantly postconsumer.

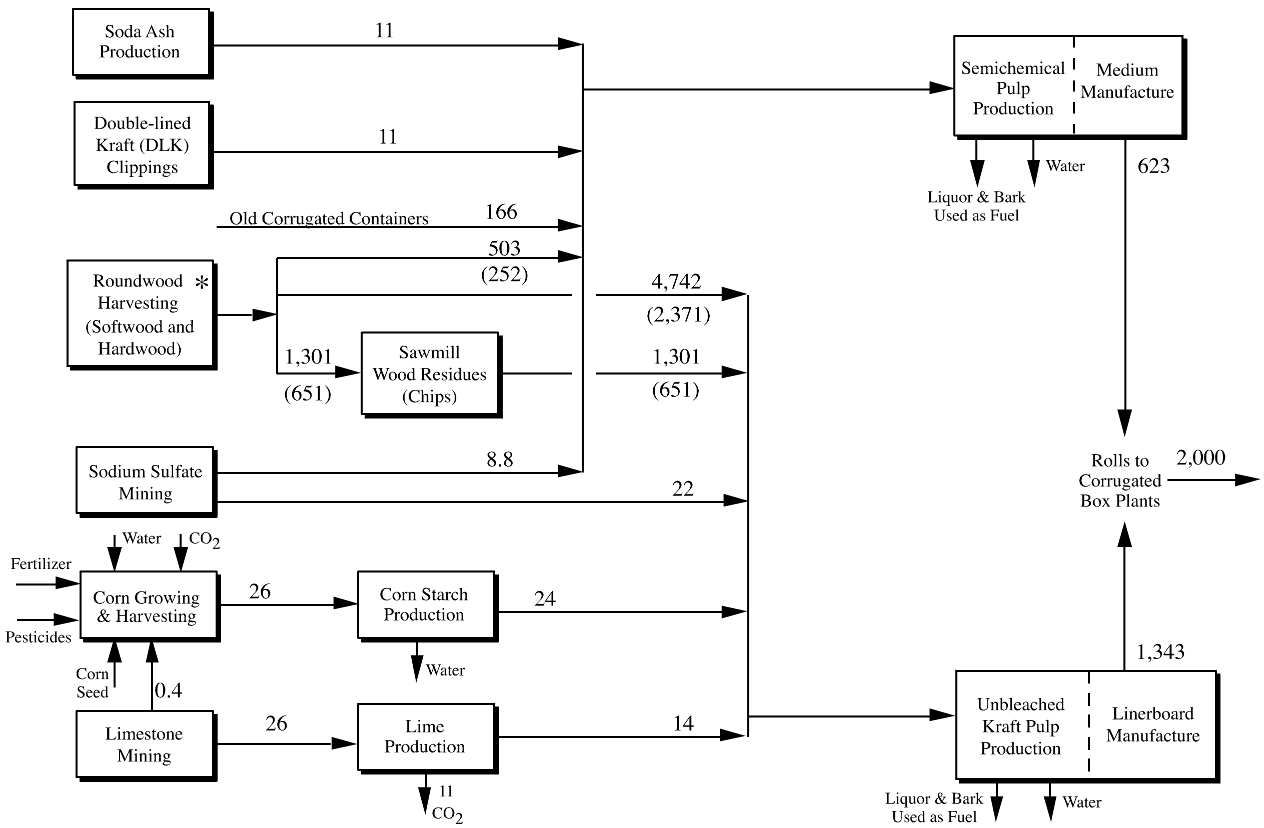
Figure 5.2-1. 1996 U.S. containerboard raw material and product flows (primary fiber sources are not shown.) All weights shown in thousand tons. The materials going into the flow boxes on the left side of the figure include only DLK, OCC, and other recovered fiber. Primary materials account for the remaining board produced. Weight data shown in this figure are derived from statistical sources referenced in Table 5.2-1.

Table 5.2-1. 1996 U.S. Composite Containerboard Characteristics

	Linerboard		Medium	
	Kraft Linerboard (%)	**Recycled Linerboard (%)**	**Semichemical Medium (%)**	**Recycled Medium (%)**
% of Fiber Weight of Containerboard	56.4	11.9	18.7	13.0
Recycled Content[a]	24.4	100	35.2	100
Industrial Scrap Content (DLK)	9.3	2.3	2.1	0.0
OCC Content[a]	15.1	97.7	33.1	100

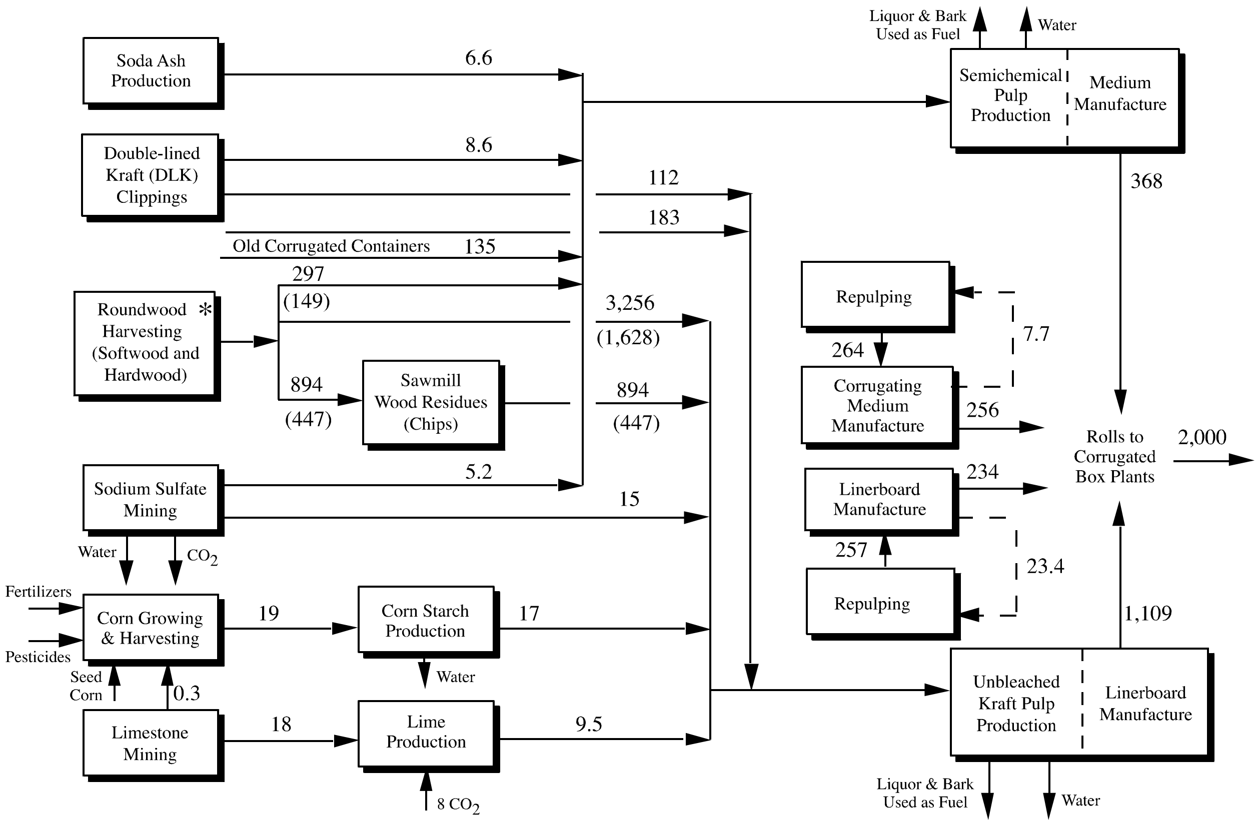
[a] Assumes a yield loss of approximately 7 percent. Industrial scrap (DLK) and OCC content values may not sum to the recycled content due to rounding.

Sources: Fibre Box Association, 1997; AF&PA, 1997a, 1997b, 1997c.



* Managed and/or unmanaged forest.

Figure 5.2-2. Process flow diagram for producing 1 ton of primary linerboard and medium rolls for corrugated containers. (The system presented here represents a minimum recycled content of 14.7 percent.) All weights shown in pounds. Numbers in parentheses represent bone-dry weight of wood.



*Managed and/or unmanaged forest.

Figure 5.2-3. Process flow diagram for producing 1 ton of composite linerboard and medium rolls for corrugated containers. (The composite system presented here represents an average secondary content of 45 percent.) All weights shown in pounds. Numbers in parentheses represent bone-dry weight of wood.

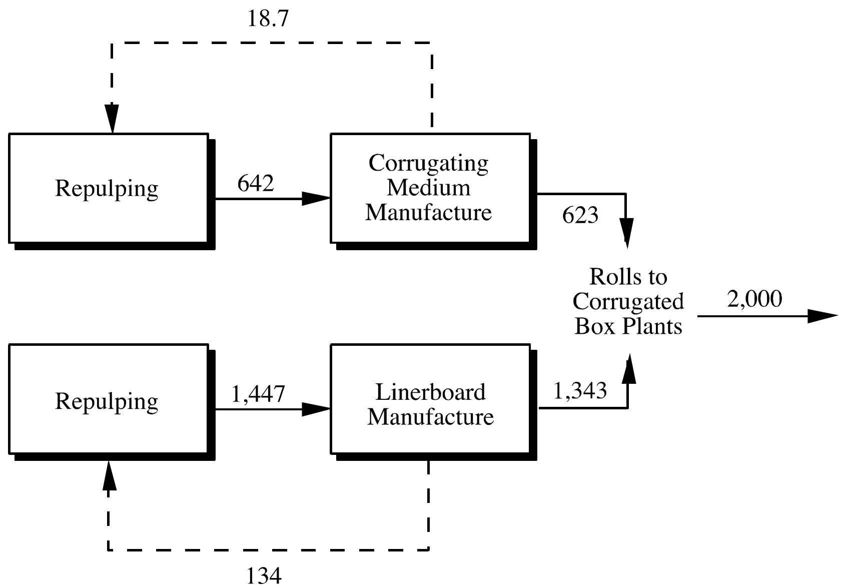


Figure 5.2-4. Process flow diagram for producing 1 ton of secondary linerboard and medium rolls for corrugated containers.

Table 5.2-2. Data for Production of 1 Ton of Primary Liner and Medium for Corrugated Containers

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	3.37E+02	3.74E+00	1.11E-02
Natural Gas	cu ft	1.76E+03	1.81E+00	1.03E-03
LPG	gal	1.80E-03	1.70E-04	9.55E-02
Coal	lb	3.75E+02	4.18E+00	1.12E-02
Distillate oil	gal	3.20E-02	4.50E-03	1.39E-01
Residual oil	gal	8.60E-01	1.30E-01	1.50E-01
Gasoline	gal	2.40E-03	3.10E-04	1.25E-01
Diesel	gal	2.17E+00	3.00E-01	1.39E-01
Wood	Btu	1.54E+07	1.54E+01	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	3.90E+01	4.00E-02	1.03E-03
Residual oil	gal	4.50E-02	7.00E-03	1.50E-01
Distillate oil	gal	1.30E-02	2.00E-03	1.39E-01
Gasoline	gal	1.60E-02	2.00E-03	1.25E-01
LPG	gal	1.30E-03	1.20E-04	9.55E-02
Coal	lb	3.30E-04	3.70E-06	1.12E-02
Nuclear	lb U238	1.40E+00	1.40E-03	9.85E+02
Hydropower	Btu	2.30E+02	2.00E-04	1.00E-06
Other	Btu	2.00E+02	2.00E-04	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	8.78E+02		
Diesel	gal	8.30E+00	1.14E+00	1.39E-01
Rail	ton-miles	4.20E+02		
Diesel	gal	1.01E+00	1.40E-01	1.39E-01
Barge	ton-miles	4.11E+00		
Diesel	gal	8.20E-03	1.10E-03	1.39E-01
Residual oil	gal	3.30E-03	4.90E-04	1.50E-01
Ocean freighter	ton-miles	1.40E-01		
Diesel	gal	1.40E+00	2.00E-06	1.39E-01
Residual	gal	3.00E-04	3.80E-05	1.50E-01
Pipeline-natural gas	ton-miles	1.90E-02		
Natural gas	cu ft	4.00E-02	4.60E-05	1.03E-03
Pipeline-petroleum products	ton-miles	9.00E-03		
Electricity	kWh	1.90E-04	2.10E-06	1.11E-02
Precombustion Transportation Energy				
Natural Gas	cu ft	1.37E+01	1.40E-02	1.03E-03
Residual oil	gal	2.00E-02	3.00E-03	1.50E-01
Distillate oil	gal	5.00E-03	6.00E-04	1.39E-01
Gasoline	gal	5.30E-03	7.00E-04	1.25E-01

(continued)

Table 5.2-2. (continued)

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
LPG	gal	6.00E-04	5.80E-05	9.55E-02
Coal	lb	6.50E-05	7.20E-07	1.12E-02
Nuclear	lb U238	4.80E-07	5.00E-04	9.85E+02
Hydropower	Btu	8.00E+01	7.70E-05	1.00E-06
Other	Btu	7.00E+01	6.80E-05	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	7.20E-06		7.20E-06
Aldehydes	lb	1.60E-02	1.60E-02	
Ammonia	lb	1.61E-01	1.58E-01	3.60E-03
Antimony	lb	6.40E-06		6.40E-06
Arsenic	lb	5.00E-04		5.00E-04
Benzene	lb	6.30E-03		6.30E-03
Beryllium	lb	4.10E-05		4.10E-05
Cadmium	lb	1.20E-04		1.20E-04
Carbon Dioxide-fossil	lb	1.98E+03	1.18E+01	1.97E+03
Carbon Dioxide-nonfossil (1)	lb	-3.78E+03	-3.78E+03	
Carbon Dioxide-nonfossil (2)	lb	1.18E+03		1.18E+03
Carbon Monoxide	lb	3.77E+01	1.12E+01	2.65E+01
Carbon Tetrachloride	lb	1.30E-05		1.30E-05
Chlorine	lb	1.30E-02		1.30E-02
Chromium	lb	7.70E-04		7.70E-04
Cobalt	lb	1.90E-05		1.90E-05
Dioxins	lb	4.00E-11		4.00E-11
Formaldehyde	lb	3.60E-05		3.60E-05
Hydrocarbons	lb	2.50E+00	9.00E-03	2.49E+00
Hydrochloric Acid	lb	3.60E-02		3.60E-02
Hydrogen Fluoride	lb	5.00E-03		5.00E-03
Kerosene	lb	1.80E-04		1.80E-04
Lead	lb	2.10E-03		2.10E-03
Manganese	lb	1.70E-02		1.70E-02
Mercury	lb	1.63E-04	1.40E-04	2.30E-05
Metals	lb	1.46E+00		1.46E+00
Methane	lb	3.65E+00		3.65E+00
Methylene Chloride	lb	3.20E-05		3.20E-05
Naphthalene	lb	4.00E-03		4.00E-03
Nickel	lb	1.60E-03		1.60E-03
Nitrogen Oxides	lb	2.02E+01	9.57E+00	1.06E+01
Nitrous Oxide	lb	1.90E-02		1.90E-02
N-Nitrosodimethylamine	lb	1.50E-06		1.50E-06
Other Aldehydes	lb	9.00E-02		9.00E-02

(continued)

Table 5.2-2. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Other Organics	lb	1.35E+00		1.35E+00
Particulate	lb	2.77E+01	2.46E+00	2.52E+01
Perchloroethylene	lb	6.90E-06		6.90E-06
Phenols	lb	6.60E-02		6.60E-02
Radionuclides	Ci	1.50E-04	1.50E-04	
Selenium	lb	5.50E-05		5.50E-05
Sulfur Oxides	lb	3.10E+01	1.62E+01	1.48E+01
Total Reduced Sulfur	lb	7.90E-02	7.90E-02	
Trichloroethylene	lb	6.80E-06		6.80E-06
Solid Wastes				
Ash	lb	4.24E+02		4.24E+02
Sludge	lb	5.06E+01	5.06E+01	
Unspecified	lb	6.23E+01	6.23E+01	
Waterborne Wastes				
Acid	lb	2.50E-03	2.50E-03	1.10E-07
Aluminum	lb	1.50E-01	1.50E-01	
Ammonia	lb	5.86E-02	5.80E-02	5.90E-04
BOD	lb	3.82E+00	3.81E+00	9.00E-03
Boron	lb	5.30E-02		5.30E-02
Cadmium	lb	3.50E-04		3.50E-04
Calcium	lb	1.50E-04		1.50E-04
Chloride	lb	3.50E-01		3.50E-01
Chromates	lb	1.50E-05		1.50E-05
Chromium	lb	3.50E-04	1.10E-08	3.50E-04
COD	lb	2.19E+00	2.08E+00	1.10E-01
Cyanide	lb	6.02E-07	9.20E-08	5.10E-07
Dissolved Solids	lb	7.78E+00	8.00E-02	7.70E+00
Fluorides	lb	7.00E-04		7.00E-04
Iron	lb	7.20E-02	3.30E-05	7.20E-02
Lead	lb	2.00E-07		2.00E-07
Manganese	lb	4.50E-02		4.50E-02
Mercury	lb	2.70E-08		2.70E-08
Metal Ion	lb	2.40E-03		2.40E-03
Nitrates	lb	3.37E-03	3.30E-03	6.60E-05
Nitrogen	lb	3.10E-02	3.10E-02	
Oil	lb	1.40E-01	5.80E-05	1.40E-01
Other Organics	lb	3.20E-02		3.20E-02
Phenol	lb	8.04E-06	2.40E-07	7.80E-06
Phosphates	lb	6.61E+01	1.30E-01	6.60E+01
Phosphorus	lb	8.80E-02	8.80E-02	
Sodium	lb	2.80E-04		2.80E-04

(continued)

Table 5.2-2. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Sulfates	lb	3.50E-01		3.50E-01
Sulfides	lb	1.60E-05	1.60E-05	
Sulfuric Acid	lb	1.30E-02		1.30E-02
Suspended Solids	lb	6.00E+00	4.98E+00	1.02E+00
Zinc	lb	2.20E+00	2.20E+00	1.20E-04

* Liner and medium for corrugated boxes are always manufactured with some secondary content. The primary data presented here represent the minimum possible secondary content of 14.7% and recycling level of 10.5%.

(1) Carbon dioxide credit was given for the ton of linerboard and medium produced (wood contains 86% carbon content and 2.2 lb CO_2/1 lb wood product).

(2) Carbon dioxide credit was given for the difference between the input wood and output product. It is possible that extra purchased wood products are used in the biomass furnace which are not accounted for in this calculation. (Wood contains 86% carbon content and 2.2 lb CO_2/lb wood burned.)

Source: Franklin Associates, 2000.

Table 5.2-3. Data for Production of 1 Ton of Secondary Liner and Medium for Corrugated Containers

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	5.72E+02	6.37E+00	1.11E-02
Natural Gas	cu ft	1.04E+03	1.08E+00	1.03E-03
LPG	gal	5.70E-02	5.40E-03	9.55E-02
Coal	lb	4.33E+02	4.83E+00	1.12E-02
Distillate oil	gal	2.80E-02	3.80E-03	1.39E-01
Residual oil	gal	4.70E-01	7.10E-02	1.50E-01
Diesel	gal	2.60E-01	3.50E-02	1.39E-01
Precombustion Process Energy				
Natural Gas	cu ft	3.50E+01	4.00E-02	1.03E-03
Residual oil	gal	4.70E-02	7.00E-03	1.50E-01
Distillate oil	gal	1.20E-02	2.00E-03	1.39E-01
Gasoline	gal	1.40E-02	1.80E-03	1.25E-01
LPG	gal	1.40E-03	1.40E-04	9.55E-02
Coal	lb	3.53E-02	4.10E-04	1.16E-02
Nuclear	lb U238	1.50E-06	1.40E-03	9.85E+02
Hydropower	Btu	2.30E+02	2.00E-04	1.00E-06
Other	Btu	2.10E+02	2.10E-04	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	5.47E+02		
Diesel	gal	5.14E+00	7.10E-01	1.39E-01
Rail	ton-miles	2.26E+02		
Diesel	gal	5.40E-01	7.50E-01	1.39E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	8.40E+00	9.00E-03	1.03E-03
Residual oil	gal	1.20E-02	2.00E-03	1.50E-01
Distillate oil	gal	3.00E-03	4.00E-04	1.39E-01
Gasoline	gal	3.30E-03	4.10E-04	1.25E-01
LPG	gal	4.00E-04	3.60E-05	9.55E-02
Coal	lb	4.00E-05	4.50E-07	1.12E-02
Nuclear	lb U238	3.00E-07	3.70E-04	9.85E+02
Hydropower	Btu	5.00E+01	4.80E-05	1.00E-06
Other	Btu	4.00E+01	4.20E-05	1.00E-06

(continued)

Table 5.2-3. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	1.20E-05		1.20E-05
Ammonia	lb	5.50E-03		5.50E-03
Antimony	lb	7.20E-06		7.20E-06
Arsenic	lb	4.10E-04		4.10E-04
Benzene	lb	1.60E-04		1.60E-04
Beryllium	lb	4.80E-05		4.80E-05
Cadmium	lb	1.30E-04		1.30E-04
Carbon Dioxide-fossil	lb	2.22E+03		2.22E+03
Carbon Dioxide-nonfossil	lb	5.00E-01		5.00E-01
Carbon Monoxide	lb	2.35E+00		2.35E+00
Carbon Tetrachloride	lb	2.20E-05		2.20E-05
Chromium	lb	8.10E-04		8.10E-04
Clorine	lb	1.40E-05		1.40E-05
Cobalt	lb	2.20E-05		2.20E-05
Dioxins	lb	6.70E-11		6.70E-11
Formaldehyde	lb	6.00E-05		6.00E-05
Hydrocarbons	lb	1.84E+00		1.84E+00
Hydrochloric Acid	lb	6.10E-02		6.10E-02
Hydrogen Fluoride	lb	8.40E-03		8.40E-03
Kerosene	lb	3.00E-04		3.00E-04
Lead	lb	8.90E-05		8.90E-05
Manganese	lb	1.40E-03		1.40E-03
Mercury	lb	3.30E-05		3.30E-05
Metals	lb	2.00E-04		2.00E-04
Methane	lb	4.42E+00		4.42E+00
Methylene Chloride	lb	5.30E-05		5.30E-05
Naphthalene	lb	1.10E-06		1.10E-06
Nickel	lb	6.90E-04		6.90E-04
Nitrogen Oxides	lb	7.57E+00		7.57E+00
Nitrous Oxide	lb	2.40E-02		2.40E-02
n-Nitrosodimethylamine	lb	2.50E-06		2.50E-06
Other Aldehydes	lb	4.00E-02		4.00E-02
Other Organics	lb	6.10E-01		6.10E-01
Particulate	lb	2.61E+00		2.61E+00
Perchloroethylene	lb	1.20E-05		1.20E-05
Phenols	lb	3.60E-05		3.60E-05
Radionuclides	Ci	2.60E-04		2.60E-04
Selenium	lb	8.80E-05		8.80E-05
Sulfur Oxides	lb	1.66E+01		1.66E+01
Trichloroethylene	lb	1.10E-05		1.10E-05
Solid Waste				
Ash	lb	3.54E+02		3.54E+02

(continued)

Table 5.2-3. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Sludge	lb	4.18E+01	4.18E+01	
Unspecified	lb	8.06E+01	8.06E+01	
Waterborne Wastes				
Acid	lb	7.00E-08		7.00E-08
Aluminum	lb	2.00E-01	2.00E-01	
Ammonia	lb	1.07E-02	1.00E-02	6.80E-04
BOD	lb	5.97E+00	5.96E+00	7.00E-03
Boron	lb	7.00E-02		7.00E-02
Cadmium	lb	3.00E-04		3.00E-04
Calcium	lb	2.60E-04		2.60E-04
Chloride	lb	3.00E-01		3.00E-01
Chromates	lb	1.60E-05		1.60E-05
Chromium	lb	3.00E-04		3.00E-04
COD	lb	9.45E+00	9.36E+00	9.00E-02
Cyanide	lb	4.30E-07		4.30E-07
Dissolved Solids	lb	7.13E+00	5.90E-01	6.54E+00
Fluorides	lb	1.20E-03		1.20E-03
Iron	lb	4.90E-01	3.90E-01	1.00E-01
Lead	lb	1.20E-07		1.20E-07
Manganese	lb	6.00E-02		6.00E-02
Mercury	lb	2.30E-08		2.30E-08
Metal Ion	lb	1.50E-03		1.50E-03
Nitrates	lb	1.10E-05	1.10E-05	
Oil	lb	5.10E-01	3.90E-01	1.20E-01
Other Organics	lb	3.20E-02		3.20E-02
Phenol	lb	4.70E-03	4.70E-03	4.80E-06
Phosphates	lb	1.39E-01	1.30E-01	8.80E-03
Sodium	lb	4.70E-04		4.70E-04
Sulfates	lb	3.80E-01		3.80E-01
Sulfides	lb	3.90E-01	3.90E-01	
Sulfuric Acid	lb	1.80E-02		1.80E-02
Suspended Solids	lb	7.21E+00	5.92E+00	1.29E+00
Zinc	lb	5.60E-03	5.50E-03	1.00E-04

Note: Materials collection, separation, and transport to a remanufacturing facility are handled by the collection, materials recovery facility, and transportation process models, respectively, of the MSW-DST.

Source: Franklin Associates, 2000.

5.2.3 Roundwood Harvesting

The technique of harvesting trees has become a highly mechanized process. Typically, trees are harvested by using a feller buncher to fell the wood and then pulling the wood to the roadside where branches are removed and the wood is cut to manageable lengths for loading on trucks and delivery to the mill. After the wood is cleared from the forest, a variety of site preparations are used. On some sites, debris is manually removed from the forest before replanting, while other sites are left to grow back naturally. Some harvested sites are burned to remove any remaining debris before replanting. Emissions do result from clearing the site by burning, but this practice occurs infrequently compared to the mass of trees harvested. It is assumed that these emissions are negligible for this study (Franklin Associates, 2000).

In this study, trees harvested specifically for wood pulp production account for 53 percent of the wood delivered to the paper mill. This amount varies for each paper mill. The remainder comes from wood residues (sawdust and chips) generated by lumber production or other wood processing operations.

Roundwood debarking is generally done at the pulp mill or at a forest products site. The bark from logs is removed to abate any chances of it interfering with the cooking process, which in turn would reduce the quality of the pulp.

5.2.4 Wood Residues Production

Wood residues used in the production of paper are either mill residues generated by lumber mills or other wood processing operations or forest residues. It is estimated that forest product mill residues make up about 90 percent of the wood residues used by paper mills, and forest residues make up the remaining 10 percent.

The roundwood is sorted by diameter and then sent to a debarker. Depending on the kind of tree, its age, and the growth conditions, the bark of the tree might account for 10 to 20 percent of the trunk.

The higher the quality of pulp required, the lower the content of bark that can be tolerated. Bark has a higher content of lignin and extractives and a much lower content of cellulose than wood. The presence of bark leads to an increased consumption of cooking chemicals and reduces not only pulp yield, but also the technological properties and the brightness of the pulp.

Drum barking is the most frequently used debarking process in the pulp industry today. In this process, small, short logs are continuously fed into a slightly inclined, horizontal-rotating drum. The bark is sheared off by friction between the logs and the inner walls of the drum. The bark falls through slots in the drum wall onto a conveyor belt below the drum. Water spraying improves debarking, but this process is not employed today because the resulting wastewater is polluted, and the heating value of the bark is reduced by the increased moisture content.

Table 5.2-4. Data for Production of 1 Ton of Composite (45 Percent Secondary/55 Percent Primary) Liner and Medium for Corrugated Containers

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	4.58E+02	5.09E+00	1.11E-02
Natural gas	cu ft	4.54E+03	1.58E+00	1.03E-03
LPG	gal	3.00E-02	2.90E-03	9.55E-02
Coal	lb	4.36E+02	4.87E+00	1.12E-02
Distillate oil	gal	3.10E-02	4.30E-03	1.39E-01
Residual oil	gal	7.20E-01	1.10E-01	1.50E-01
Gasoline	gal	1.30E-03	1.60E-04	1.25E-01
Diesel	gal	1.37E+00	1.90E-01	1.39E-01
Wood	Btu	8.61E+06	8.61E+00	1.00E-06
Precombustion Process Energy				
Natural gas	cu ft	8.79E+01	9.10E-02	1.03E-03
Residual oil	gal	8.70E-02	1.30E-02	1.50E-01
Distillate oil	gal	1.90E-01	2.60E-02	1.39E-01
Gasoline	gal	4.40E-02	5.50E-03	1.25E-01
LPG	gal	2.00E-03	1.90E-04	9.55E-02
Coal	lb	9.10E-02	1.00E-03	1.16E-02
Nuclear	lb U238	1.00E-05	1.00E-02	9.85E+02
Hydropower	Btu	1.61E+03	1.60E-03	1.00E-06
Other	Btu	1.42E+03	1.40E-03	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	7.72E+02		
Diesel	gal	7.26E+00	1.01E+00	1.39E-01
Rail	ton-miles	3.31E+02		
Diesel	gal	7.90E-01	1.10E-01	1.39E-01
Barge	ton-miles	1.89E+00		
Diesel	gal	3.80E-03	5.20E-04	1.39E-01
Residual oil	gal	1.50E-03	2.30E-04	1.50E-01
Ocean freighter	ton-miles	8.40E-02		
Diesel	gal	8.40E-06	1.20E-06	1.39E-01
Residual	gal	1.50E-04	2.30E-05	1.50E-01
Pipeline-natural gas	ton-miles	1.10E-02		
Natural gas	cu ft	2.60E-02	2.70E-05	1.03E-03
Pipeline-petroleum products	ton-miles	5.00E-03		
Electricity	kWh	1.10E-04	1.20E-06	1.11E-02
Precombustion Transportation Energy				
Natural gas	cu ft	2.28E+01	2.40E-02	1.03E-03
Residual oil	gal	6.90E-02	1.00E-02	1.50E-01
Distillate oil	gal	9.30E-03	1.30E-03	1.39E-01
Gasoline	gal	5.40E-03	6.70E-04	1.25E-01

(continued)

Table 5.2-4. (continued)

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
LPG	gal	2.20E-03	2.10E-04	9.55E-02
Coal	lb	1.40E-04	1.60E-06	1.12E-02
Nuclear	lb U238	1.10E-06	1.00E-03	9.85E+02
Hydropower	Btu	1.70E+02	1.70E-04	1.00E-06
Other	Btu	1.50E+02	1.50E-04	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	9.70E-06		9.70E-06
Aldehydes	lb	9.50E-03	9.50E-03	
Ammonia	lb	7.66E-02	7.20E-02	4.60E-03
Antimony	lb	7.00E-06		7.00E-06
Arsenic	lb	4.90E-04		4.90E-04
Benzene	lb	3.60E-03		3.60E-03
Beryllium	lb	4.80E-05		4.80E-05
Cadmium	lb	1.30E-04		1.30E-04
Carbon Dioxide-fossil	lb	2.22E+03	6.76E+00	2.22E+03
Carbon Dioxide-nonfossil (1)	lb	-2.79E+03	-2.79E+03	
Carbon Dioxide-nonfossil (2)	lb	5.94E+02		5.94E+02
Carbon Monoxide	lb	2.25E+01	6.49E+00	1.60E+01
Carbon Tetrachloride	lb	1.80E-05		1.80E-05
Chlorine	lb	2.00E-10	2.00E-10	
Chromium	lb	8.50E-04		8.50E-04
Clorine	lb	7.50E-03		7.50E-03
Cobalt	lb	2.10E-05		2.10E-05
Dioxins	lb	5.40E-11		5.40E-11
Formaldehyde	lb	4.80E+00		4.80E+00
Hydrocarbons	lb	2.32E+00	5.20E-03	2.31E+00
Hydrochloric Acid	lb	4.90E-02	4.00E-11	4.90E-02
Hydrogen Fluoride	lb	6.80E-03		6.80E-03
Kerosene	lb	2.40E-04		2.40E-04
Lead	lb	1.57E-03	3.70E-04	1.20E-03
Manganese	lb	1.00E-02		1.00E-02
Mercury	lb	1.08E-04	7.90E-05	2.90E-05
Metals	lb	8.20E-01		8.20E-01
Methane	lb	4.26E+00		4.26E+00
Methylene Chloride	lb	4.30E-05		4.30E-05
Naphthalene	lb	2.20E-03		2.20E-03
Nickel	lb	1.20E-03		1.20E-03
Nitrogen Oxides	lb	1.53E+01	5.57E+00	9.69E+00

(continued)

Table 5.2-4. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Nitrous Oxide	lb	2.30E-02		2.30E-02
n-Nitrosodimethylamine	lb	2.10E-06		2.10E-06
Other Aldehydes	lb	7.20E-02		7.20E-02
Other Organics	lb	1.07E+00		1.07E+00
Particulate	lb	4.16E+00	1.44E+00	2.72E+00
Perchloroethylene	lb	9.30E-06		9.30E-06
Phenols	lb	3.70E-02		3.70E-02
Radionuclides	Ci	2.10E-03		2.10E-03
Selenium	lb	7.20E-05		7.20E-05
Sulfur Oxides	lb	2.60E+01	9.41E+00	1.66E+01
Total Reduced Sulfur	lb	4.60E-02	4.60E-02	
Trichloroethylene	lb	9.20E-06		9.20E-06
Solid Waste				
Ash	lb	4.15E+02		4.15E+02
Sludge	lb	4.48E+01	4.48E+01	
Unspecified	lb	8.13E+01	8.13E+01	
Waterborne Wastes				
Acid	lb	1.40E-03	1.40E-03	9.90E-08
Aluminum	lb	1.90E-01	1.90E-01	
Ammonia	lb	3.97E-02	3.90E-02	6.50E-04
BOD	lb	4.96E+02	4.96E+02	8.50E-03
Boron	lb	6.50E-02		6.50E-02
Cadmium	lb	3.40E-04		3.40E-04
Calcium	lb	2.10E-04		2.10E-04
Chloride	lb	3.50E-01		3.50E-01
Chromates	lb	1.60E-05		1.60E-05
Chromium	lb	3.40E-04	6.70E-09	3.40E-04
COD	lb	1.65E+01	1.64E+01	1.10E-01
Cyanide	lb	5.54E-07	5.40E-08	5.00E-07
Dissolved Solids	lb	7.92E+00	3.50E-01	7.57E+00
Fluorides	lb	9.50E+00		9.50E+00
Iron	lb	2.89E-01	2.00E-01	8.90E-02
Lead	lb	1.80E-04	1.00E-12	1.80E-04
Manganese	lb	5.50E-02		5.50E-02
Mercury	lb	2.60E-08	7.30E-13	2.60E-08
Metal Ion	lb	2.10E-03	6.20E-09	2.10E-03
Nickel	lb	5.20E-13	5.20E-13	
Nitrates	lb	9.02E+00	1.90E-02	9.00E+00
Nitrogen	lb	1.80E-02	1.80E-02	
Oil	lb	3.40E-01	2.00E-01	1.40E-01
Other Organics	lb	3.40E-02		3.40E-02

(continued)

Table 5.2-4. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Phenol	lb	2.41E-03	2.40E-03	6.80E-06
Phosphates	lb	1.48E-01	1.40E-01	8.10E-03
Phosphorus	lb	5.10E-02	5.10E-02	
Sodium	lb	3.80E-04		3.80E-04
Sulfates	lb	3.80E-01		3.80E-01
Sulfides	lb	2.00E-01	2.00E-01	
Sulfuric Acid	lb	1.60E-02		1.60E-02
Suspended Solids	lb	6.80E+00	5.58E+00	1.22E+00
Zinc	lb	2.92E-03	2.80E-03	1.20E-04

*Liner and medium for corrugated boxes may contain some recycled content. The composite data presented here represent the average secondary content of 45% and a recycling level of 67%.

(1) Carbon dioxide credit was given for the ton of linerboard and medium produced (Wood contains 86% carbon content and 2.2 lb CO_2/lb wood product).

(2) Carbon dioxide credit was given for the difference between the input wood and output product. It is possible that extra purchased wood products are used in the biomass furnace which are not accounted for in this calculation. (Wood contains 86% carbon content and 2.2 lb CO_2/lb wood burned.)

Source: Franklin Associates, 2000.

Drum barkers have diameters of 3 to 5 meters, lengths of up to 30 meters, and rotate at 5 to 10 rpm. Since the wood is subjected to intense mechanical stress in the drum, losses occur, but these do not exceed 3 percent for normal wood.

For large-diameter logs, ring barkers are normally used. In the process, logs are passed through a rotating ring and scrapers are hydraulically pressed against the surface of the trunk. Wood losses of 3 to 5 percent can occur, and the barking efficiency for strongly adhering bark is frequently inadequate.

The bark obtained from the debarking is usually used, either directly or after press dewatering, to produce power in a bark combustion furnace.

After debarking, the logs are conveyed through a series of cutting and planing operations. Roughly 75 to 80 weight percent of the tree as received is converted to lumber, with the remaining 20 to 25 percent becoming wood chips and fines. The chips are sold to pulp mills, and the fines are burned either as an energy source or for waste disposal.

Forest residues are small diameter trees, limbs, and cuttings, which are turned into chips in the forest. In general, wood residues are generated on site or quite close to the paper mills. An average distance of 34 miles by single-unit diesel truck for transport of the chips to the pulp mill is used.

5.2.5 Sodium Sulfate Mining and Processing

Sodium sulfate is consumed in the Kraft pulping process. The upper levels of Searles Lake, California, the Great Salt Lake in Utah, and the brines of west Texas all contain sodium sulfate. Typically, sodium sulfate crystals are removed from cooled brine. The crystals are then dissolved again and precipitated to achieve the desired purity.

5.2.6 Soda Ash Production

Soda ash (sodium carbonate) produced in the United States comes from natural soda ash obtained from trona or from alkaline brines. Almost all of the soda ash is mined from either the Green River basin in Wyoming or from Searles Lake in California. Underground trona mining is similar to coal mining. The most common methods are the room and pillar method and the long wall method.

In both of these processes, the material is undercut, drilled, blasted, crushed, and then transported to the surface. Solution mining is currently under development as a more efficient technique. In the refining process, the predominant energy use is in the calcining of bicarbonate to produce carbonate (U.S. Bureau of Mines, 1989 and earlier years).

5.2.7 Corn Starch Manufacture

Corn starch is produced from corn by wet milling. The corn is soaked in steeping tanks containing a solution of 0.3 percent sulfur dioxide in water to soften the kernel and dissolve inorganic components. This steep liquor is later concentrated for sale as a coproduct. The softened corn is lightly milled to free the germ from the kernel. The germ is then processed for oil removal. The remaining corn fraction, mostly starch, protein, and hulls, is then heavily milled. The starch is washed from the hulls, and the resulting starch slurry is separated, refined, washed, and dried.

Starch is a surface sizing material that fills in surface voids, thus reducing the rate of liquid penetration in the dry paperboard.

5.2.8 Primary Unbleached Kraft Paperboard Production (Linerboard)

Kraft pulp is the most widely used type of wood pulp in the United States today, accounting for approximately 80 percent of the total wood pulp produced. The kraft pulping process is based on chemical digestion of wood that has been previously debarked and chipped. The digester is a closed container that holds the wood chips and digestion liquors. The liquor is mainly an aqueous solution of chemicals including sodium sulfide and sodium hydroxide.

For digestion to take place, heat and pressure are applied to the mixture of wood and liquor. The digestion process delignifies the wood and removes other chemical components from the wood, leaving mostly wood fiber with some lignin and complex sugars.

In the kraft process, the used digestion liquor, called black liquor, is burned for energy. Because the liquor contains a high percentage of flammable wood components, it burns readily. The remaining digestion chemicals, called green liquor, are removed and reacted with quicklime. The resulting white liquor, containing sodium hydroxide and sodium sulfide, is returned to the digester.

Combustion of black liquor and the bark removed from logs entering the mill often provides sufficient energy to operate a pulp mill. The black liquor that is burned in the recovery furnace is treated as fuel for the process.

After the wood pulp is “blown” from the digester by the steam used in the process, the pulp is washed free of the chemicals, screened, and refined for entry into the paper-forming section of the mill.

The fiber is pumped to the paper machine as a very dilute suspension in water. To form the paperboard, the fiber suspension drains onto a finely woven plastic or wire mesh belt, which moves over a series of vacuum boxes where the sheet is mechanically dewatered. Next, the sheet is transferred from the wire mesh to a synthetic fabric. This felt conveys the sheet to a pressure roll with an internal vacuum box designed to remove additional water. This same pressure roll also transfers the web to the dryer. This operation is the final drying operation for the sheet. The paperboard (containing about 5 percent moisture) is then wound onto rolls.

5.2.9 Semichemical Paperboard Production (Medium)

Most of the increase in semichemical pulp production in the past 40 years has been made using nonsulfur semichemical processes, not only because of tightened environmental regulations, but also because of higher yields and simpler recovery systems. There are three major pulping processes used to manufacture semichemical pulps in integrated as well as stand-alone semichemical pulp mills.

- Neutral sulfite (NSSC) process—uses sodium carbonate and sulfur or, in some cases, sodium sulfite purchased as a byproduct from a nearby chemical operation as the cooking chemical.

- Green liquor process—uses green liquor from the kraft recovery process as the cooking chemical.

- Nonsulfur process—uses a combination of sodium carbonate, sodium hydroxide, and traces of other proprietary chemicals to enhance the properties of the pulp.

Many semichemical operations integrated with kraft mills use green liquor from the kraft recovery process as the cooking chemical. This allows integration of the semichemical cooking chemical preparation and recovery into the kraft recovery cycle. The quality of semichemical pulp is superior when produced by the neutral sulfite process, but it produces less pulp per pound of wood. The pulp yields from wood in the semichemical pulping processes range from 75 to 88 percent.

Semichemical pulp and paper mills purchase more energy in the form of fuel and/or electrical energy than full chemical pulp mills. A relatively small part of the steam and electrical power required to operate the pulp mill is generated by burning recovered chemicals. In contrast, kraft pulp mills burn black liquor as well as bark and wood wastes.

The data presented are based on two different processes—the nonsulfur process and the NSSC process. A market share average of 60 percent nonsulfur and 40 percent NSSC was used in combining the data sets.

Semichemical paperboard typically contains some recycled fiber. The proportion of recycled fiber will vary for specific mills. For this study, the fibrous raw materials used by the mills surveyed are very similar to the national averages for semichemical paperboard shown in Table 5.2-1.

5.2.10 Secondary Paperboard Production (Linerboard and Medium)

The collected wastepaper includes primarily OCC and DLK. Also, small amounts of postconsumer office wastepaper and old newspapers can be used. Typically, these products are recycled by repulping shredded material.

In the repulping process, the recovered paper is mixed with water in a huge blender-like vat called a repulper. Blades at the bottom of the vat churn the water and beat the paper fiber away from any coatings. As the repulper is drained, filters allow the paper fibers to pass through. The coating is screened off and disposed of. Much of the short fibers are also screened off of the pulp. The sludge can be collected from the repulper for beneficial uses, such as animal bedding or ground cover at landfills, or can be disposed of as solid waste.

The proportion of postconsumer fiber and industrial scrap consumed varies for specific secondary paperboard mills. The fibrous raw materials used in this data set reflect the national averages shown in Table 5.2-1.

5.2.11 Data Quality

Table 5.2-5 summarizes data quality information for corrugated linerboard and medium. Overall, the data are considered to be of very good quality.

5.3 Newsprint

5.3.1 Introduction

This section includes LCI profiles for newsprint production in three scenarios: production of newsprint using primary fiber pulps (derived by three pulping processes); production of newsprint using 100 percent secondary fiber; and production of newsprint using the composite primary and secondary fiber content for the U.S. for 1996. Newspaper production and publishing are excluded because the boundary for this study is newsprint rolls. This section includes a fiber

Table 5.2-5. Data Quality Information for Corrugated Linerboard and Medium

Data Quality Indicator	Primary and Secondary Corrugated Linerboard and Medium
Geographical Coverage	Midwest and East Coast
Time-Related Coverage	1990-1992
Technological Coverage	Straight average of unknown technology differences
Precision	The data sets vary by less than 15 percent
Completeness	Small number of data points compared to total U.S. plants
Consistency	Excellent
Representativeness	Good (2-4 years before basis time period, part of region considered)
Reproducibility	If a company has data, they should be able to reproduce numbers close to the results using the flow diagrams and methodological section. However, the data are not transparent.
Uncertainty/Limitations	The data are based on a representative, but smaller, sample of a specific process from a confidential industry source.
Data Quality Rating	The data are considered to be of very good quality.

flow diagram for newsprint to show the disposition and recovery applications for newspaper products for 1996, including recovery for recycling and other uses as well as LCI profiles for energy, air and water releases, and solid waste for the production scenarios. Data quality information for the newsprint profiles is included in Section 5.3.7.

5.3.2 Newsprint Production

The following sections describe the principal steps for the manufacture of newsprint from trees (primary fiber); secondary newsprint from old newspapers, old magazines, and deinking grade paper; and a statistical average of the two.

The primary pulp used for newsprint is typically made from mechanical pulp and small quantities of kraft pulp. The primary pulp used to produce newsprint in this study is assumed to contain 37 percent groundwood pulp, 51 percent thermomechanical pulp (TMP), and 12 percent bleached kraft pulp (Lockwood-Post, 1997).

Statistical 1996 U.S. data for old newspaper consumption at newsprint mills are used to construct an “composite” newspaper. A statistical average of 38 percent secondary pulp from recovered newspapers was recycled into newsprint in 1996 (AF&PA, 1997a). A small amount of old magazines and deinking grade paper is also used as postconsumer content in the secondary newsprint. Figure 5.3-1 shows the 1996 U.S. fiber and product flows for newspapers (AF&PA, 1997a; Recycling Advisory Council, 1992). The use of old magazines and other sources of secondary fiber besides old newspaper is not analyzed in this study. Therefore, values presented for the manufacture of newsprint from secondary fiber represent recycling of old newspapers only.

As discussed, primary newsprint is typically made from mechanical pulps. The fiber products are brought into the stock storage chest where they are mixed with water and combined with other pulps to form a suspension (furnish), which is ready to be made into paper.

From stock preparation, the furnish is fed into the headbox. With the use of pressure, the headbox deposits the furnish in a regulated fashion onto a wire mesh. From the headbox, the wire mesh moves over a series of vacuum boxes where the sheet is mechanically dewatered.

Next, the furnish sheet is transferred from the wire mesh to a synthetic fabric. This felt conveys the sheet to a pressure roll with an internal vacuum box designed to remove additional water. This same pressure roll also transfers the web to the dryer. This operation is the final drying operation for the sheet.

Once the fiber has passed through the dryer, it has entered the “dry end” of the papermaking operation. From the dryer, the paper is passed through calender rolls to soften and smooth the paper and wound onto a large, bulk size reel (now referred to as a parent roll). As the fiber passes through the papermaking process, scrap or broke that is created is fed directly into the holding chest underneath the machine to be repulped and sent back to the headbox. This internally recycled scrap is referred to as machine broke.

The secondary pulp/newsprint production step has a 15 percent loss of fiber from the system (Recycling Advisory Council, 1992). Emissions for this process are estimations from kraft and other paper production steps.

The following steps in the production of newsprint are discussed in the sections below.

- Mechanical pulp manufacture
- TMP pulp manufacture
- Deinked pulp manufacture
- Bleaching agent production
- Newsprint production.

Salt mining and sodium hydroxide production process descriptions are found in the aluminum sheet LCI profiles (Section 3.0) and are not repeated here. Process descriptions for roundwood harvesting, wood residues, soda ash, and kraft pulp/paper production are found in Section 5.2 and are not repeated here. Limestone mining, sulfur mining and production, and sulfuric acid production are less than 1 percent of the system and are considered negligible in this study.

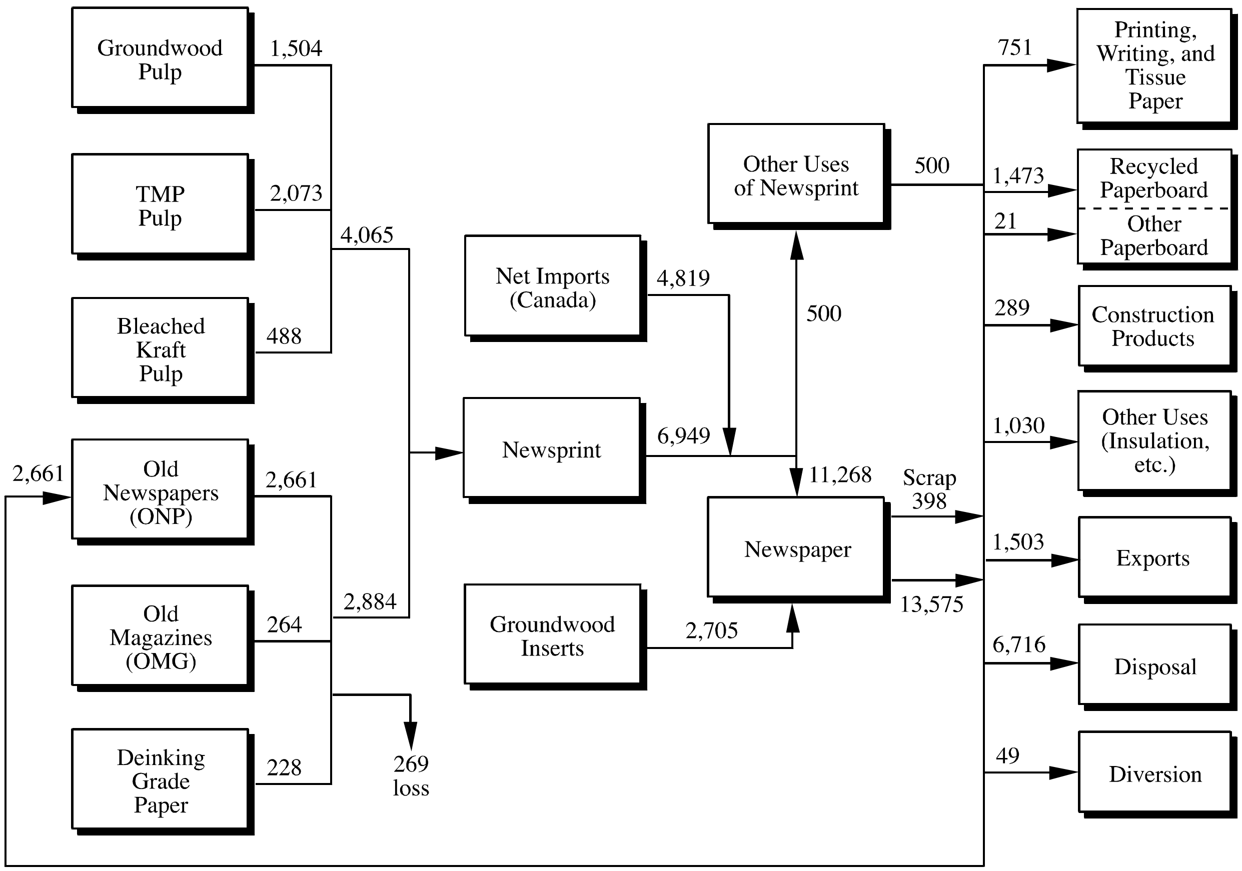


Figure 5.3-1. U.S. newsprint raw material and product flows. (Numbers represent thousand short tons of fiber.)

The flow diagram for producing 1 ton of primary fiber based newsprint and newspapers is given in Figure 5.3-2. Figure 5.3-4 shows the flow diagram for the production of 100 percent secondary fiber newsprint. The flow diagram for producing 1 ton of 38 percent secondary/62 percent primary fiber newsprint is presented in Figure 5.3-3. The energy and emissions data for producing 1 ton of primary fiber newsprint are shown in Table 5.3-1. Table 5.3-2 displays the energy and emissions data for producing 1 ton of 100 percent secondary fiber newsprint. Table 5.3-3 presents energy and emissions data for producing 1 ton of 38 percent secondary/62 percent primary fiber content newsprint. Tables 5.3-1 and 5.3-2 show a carbon dioxide credit for the sequestration of carbon dioxide within the product and for the wood used as fuel. The wood used as fuel was calculated from the mass balance—input wood minus output product. The carbon content of wood is 86 percent.

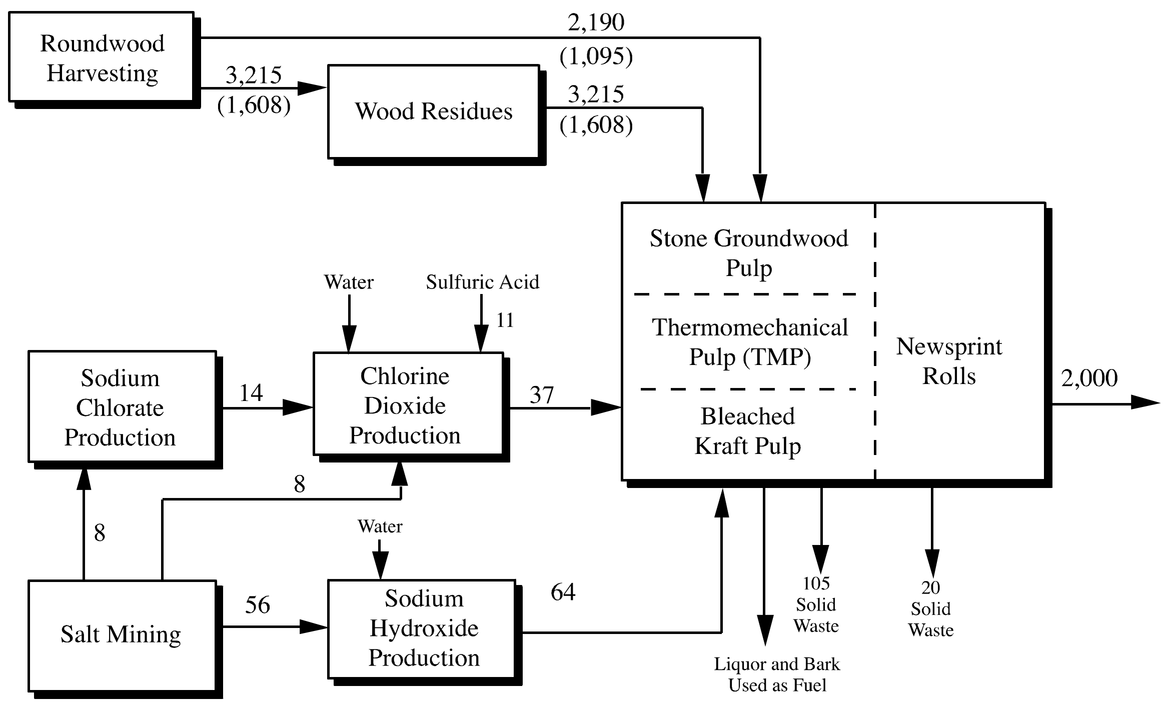


Figure 5.3-2. Process flow diagram for producing 1 ton of primary newsprint. Numbers represent weight of materials in pounds. Numbers in parentheses represent bone-dry weight of wood.

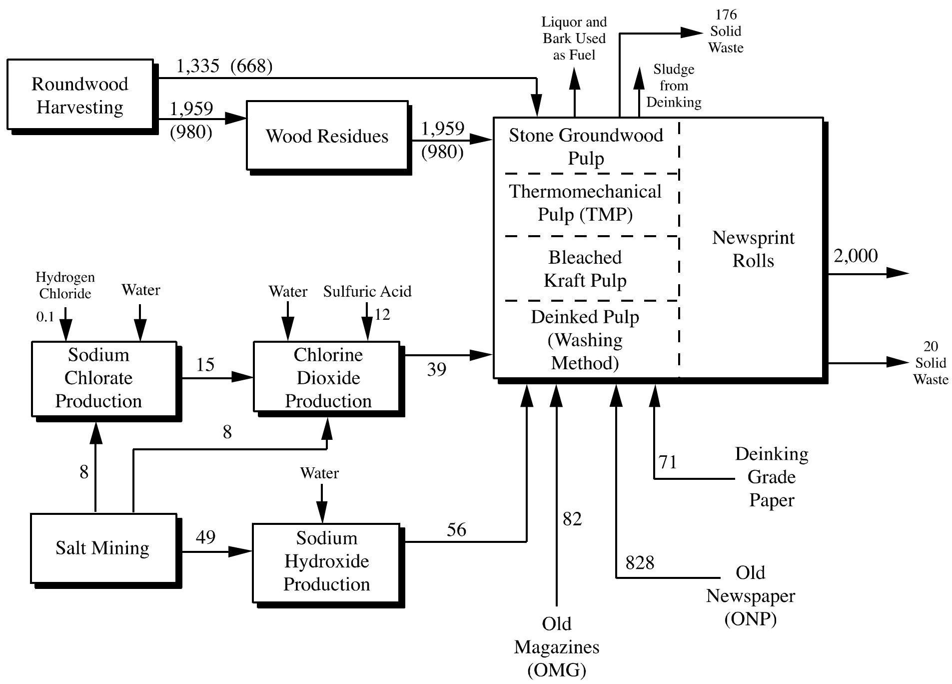


Figure 5.3-3. Process flow diagram for producing 1 ton of composite newsprint. (The composite system presented here represents an average secondary content of 38 percent.) Numbers represent weight of materials in pounds. Numbers in parentheses represent bone-dry weight of wood.

The steps for collection, processing, baling, and shipment to a recycling mill are **not included** in the process descriptions or the data. These are included in separate modules of the MSW-DST. The energy and environmental data for printing and conversion of newsprint to newspaper are excluded because this step is the same and independent of the makeup of the newsprint itself. The processes represented in each table are shown on the corresponding figure.

5.3.3 Mechanical Pulp Manufacture

Mechanical pulp, which is commonly either stone groundwood pulp (SGP) or refiner mechanical pulp (RMP), is the one of the types of pulp used for manufacturing newsprint (Smook, 1987). Data on refiner mechanical pulp production, which employs a disc refiner to break down wood chips, are not available. The data for mechanical pulp represent only the stone groundwood process. The SGP process produces pulp by pressing blocks of wood against an abrasive rotating stone surface. Very little, if any, chemicals are used in this process (Smook, 1987). No chemicals are assumed to be used in the production of groundwood pulp. (Usually bleached kraft pulp is blended with groundwood to make newsprint.)

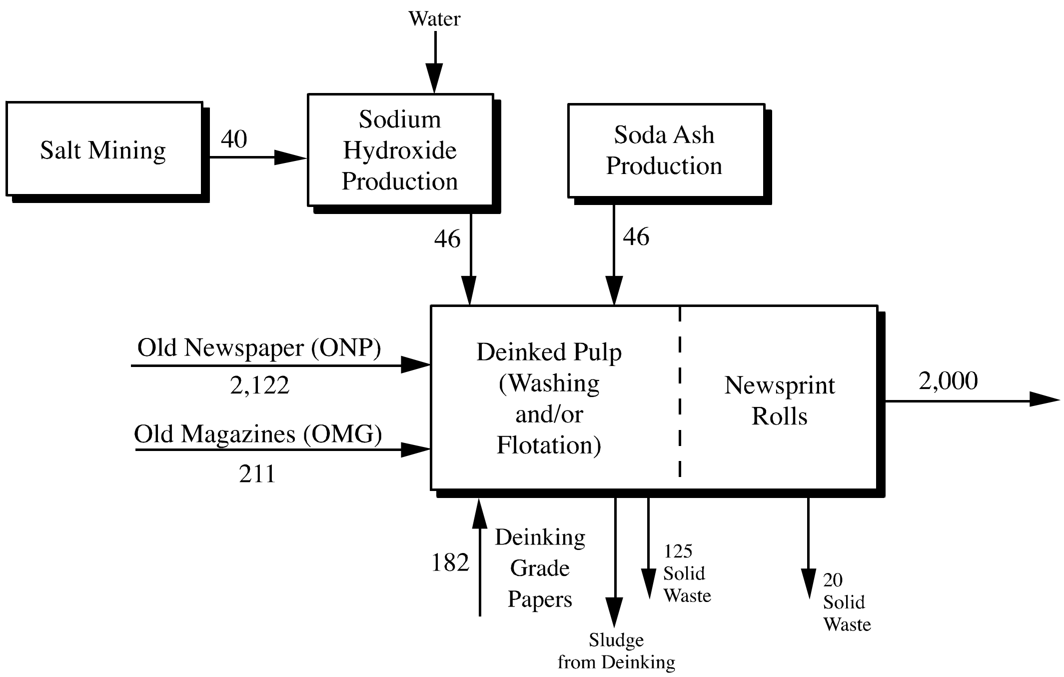


Figure 5.3.4. Process flow diagram for producing 1 ton of secondary newsprint. Numbers represent weight of materials in pounds.

5.3.4 Thermomechanical Pulp (TMP) Manufacture

TMP uses wood chips as its source of fiber. The wood chips are steamed for a short period of time prior to and during refining. Steam softens the chips, resulting in a greater percentage of long fibers and less imperfections in the pulp produced compared to mechanical pulp. Longer fibers produce a stronger pulp than the stone groundwood or refiner mechanical pulp.

Table 5.3-1. Data for Production of 1 Ton of Primary Newsprint Rolls

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	2.07E+03	2.30E+01	1.11E-02
Natural Gas	cu ft	1.10E+04	1.13E+01	1.03E-03
LPG	gal	3.90E-05	3.70E-06	9.55E-02
Coal	lb	3.92E+01	4.40E-01	1.12E-02
Residual oil	gal	1.23E+00	1.80E-01	1.50E-01
Gasoline	gal	1.20E-03	1.50E-04	1.25E-01
Diesel	gal	1.94E+00	2.70E-01	1.39E-01
Wood	Btu	3.51E+06	3.51E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.66E+03	1.72E+00	1.03E-03
Residual oil	gal	7.70E-01	1.20E-01	1.50E-01
Distillate oil	gal	1.50E+00	2.10E-01	1.39E-01
Gasoline	gal	8.10E-01	1.00E-01	1.25E-01
LPG	gal	1.40E-02	1.30E-03	9.55E-02
Coal	lb	2.81E+01	3.10E-01	1.12E-02
Nuclear	lb U238	1.10E-04	1.10E-01	9.85E+02
Hydropower	Btu	1.78E+04	1.80E-02	1.00E-06
Other	Btu	1.58E+04	1.60E-02	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	2.92E+02		
Diesel	gal	2.75E+00	3.80E-01	1.39E-01
Rail	ton-miles	1.62E+02		
Diesel	gal	3.90E-01	5.40E-02	1.39E-01
Barge	ton-miles	6.20E-01		
Diesel	gal	1.20E-03	1.70E-04	1.39E-01
Residual oil	gal	5.00E-04	7.40E-05	1.50E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	3.17E+01	3.30E-02	1.03E-03
Residual oil	gal	1.20E-01	1.90E-02	1.50E-01
Distillate oil	gal	1.40E-02	1.90E-03	1.39E-01
Gasoline	gal	4.00E-03	5.00E-04	1.25E-01
LPG	gal	4.10E-03	3.90E-04	9.55E-02
Coal	lb	4.10E-01	4.60E-03	1.12E-02
Nuclear	lb U238	1.70E-06	1.60E-03	9.85E+02
Hydropower	Btu	2.60E+02	2.60E-04	1.00E-06
Other	Btu	2.30E+02	2.30E-04	1.00E-06

(continued)

Table 5.3-1. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	4.30E-05		4.30E-05
Aldehydes	lb	1.90E-02	1.90E-02	
Ammonia	lb	3.60E-03		3.60E-03
Antimony	lb	2.30E-05		2.30E-05
Arsenic	lb	1.70E-04		1.70E-04
Benzene	lb	1.50E-03		1.50E-03
Beryllium	lb	1.60E-05		1.60E-05
Cadmium	lb	3.60E-05		3.60E-05
Carbon Dioxide-fossil	lb	4.90E+03		4.90E+03
Carbon Dioxide-nonfossil (1)	lb	-3.78E+03	-3.78E+03	
Carbon Dioxide-nonfossil (2)	lb	-5.11E+02		-5.11E+02
Carbon Monoxide	lb	1.09E+01		1.09E+01
Carbon Tetrachloride	lb	7.60E-05		7.60E-05
Chlorine	lb	3.11E-03	1.10E-05	3.10E-03
Chlorine Dioxide	lb	8.30E-03	8.30E-03	
Chromium	lb	2.20E-04		2.20E-04
Cobalt	lb	7.20E-05		7.20E-05
Dioxins	lb	2.40E-10		2.40E-10
Formaldehyde	lb	2.20E-04		2.20E-04
Hydrocarbons	lb	8.93E+00	1.90E-01	8.74E+00
Hydrochloric Acid	lb	2.20E-01		2.20E-01
Hydrogen Fluoride	lb	3.00E-02		3.00E-02
Kerosene	lb	1.14E-03		1.14E-03
Lead	lb	6.20E-04		6.20E-04
Manganese	lb	3.90E-03		3.90E-03
Mercury	lb	1.04E-04	2.00E-05	8.40E-05
Metals	lb	3.30E-01		3.30E-01
Methane	lb	1.14E+01		1.14E+01
Methylene Chloride	lb	1.90E-04		1.90E-04
Naphthalene	lb	9.20E-04		9.20E-04
Nickel	lb	1.00E-03		1.00E-03
Nitrogen Oxides	lb	1.97E+01	6.70E-01	1.90E+01
Nitrous Oxide	lb	2.60E-02		2.60E-02
N-Nitrosodimethylamine	lb	9.10E-06		9.10E-06
Odorous Sulfur	lb	2.10E-01	2.10E-01	
Other Aldehydes	lb	4.90E-02		4.90E-02
Other Organics	lb	2.43E+00	2.00E+00	4.30E-01
Particulate	lb	7.26E+00	3.11E+00	4.15E+00
Perchloroethylene	lb	4.10E-05		4.10E-05
Phenols	lb	1.50E-02		1.50E-02
Radionuclides	Ci	9.30E-04		9.30E-04
Selenium	lb	3.10E-04		3.10E-04

(continued)

Table 5.3-1. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Sulfur Oxides	lb	4.97E+01	1.32E+00	4.84E+01
Trichloroethylene	lb	4.10E-05		4.10E-05
Solid Wastes				
Ash	lb	6.68E+02		6.68E+02
Sludge	lb	5.28E+01	5.28E+01	
Unspecified	lb	2.81E+01	2.81E+01	
Waterborne Wastes				
Acid	lb	1.10E-07		1.10E-07
Ammonia	lb	2.60E-03		2.60E-03
BOD	lb	7.11E+00	7.06E+00	4.50E-02
Boron	lb	1.20E-01		1.20E-01
Cadmium	lb	2.10E-03		2.10E-03
Calcium	lb	9.20E-04		9.20E-04
Chloride	lb	2.07E+00		2.07E+00
Chromates	lb	4.90E-05		4.90E-05
Chromium	lb	2.10E-03		2.10E-03
COD	lb	2.20E+00	1.57E+00	6.30E-01
Cyanide	lb	3.00E-06		3.00E-06
Dissolved Solids	lb	4.54E+01	1.80E-01	4.52E+01
Fluorides	lb	4.20E-03	0.00E+00	4.20E-03
Iron	lb	1.70E-01		1.70E-01
Lead	lb	2.99E-06	2.80E-06	1.90E-07
Manganese	lb	9.80E-02		9.80E-02
Mercury	lb	2.15E-07	5.50E-08	1.60E-07
Metal Ion	lb	2.30E-03		2.30E-03
Methanol	lb	2.80E-02	2.80E-02	
Nickel	lb	3.90E-08	3.90E-08	
Nitrates	lb	4.00E-04		4.00E-04
Oil	lb	8.00E-01		8.00E-01
Other Organics	lb	1.50E-01		1.50E-01
Phenol	lb	8.02E-06	6.20E-07	7.40E-06
Phosphates	lb	1.50E-02		1.50E-02
Sodium	lb	1.70E-03		1.70E-03
Sulfates	lb	2.12E+00		2.12E+00
Sulfides	lb	5.30E-06	5.30E-06	
Sulfuric Acid	lb	2.90E-02		2.90E-02
Suspended Solids	lb	1.38E+01	1.11E+01	2.71E+00
Zinc	lb	1.05E-03	3.50E-04	7.00E-04

(1) Carbon dioxide credit was given for the ton of newsprint produced (wood contains 86% carbon content and 2.2 lb CO_2/1 lb wood product).

(2) Carbon dioxide credit was given for the difference between the input wood and output product. It is possible that extra purchased wood products are used in the biomass furnace which are not accounted for in this calculation. (Wood contains 86% carbon content and 2.2 lb CO_2/lb wood burned.)

Source: Franklin Associates, 2000.

Table 5.3-2. Data for Production of 1 Ton of Secondary Newsprint Rolls

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	1.21E+03	1.35E+01	1.11E-02
Natural Gas	cu ft	7.45E+03	7.68E+00	1.03E-03
Coal	lb	6.38E+00	7.10E-02	1.12E-02
Distillate oil	gal	2.90E-02	4.00E-03	1.39E-01
Residual oil	gal	4.50E-02	6.70E-03	1.50E-01
Gasoline	gal	2.30E-03	2.90E-04	1.25E-01
Precombustion Process Energy				
Natural Gas	cu ft	1.06E+03	1.09E+00	1.03E-03
Residual oil	gal	4.00E-01	6.00E-02	1.50E-01
Distillate oil	gal	8.90E-01	1.20E-01	1.39E-01
Gasoline	gal	5.20E-01	6.50E-02	1.25E-01
LPG	gal	6.00E-03	5.70E-04	9.55E-02
Coal	lb	1.67E+01	1.90E-01	1.12E-02
Nuclear	lb U238	6.60E-05	6.50E-02	9.85E+02
Hydropower	Btu	1.06E+04	1.10E-02	1.00E-06
Other	Btu	9.37E+03	9.40E-03	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	1.02E+01		
Diesel	gal	9.60E-02	1.30E-02	1.39E-01
Rail	ton-miles	4.01E+01		
Diesel	gal	9.60E-02	1.30E-02	1.39E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	1.94E+00	2.00E-03	1.03E-03
Residual oil	gal	7.60E-03	1.10E-03	1.50E-01
Distillate oil	gal	8.60E-04	1.20E-04	1.39E-01
Gasoline	gal	2.50E-04	3.10E-05	1.25E-01
LPG	gal	2.50E-04	2.40E-05	9.55E-02
Coal	lb	2.50E-02	2.80E-04	1.12E-02
Nuclear	lb U238	1.00E-07	1.00E-04	9.85E+02
Hydropower	Btu	1.60E+02	1.60E-05	1.00E-06
Other	Btu	1.40E+02	1.40E-05	1.00E-06

(continued)

Table 5.3-2. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	2.50E-05		2.50E-05
Ammonia	lb	1.10E-02		1.10E-02
Antimony	lb	1.20E-05		1.20E-05
Arsenic	lb	6.20E-05		6.20E-05
Benzene	lb	2.60E-05		2.60E-05
Beryllium	lb	7.20E-06		7.20E-06
Cadmium	lb	1.00E-05		1.00E-05
Carbon Dioxide-fossil	lb	2.88E+03		2.88E+03
Carbon Dioxide-nonfossil (2)	lb	8.50E-01		8.50E-01
Carbon Monoxide	lb	3.09E+00		3.09E+00
Carbon Tetrachloride	lb	4.40E-05		4.40E-05
Chlorine	lb	1.58E-05	6.40E-06	9.40E-06
Chromium	lb	8.50E-05		8.50E-05
Cobalt	lb	3.70E-05		3.70E-05
Dioxins	lb	1.40E-10		1.40E-10
Formaldehyde	lb	1.30E-04		1.30E-04
Hydrocarbons	lb	5.38E+00		5.38E+00
Hydrochloric Acid	lb	1.30E-01		1.30E-01
Hydrogen Fluoride	lb	1.80E-02		1.80E-02
Kerosene	lb	6.30E-04		6.30E-04
Lead	lb	8.60E-05		8.60E-05
Manganese	lb	1.90E-04		1.90E-04
Mercury	lb	6.00E-05	1.20E-05	4.80E-05
Metals	lb	3.50E-04		3.50E-04
Methane	lb	7.00E+00		7.00E+00
Methylene Chloride	lb	1.10E-04		1.10E-04
Naphthalene	lb	2.10E-06		2.10E-06
Nickel	lb	3.80E-04		3.80E-04
Nitrogen Oxides	lb	1.02E+01	1.30E-03	1.02E+01
Nitrous Oxide	lb	1.50E-02		1.50E-02
N-Nitrosodimethylamine	lb	5.40E-06		5.40E-06
Other Aldehydes	lb	8.40E-03		8.40E-03
Other Organics	lb	2.03E+00	2.00E+00	2.60E-02
Particulate	lb	4.27E+00	2.02E+00	2.25E+00
Perchloroethylene	lb	2.40E-05		2.40E-05
Phenols	lb	7.20E-05		7.20E-05
Radionuclides	Ci	5.50E-04		5.50E-04
Selenium	lb	1.80E-04		1.80E-04
Sulfur Oxides	lb	2.98E+01	2.50E-05	2.98E+01
Trichloroethylene	lb	2.40E-05		2.40E-05

(continued)

Table 5.3-2. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Solid Wastes				
Ash	lb	3.69E+02		3.69E+02
Sludge	lb	1.43E+02	1.43E+02	
Unspecified	lb	2.15E+01	2.15E+01	
Waterborne Wastes				
Acid	lb	3.50E-08		3.50E-08
Ammonia	lb	1.50E-03		1.50E-03
BOD	lb	1.30E+01	1.30E+01	2.90E-02
Boron	lb	6.70E-02		6.70E-02
Cadmium	lb	1.30E-03		1.30E-03
Calcium	lb	5.40E-04		5.40E-04
Chloride	lb	1.35E+00		1.35E+00
Chromates	lb	2.40E-05		2.40E-05
Chromium	lb	1.30E-03		1.30E-03
COD	lb	1.13E+01	1.09E+01	4.10E-01
Cyanide	lb	2.00E-06		2.00E-06
Dissolved Solids	lb	3.03E+01	8.00E-01	2.95E+01
Fluorides	lb	2.50E-03		2.50E-03
Iron	lb	9.70E-02		9.70E-02
Lead	lb	8.50E-08	2.30E-08	6.20E-08
Manganese	lb	5.60E-02		5.60E-02
Mercury	lb	1.32E-07	3.20E-08	1.00E-07
Metal Ion	lb	7.40E-04		7.40E-04
Nickel	lb	2.30E-08	2.30E-08	
Nitrates	lb	2.40E-04		2.40E-04
Oil	lb	5.20E-01		5.20E-01
Other Organics	lb	9.70E-02		9.70E-02
Phenol	lb	2.40E-06		2.40E-06
Phosphates	lb	8.30E-03		8.30E-03
Sodium	lb	1.00E-03		1.00E-03
Sulfates	lb	1.35E+00		1.35E+00
Sulfides	lb	3.10E-06	3.10E-06	
Sulfuric Acid	lb	1.70E-02		1.70E-02
Suspended Solids	lb	1.86E+01	1.70E+01	1.62E+00
Zinc	lb	4.60E-04	2.30E-08	4.60E-04

Note: Materials collection, separation, and transport to a remanufacturing facility are handled by the collection, materials recovery facility, and transportation process models, respectively, of the decision support tool.
Source: Franklin Associates, 2000.

Table 5.3-3. Data for Production of 1 Ton of Composite (38 Percent Secondary/62 Percent Primary) Newsprint Rolls

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	1.73E+03	1.93E+01	1.11E-02
Natural Gas	cu ft	9.61E+03	9.91E+00	1.03E-03
LPG	gal	2.40E-05	2.20E-06	9.55E-02
Coal	lb	2.49E+01	2.80E-01	1.12E-02
Residual oil	gal	7.70E-01	1.20E-01	1.50E-01
Gasoline	gal	7.20E-04	9.00E-05	1.25E-01
Diesel	gal	1.18E+00	1.60E-01	1.39E-01
Wood	Btu	2.14E+06	2.14E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.43E+03	1.47E+00	1.03E-03
Residual oil	gal	6.30E-01	9.40E-02	1.50E-01
Distillate oil	gal	1.26E+00	1.70E-01	1.39E-01
Gasoline	gal	7.00E-01	8.70E-02	1.25E-01
LPG	gal	1.10E-02	1.00E-03	9.55E-02
Coal	lb	2.36E+01	2.60E-01	1.12E-02
Nuclear	lb U238	9.40E-05	9.20E-02	9.85E+02
Hydropower	Btu	1.50E+04	1.50E-02	1.00E-06
Other	Btu	1.33E+04	1.30E-02	1.00E-06
Combustion Transportation Energy				
Combination Truck	ton-miles	1.79E+02		
Diesel	gal	1.68E+00	2.30E-01	1.39E-01
Rail	ton-miles	1.11E+02		
Diesel	gal	2.70E-01	3.70E-02	1.39E-01
Barge	ton-miles	3.80E-01		
Diesel	gal	7.60E-04	1.00E-04	1.39E-01
Residual oil	gal	3.00E-04	4.50E-05	1.50E-01
Precombustion Transportation Energy				
Natural Gas	cu ft	1.97E+01	2.00E-02	1.03E-03
Residual oil	gal	7.70E-02	1.20E-02	1.50E-01
Distillate oil	gal	8.70E-03	1.20E-03	1.39E-01
Gasoline	gal	2.50E-03	3.10E-05	1.25E-01
LPG	gal	2.50E-03	2.40E-04	9.55E-02
Coal	lb	2.50E-01	2.80E-03	1.12E-02
Nuclear	lb U238	1.00E-06	1.00E-03	9.85E+02
Hydropower	Btu	1.60E+02	1.60E-04	1.00E-06
Other	Btu	1.50E+02	1.50E-04	1.00E-06

(continued)

Table 5.3-3. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	3.60E-05		3.60E-05
Aldehydes	lb	1.20E-02	1.20E-02	
Ammonia	lb	1.60E-02		1.60E-02
Antimony	lb	1.90E-05		1.90E-05
Arsenic	lb	1.30E-04		1.30E-04
Benzene	lb	9.00E-04		9.00E-04
Beryllium	lb	1.20E-05		1.20E-05
Cadmium	lb	2.60E-05		2.60E-05
Carbon Dioxide-fossil	lb	4.11E+03		4.11E+03
Carbon Dioxide-nonfossil (1)	lb	-2.35E+03	-2.35E+03	
Carbon Dioxide-nonfossil (2)	lb	-2.72E+02		-2.72E+02
Carbon Monoxide	lb	7.84E+00		7.84E+00
Carbon Tetrachloride	lb	6.40E-05		6.40E-05
Chlorine	lb	9.90E+00	9.90E+00	1.90E-03
Chlorine Dioxide	lb	5.00E-03	5.00E-03	
Chromium	lb	1.60E-04		1.60E-04
Cobalt	lb	5.80E-05		5.80E-05
Dioxins	lb	2.00E-10		2.00E-10
Formaldehyde	lb	1.80E-04		1.80E-04
Hydrocarbons	lb	7.53E+00	1.10E-01	7.42E+00
Hydrochloric Acid	lb	1.80E-01		1.80E-01
Hydrogen Fluoride	lb	2.50E-02		2.50E-02
Kerosene	lb	8.90E-04		8.90E-04
Lead	lb	4.10E-04		4.10E-04
Manganese	lb	2.50E-03		2.50E-03
Mercury	lb	1.80E+00	1.80E+00	7.00E-05
Metals	lb	2.00E-01		2.00E-01
Methane	lb	9.69E+00		9.69E+00
Methylene Chloride	lb	0.00E+00		1.6-E04
Naphthalene	lb	5.60E-04		5.60E-04
Nickel	lb	7.80E-04		7.80E-04
Nitrogen Oxides	lb	1.59E+01	4.10E-01	1.55E+01
Nitrous Oxide	lb	2.20E-02		2.20E-02
N-Nitrosodimethylamine	lb	7.70E-06		7.70E-06
Odorous Sulfur	lb	1.30E-01	1.30E-01	
Other Aldehydes	lb	3.30E-02		3.30E-02
Other Organics	lb	2.27E+00	2.00E+00	2.70E-01
Particulate	lb	6.07E+00	2.67E+00	3.40E+00
Phenols	lb	9.30E-03		9.30E-03
Perchloroethylene	lb	3.50E-05		3.50E-05
Radionuclides	Ci	7.80E-04		7.80E-04
Selenium	lb	2.60E-04		2.60E-04

(continued)

Table 5.3-3. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Sulfur Oxides	lb	4.19E+01	8.00E-01	4.11E+01
Trichloroethylene	lb	3.40E-05		3.40E-05
Solid Wastes				
Sludge	lb	8.80E+01	8.80E+01	
Unspecified	lb	2.57E+01	2.57E+01	
Ash	lb	5.51E+02		5.51E+02
Waterborne Wastes				
Acid	lb	7.90E-08		7.90E-08
Ammonia	lb	2.20E-03		2.20E-03
BOD	lb	9.42E+00	9.38E+00	3.90E-02
Boron	lb	9.80E-02		9.80E-02
Cadmium	lb	1.80E-03		1.80E-03
Calcium	lb	7.70E-04		7.70E-04
Chloride	lb	1.79E+00		1.79E+00
Chromates	lb	3.90E-05		3.90E-05
Chromium	lb	1.80E-03		1.80E-03
COD	lb	5.78E+00	5.23E+00	5.50E-01
Cyanide	lb	2.63E-06		2.63E-06
Dissolved Solids	lb	3.94E+01	4.30E-01	3.90E+01
Fluorides	lb	3.60E-03		3.60E-03
Iron	lb	1.40E-01		1.40E-01
Lead	lb	1.84E-06	1.70E-06	1.40E-07
Manganese	lb	8.20E-03		8.20E-03
Mercury	lb	1.90E-07	5.00E-08	1.40E-07
Metal Ion	lb	1.70E-03		1.70E-03
Methanol	lb	1.70E-02	1.70E-02	
Nickel	lb	3.60E-08	3.60E-08	
Nitrates	lb	3.40E-04		3.40E-04
Oil	lb	6.90E-01		6.90E-01
Other Organics	lb	1.30E-01		1.30E-01
Phenol	lb	5.78E-06	3.80E-07	5.40E-06
Phosphates	lb	1.20E-02		1.20E-02
Sodium	lb	1.40E-03		1.40E-03
Sulfates	lb	1.81E+00		1.81E+00
Sulfides	lb	4.80E-06	4.80E-06	
Sulfuric Acid	lb	2.40E-02		2.40E-02
Suspended Solids	lb	1.57E+01	1.34E+01	2.28E+00
Zinc	lb	8.10E-04	2.10E-04	6.00E-04

*The composite data presented here represent the average recycled content of 38% and an average recycling rate of 53%.

(1) Carbon dioxide credit was given for the ton of newsprint produced (wood contains 86% carbon content and 2.2 lb CO_2/1 lb wood product).
(2) Carbon dioxide credit was given for the difference between the input wood and output product. It is possible that extra purchased wood products are used in the biomass furnace which are not accounted for in this calculation (wood contains 86% carbon content and 2.2 lb CO_2/lb wood burned).

Source: Franklin Associates, 2000.

5.3.5 Deinked Pulp Manufacture

The following discussion describes the production of deinked newsprint from recovered fiber sources, either industrial scrap or postconsumer. For many paper products, repulped wastepaper can be used as a raw material substitute for wood pulp.

The most common method of preparing recovered paper for reuse begins with repulping the fiber sources. During the repulping step, large-sized contaminants are separated from the fiber. Immediately following pulping, smaller-sized contaminants are screened for removal prior to deinking.

If inks are present, chemicals, heat, and mechanical energy are used to dislodge the ink particles and disperse them. The ink particles are separated from the fiber either by washing or flotation or a hybrid process of both. In this study, the washing process is assumed. In the washing process, detergents and dispersants are used to disperse the ink into fine particulates. The separation of these ink particulates from the pulp corresponds to a stock-thickening process, whether achieved using conventional washing equipment or screens.

Surfactants are the key chemicals used for deinking. These surfactants, which affect surface tension, include detergents, dispersants, and foaming agents. Other chemicals used to enhance the action of the surfactants are caustic soda, sodium silicate, and borax. The deinking process also removes some coatings and fillers from the coated papers such as magazines and catalogs.

The deinked pulp is then sent to the newsprint part of the mill. No emissions data are available for the deinking process. This study assumes the deinking process uses sodium hydroxide, soda ash, and chlorine dioxide. The sodium hydroxide and soda ash are each assumed to be 2 percent of the pulp weight produced, while the chlorine dioxide is assumed to be 75 percent of the pulp weight produced (Argonne National Laboratory, 1993).

5.3.6 Bleaching Agent Production

Many different bleaching agents are available to be used in pulp production. Some of the more common ones include sodium hydrosulfite, chlorine dioxide, hydrogen peroxide, and sodium bisulfide. No statistical data were available for uses of different bleaching agents. Chlorine dioxide is used in this study because data were readily available. The amount of bleaching agent used is variable with pulp and type of agent. This study includes an estimate for the amount of bleaching agent in newspaper.

5.3.6.1 <u>Sodium Chlorate Production</u>. Sodium chlorate is used to produce chlorine dioxide at the pulp mill site. Sodium chlorate is produced from electrolysis of salt brine similar to the production of caustic and chlorine, except that the chlorine and caustic are not separated, but are instead allowed to mix (Smook, 1987). Hypochlorite forms first, followed by the formation of sodium chlorate. It is assumed that the energy and emissions for the manufacture of sodium chlorate are the same as those for chlorine (Franklin Associates, Ltd., 2000).

5.3.6.2 <u>Chlorine Dioxide Production</u>. Chlorine dioxide is a very unstable molecule. This makes transportation difficult, but it is easily prepared at the paper mill. To produce chlorine dioxide, a solution of sodium chlorate and sodium chloride is treated with sulfuric acid. Concentrations of chlorine dioxide above 10 percent are avoided because they can lead to explosion from self-decomposition (Kent, 1992).

5.3.7 Data Quality

Data quality information for newsprint is presented in Table 5.3-4. The newsprint data are considered to be of average quality.

Table 5.3-4. Data Quality Information for Newsprint

Data Quality Indicator	Primary and Secondary Newsprint
Geographical Coverage	East Coast and unknown
Time-Related Coverage	1981, 1988-1992
Technological Coverage	Straight average of unknown technical differences
Precision	The largest variance of points is 40 percent. Three of the data sets from the Argonne report are within 13 percent of each other.
Completeness	Small number of data points compared to total U.S. plants
Consistency	Excellent
Representativeness	Average data (one older data set, part of region considered)
Reproducibility	If a company has data, they should be able to reproduce numbers close to the results using the flow diagrams and methodological section. However, the data are not transparent.
Uncertainty/Limitations	The data are based on a nonverified data source: *Energy Life Cycle Analysis of Newspaper*, Argonne National Laboratory, DOE, 1993.
Data Quality Rating	The data are considered to be of average quality.

5.4 Office Paper

5.4.1 Introduction

This section contains LCI profiles for the production of 100 percent primary and secondary rolls of office paper. It contains process flow diagrams and descriptions for production processes for 1 short ton of paper product. Data quality information for the office paper profiles is included in Section 5.4.4.

5.4.2 Office Paper Production

The data for primary office paper profile represent uncoated freesheet bleached paper produced in an alkaline papermaking process using bleached kraft pulp. The product consists of 78 percent pulp, 16 percent filler, and 6 percent moisture. The profile uses an average of three different bleaching technologies (EDF, 1995c):

- 50 percent chlorine dioxide substituted for elemental chlorine in the first bleaching stage
- 100 percent chlorine dioxide substituted for elemental chlorine in the first bleaching stage
- oxygen delignification and 100 percent chlorine dioxide substituted for elemental chlorine in the first bleaching stage.

The boundaries for this study include the harvesting of trees, transporting of logs (or chips) to the mill, debarking and chipping, and manufacture of pulp and paper using primary fiber. These data for the production of primary pulp were collected and published by EDF, according to their agreed methodology (EDF, 1995c). With the addition of precombustion energy and emissions data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of primary office paper pulp. Figure 5.4-1 shows a simplified process flow diagram for processing primary office paper pulp.

The data in this profile were primarily developed through the use of the EDF's White Paper 10A on business and writing paper (EDF, 1995c). EDF's Table 3, Environmental Parameters for an average uncoated freesheet paper with 0 percent secondary content, which presents a cradle-to-gate environmental data profile for 1 short ton of primary office paper, was used along with precombustion energy and emissions data published by Franklin Associates (1998). The following steps were taken to calculate inventory data for primary office paper.

1. The primary office paper data profile (EDF) was converted from kilogram per metric ton to pounds per ton for water emissions and solid waste.

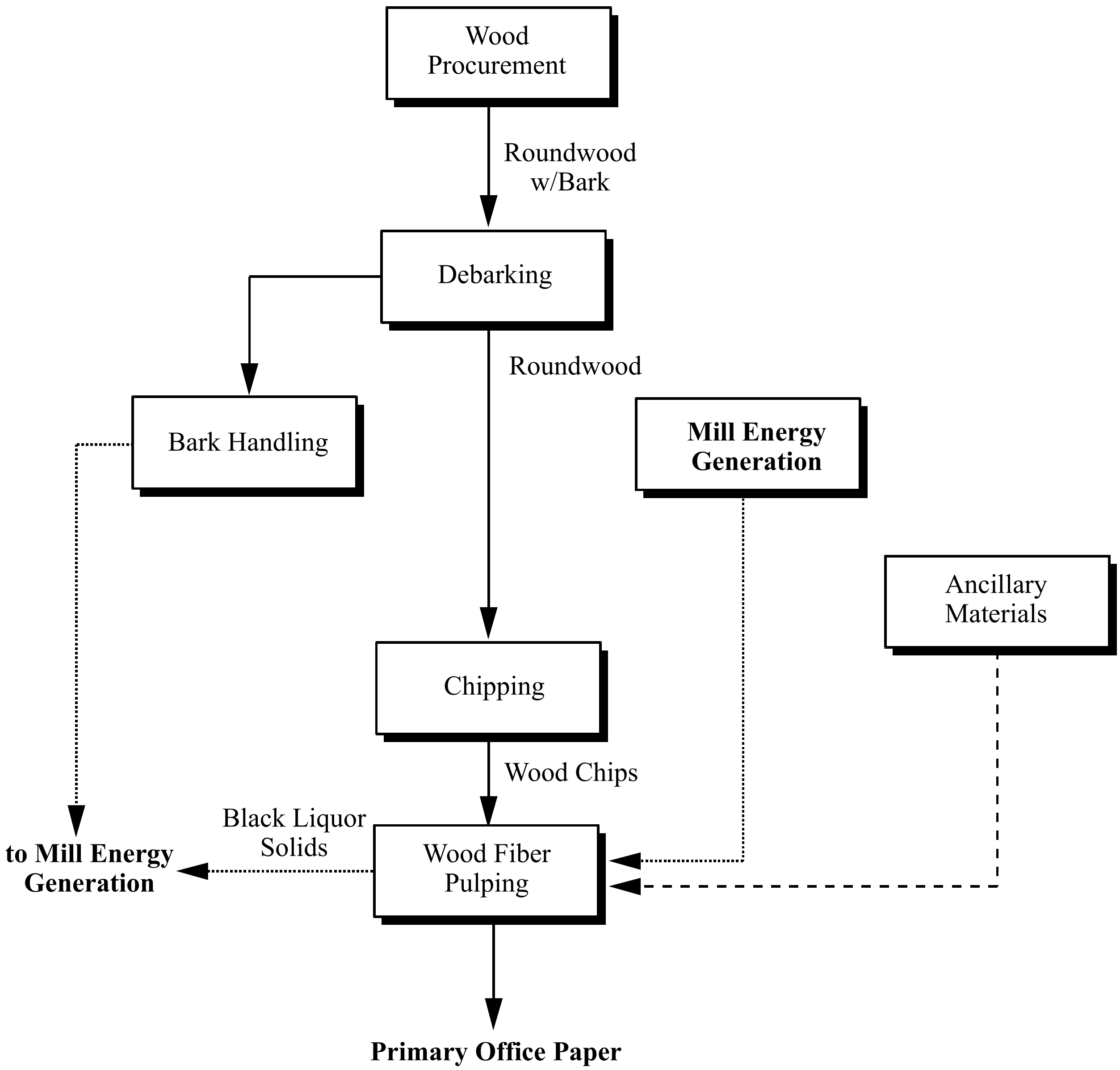


Figure 5.4-1. Primary office paper production

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels used in the process were not included in the EDF publication; hence, the appropriate emissions and precombustion energies from the Franklin report were added to make it a cradle-to-gate profile.

3. To account for the regeneration of wood (from the forest) that accompanies its removal as a a result of forest management, this profile assumes that for every pound of wood used in the paper-making process, an equivalent is regenerated. Hence, adjustments for CO_2 emissions from biomass energy were made by giving CO_2 credit at 2.2 lb/lb of wood used in the process. For every pound of wood consumed in the paper-making process (approximately 78 percent of paper weight is wood fiber), 2.2 lb of CO_2 is subtracted from the biomass material balance.

Tables 5.4-1 and 5.4-2 summarize the cradle-to-gate energy consumption and environmental aspect for primary office paper. Table 5.4-1 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water (Table 5.4-2) include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

Descriptions of the processes for wood procurement, wood residues production, pulping and paper formation are included in Sections 5.2 and 5.3 and not repeated here.

5.4.3 Secondary Office Paper

The secondary office paper LCI profile represents office paper produced from 100 percent recovered fiber pulp collected from manufacturing sources and small-volume wastepaper sources, such as houses and markets. Deinked recovered fiber pulping (DIP) technology is used to produce recovered pulp for secondary office paper. A description of the DIP process is provided in Section 5.3.

The LCI data for the production of secondary office paper pulp were collected and published by the Environmental Defense Fund (EDF, 1995c), according to their agreed methodology. With the addition of precombustion energy and emission data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of secondary office paper. Figure 5.4-2 shows a simplified process flow diagram for processing secondary office paper.

The data in the LCI profile for secondary office paper were primarily developed through the use of the EDF's White Paper 10A on business and writing paper (EDF, 1995c). EDF's Table 3, Environmental Parameters for an uncoated freesheet paper with 100 percent secondary content, which presents a cradle-to-gate environmental data profile for 1 short ton of secondary office paper, was used along with precombustion energy and emission data from the Franklin report (1998). The following steps outline the procedure taken to calculate inventory data for secondary office paper:

Table 5.4-1. Data for Production of 1 Ton of Primary Office Paper[a]

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	4.67E+02	4.90E+00	1.05E-02
Natural Gas	cu ft	3.57E+03	4.14E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	2.83E+02	3.24E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	8.88E+00	1.52E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu	6.05E+06	6.05E+00	1.00E-06
Black Liquor	Btu	1.64E+07	1.64E+01	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	4.77E+02	5.54E-01	1.16E-03
Residual Oil	gal	4.84E-01	8.28E-02	1.71E-01
Distillate oil	gal	3.87E-01	6.12E-02	1.58E-01
Gasoline	gal	2.10E-01	2.96E-02	1.41E-01
LPG	gal	1.33E-02	1.43E-03	1.08E-01
Coal	lb	4.96E+00	5.69E-02	1.15E-02
Nuclear	lb U238	1.97E-05	2.04E-02	1.04E+03
Hydropower	Btu	3.12E+03	3.12E-03	1.00E-06
Other	Btu	2.76E+03	2.76E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	1.73E-07		1.73E-07
Ammonia	lb	4.49E-04		4.49E-04
Antimony	lb	9.65E-07		9.65E-07
Arsenic	lb	2.21E-06		2.21E-06
Benzene	lb	6.48E-07		6.48E-07
Beryllium	lb	1.65E-07		1.65E-07
Cadmium	lb	3.05E-06		3.05E-06
Carbon Dioxide-fossil	lb	2.36E+03	2.27E+03	9.29E+01
Carbon Dioxide-nonfossil (1)	lb	7.53E+03	7.53E+03	2.44E-01
Carbon Dioxide-nonfossil (2)	lb	4.10E+03	4.10E+03	2.44E-01
Carbon Monoxide	lb	9.33E-01		9.33E-01
Carbon Tetrachloride	lb	1.23E-06		1.23E-06
Chlorine	lb	1.64E-05		1.64E-05
Chromium	lb	2.68E-06		2.68E-06

(continued)

Table 5.4-1. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	2.78E-06		2.78E-06
Dioxins	lb	9.52E-13		9.52E-13
Formaldehyde	lb	7.90E-07		7.90E-07
Hydrocarbons (non CH_4)	lb	9.86E+00	7.46E+00	2.40E+00
Hydrochloric Acid	lb	9.01E-04		9.01E-04
Hydrogen Fluoride	lb	1.20E-04		1.20E-04
Kerosene	lb	4.10E-06		4.10E-06
Lead	lb	3.09E-06		3.09E-06
Manganese	lb	3.88E-06		3.88E-06
Mercury	lb	7.53E-07		7.53E-07
Metals	lb	9.72E-05		9.72E-05
Methane	lb	2.72E+00		2.72E+00
Methylene Chloride	lb	7.92E-07		7.92E-07
Naphthalene	lb	2.78E-07		2.78E-07
Nickel	lb	4.26E-05		4.26E-05
Nitrogen Oxides	lb	1.35E+01	1.29E+01	5.75E-01
Nitrous Oxide	lb	1.18E-04		1.18E-04
n-nitrodimethylamine	lb	3.68E-08		3.68E-08
Other Aldehydes	lb	6.77E-03		6.77E-03
Other Organics	lb	7.82E-03		7.82E-03
Particulate	lb	1.25E+01	1.17E+01	7.54E-01
Perchloroethylene	lb	1.81E-07		1.81E-07
Phenols	lb	4.82E-06		4.82E-06
Radionuclides (Ci)	lb	3.23E-06		3.23E-06
Selenium	lb	2.19E-06		2.19E-06
Sulfur Oxides	lb	3.02E+01	2.29E+01	7.35E+00
Trichloroethylene	lb	1.63E-07		1.63E-07
Solid Wastes	lb	1.65E+02	4.55E+01	1.20E+02
Waterborne Emissions				
Acid	lb	8.40E-08		8.40E-08
Ammonia	lb	1.55E-04		1.55E-04
Boron	lb	8.49E-04		8.49E-04
BOD	lb	7.91E-02	6.82E-02	1.09E-02
COD	lb	3.67E+00	3.59E+00	7.66E-02
Cadmium	lb	5.13E-04		5.13E-04
Calcium	lb	3.54E-06		3.54E-06
Chlorides	lb	5.13E-01		5.13E-01
Chromates	lb	2.50E-06		2.50E-06
Chromium	lb	5.13E-04		5.13E-04
Cyanide	lb	7.69E-07		7.69E-07
Dissolved Solids	lb	1.15E+01	2.59E-01	1.12E+01

(continued)

Table 5.4-1. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	1.64E-05		1.64E-05
Iron	lb	3.44E-02		3.44E-02
Lead	lb	1.48E-07		1.48E-07
Manganese	lb	2.23E-02		2.23E-02
Mercury	lb	4.03E-08		4.03E-08
Metal Ion	lb	1.76E-03		1.76E-03
Nitrates	lb	1.56E-06		1.56E-06
Oil	lb	2.01E-01		2.01E-01
Other Organics	lb	3.24E-02		3.24E-02
Phenol	lb	5.81E-06		5.81E-06
Phosphate	lb	1.07E-04		1.07E-04
Sodium	lb	6.57E-06		6.57E-06
Sulfates	lb	4.04E-01		4.04E-01
Sulfuric Acid	lb	2.12E-04		2.12E-04
Suspended Solids	lb	4.71E-01	4.55E-02	4.26E-01
Zinc	lb	1.78E-04		1.78E-04

[a]The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

1. The EDF secondary office paper profile was converted from kilogram per ton to pounds per ton for water emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels and electricity used in the process were not included in the EDF published data sets. Hence, the appropriate emissions and precombustion energies from the Franklin Associates report (1998) were added to make it a cradle-to-gate profile.

Table 5.4-2 summarizes the cradle-to-gate LCI data for secondary office paper production. Table 5.4-2 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

Table 5.4-2. Data for Production of 1 Ton of Secondary Office Paper

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	6.42E+02	6.75E+00	1.05E-02
Natural Gas	cu ft	4.91E+03	5.70E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	3.90E+02	4.47E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	1.22E+01	2.09E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu			1.00E-06
Black Liquor	Btu			1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	6.57E+02	7.62E-01	1.16E-03
Residual Oil	gal	6.67E-01	1.14E-01	1.71E-01
Distillate oil	gal	5.33E-01	8.43E-02	1.58E-01
Gasoline	gal	2.88E-01	4.08E-02	1.41E-01
LPG	gal	1.83E-02	1.97E-03	1.08E-01
Coal	lb	6.83E+00	7.83E-02	1.15E-02
Nuclear	lb U238	2.71E-05	2.81E-02	1.04E+03
Hydropower	Btu	4.30E+03	4.30E-03	1.00E-06
Other	Btu	3.81E+03	3.81E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	2.38E-07		2.38E-07
Ammonia	lb	6.18E-04		6.18E-04
Antimony	lb	1.33E-06		1.33E-06
Arsenic	lb	3.04E-06		3.04E-06
Benzene	lb	8.92E-07		8.92E-07
Beryllium	lb	2.28E-07		2.28E-07
Cadmium	lb	4.20E-06		4.20E-06
Carbon Dioxide-fossil	lb	3.25E+03	3.12E+03	1.28E+02
Carbon Dioxide-nonfossil (1)	lb	3.36E-01		3.36E-01
Carbon Dioxide-nonfossil (2)	lb	3.36E-01		3.36E-01
Carbon Monoxide	lb	1.28E+00		1.28E+00
Carbon Tetrachloride	lb	1.69E-06		1.69E-06
Chlorine	lb	2.25E-05		2.25E-05
Chromium	lb	3.69E-06		3.69E-06

(continued)

Table 5.4-2. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	3.83E-06		3.83E-06
Dioxins	lb	1.31E-12		1.31E-12
Formaldehyde	lb	1.09E-06		1.09E-06
Hydrocarbons (non CH_4)	lb	6.24E+00	2.93E+00	3.31E+00
Hydrochloric Acid	lb	1.24E-03		1.24E-03
Hydrogen Fluoride	lb	1.65E-04		1.65E-04
Kerosene	lb	5.65E-06		5.65E-06
Lead	lb	4.26E-06		4.26E-06
Manganese	lb	5.34E-06		5.34E-06
Mercury	lb	1.04E-06		1.04E-06
Metals	lb	1.34E-04		1.34E-04
Methane	lb	3.75E+00		3.75E+00
Methylene Chloride	lb	1.09E-06		1.09E-06
Naphthalene	lb	3.83E-07		3.83E-07
Nickel	lb	5.86E-05		5.86E-05
Nitrogen Oxides	lb	1.00E+01	9.24E+00	7.92E-01
Nitrous Oxide	lb	1.63E-04		1.63E-04
n-nitrodimethylamine	lb	5.07E-08		5.07E-08
Other Aldehydes	lb	9.32E-03		9.32E-03
Other Organics	lb	1.08E-02		1.08E-02
Particulate	lb	4.92E+00	3.88E+00	1.04E+00
Perchloroethylene	lb	2.49E-07		2.49E-07
Phenols	lb	6.64E-06		6.64E-06
Radionuclides (Ci)	lb	4.45E-06		4.45E-06
Selenium	lb	3.02E-06		3.02E-06
Sulfur Oxides	lb	3.11E+01	2.10E+01	1.01E+01
Trichloroethylene	lb	2.25E-07		2.25E-07
Solid Wastes	lb	2.51E+02	8.64E+01	1.65E+02
Waterborne Emissions				
Acid	lb	1.16E-07		1.16E-07
Ammonia	lb	2.13E-04		2.13E-04
Boron	lb	1.17E-03		1.17E-03
BOD	lb	2.20E-01	2.05E-01	1.50E-02
COD	lb	2.61E+00	2.50E+00	1.05E-01
Cadmium	lb	7.06E-04		7.06E-04
Calcium	lb	4.88E-06		4.88E-06
Chlorides	lb	7.06E-01		7.06E-01
Chromates	lb	3.44E-06		3.44E-06
Chromium	lb	7.06E-04		7.06E-04
Cyanide	lb	1.06E-06		1.06E-06
Dissolved Solids	lb	1.54E+01		1.54E+01
Fluorides	lb	2.26E-05		2.26E-05
Iron	lb	4.74E-02		4.74E-02

(continued)

Table 5.4-2. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Lead	lb	2.03E-07		2.03E-07
Manganese	lb	3.07E-02		3.07E-02
Mercury	lb	5.55E-08		5.55E-08
Metal Ion	lb	2.42E-03		2.42E-03
Nitrates	lb	2.15E-06		2.15E-06
Oil	lb	2.77E-01		2.77E-01
Other Organics	lb	4.45E-02		4.45E-02
Phenol	lb	8.00E-06		8.00E-06
Phosphate	lb	1.47E-04		1.47E-04
Sodium	lb	9.05E-06		9.05E-06
Sulfates	lb	5.56E-01		5.56E-01
Sulfuric Acid	lb	2.92E-04		2.92E-04
Suspended Solids	lb	6.77E-01	9.09E-02	5.86E-01
Zinc	lb	2.45E-04		2.45E-04

[a]The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

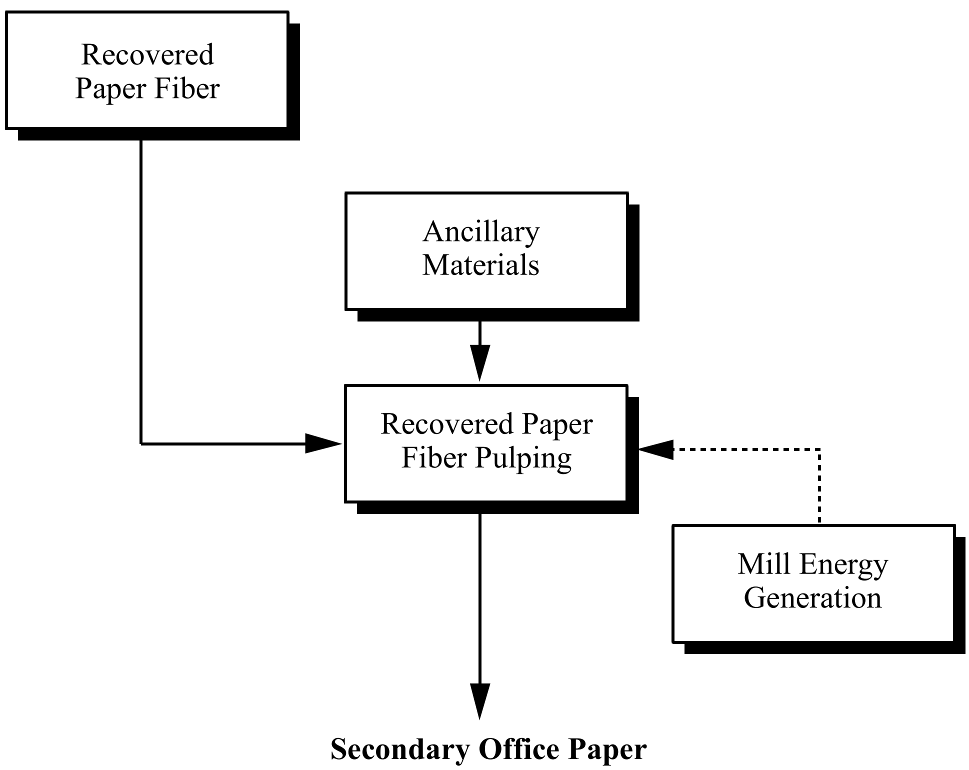


Figure 5.4-2. Simplified process flow diagram for secondary office paper production.

5.4.4 Data Quality

Table 5.4-3 summarizes data quality for the primary and secondary office paper LCI profiles. EDF data were based on a thorough survey of North American paper mills. The results determined here are thought to be representative of U.S. production. Because secondary data were used in this study, precision, consistency, and completeness of information are not available.

Table 5.4-4 shows how certain data in the primary office paper LCI profile compare with data from other public sources, and thus provides a measure of representativeness. In 1992, the World Energy Council estimated that, world wide, the pulp and paper industry consumed between 17 and 26 million Btu per ton of output (IIED, 1996). That range takes into account all products produced by the pulp and paper industry globally, from products such as newsprint, which is quite a different paper grade and requires comparatively smaller amounts of processing energy, to primary bleached kraft paper. Table 5.4-4 compares the gross energy data (the simple sum of combustion process energy and precombustion energy) from this EPA work and European data for different grades of paper. Gross energy can vary by more than 50 percent depending on the grade of paper compared. Furthermore, there is great variation in emissions among the different paper grades compared in Table 5.4-4.

Table 5.4-5 shows how the data in the secondary office paper LCI profile compare with data from other public sources, and thus provides a measure of representativeness. As with primary paper, there is great variation in inventory data for the different grades of secondary paper. The main source of data on paper is the SFAEFL database, which profiles many different paper grades, among them 100 percent secondary deinked paper and 100 percent secondary nondeinked paper (SFAEFL, 1996). Also shown in Table 5.4-5 are data for newsprint, which is a low-grade paper containing secondary fibers. Again here, as with primary paper, it must be emphasized that the wide range of different paper grades available will account for large variations in energy requirements and emissions. Gross energy data (the simple sum of combustion process energy and precombustion energy) from the current work is only 5 percent lower than 100 percent secondary deinked paper, the paper grade closest in composition to secondary office paper. There is greater variation in other emissions, such as CO_2.

The data for the primary and secondary office paper profiles is considered to be of average quality.

5.5 Textbook Paper

5.5.1 Introduction

This section contains LCI profiles for primary and secondary textbook paper production. Process flow diagrams and descriptions for production processes are provided, followed by LCI data tables for 1 short ton of product. Data quality information for the textbook paper LCI profiles is included in Section 5.5.4.

Table 5.4-3. Data Quality Summary for Primary and Secondary Office Paper

Data Quality Indicator	Office Paper	
	Primary	Secondary
Geographic Coverage	The data represents North American paper mills producing uncoated free sheet paper using bleached kraft pulp.	The data represents North American paper mills producing uncoated free sheet paper using de-inked recovered pulp
Time Period Coverage	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996
Technology Coverage	The data represents an average profile for the following three bleached Kraft pulps ■ 50% chlorine dioxide substituted for elemental chlorine in the first bleaching stage; ■ 100% chlorine dioxide substituted for elemental chlorine in the first bleaching stage; and ■ oxygen delignification and 100% chlorine dioxide substituted for elemental chlorine in the first bleaching stage.	No significant variations in technology were outlined by EDF
Precision	Information not available	Information not available
Consistency	Information not available	Information not available
Completeness	Information not available	Information not available
Representativeness	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.

(continued)

Table 5.4-3. (concluded)

Data Quality Indicator	Office Paper	
	Primary	**Secondary**
Reproducibility	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.4.1 at the product level.	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.4.1 at the product level.
Sources of Data	■ EDF's report 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.	■ EDF's report 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.
Uncertainty	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following IS0 14040 (1994), internal expert review was carried out for this data set.	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following IS0 14040, internal expert review was carried out for this data set.
Data Quality Rating	The data are considered to be of average quality.	The data are considered to be of average quality.

Table 5.4-4. Comparison to Literature of Key Inventory Data Values for Primary Office Paper

	Unit	EPA Primary Office Paper Profile	SFAEFL 1996 Kraft Bleached Uncoated	SFAEFL 1996 Graph Paper Woody Uncoated
Energy	MMBtu/ton	36.25	56.92	42.45
NO_x	lb/ton	13.5	9.50	4.64
NMVOC*	lb/ton	7.8	3.70	1.464
COD	lb/ton	3.6	84.60	16.66

[a] SFAEFL, 1996.
*Non-methane volatile organic compounds.

Table 5.4-5. Comparison to Literature of Key Inventory Data Values for Secondary Office Paper

	Unit	EPA Recycled Office Paper Profile	SFAEFL 1996 Recycled (Deinked) Paper[a]	SFAEFL 1996 Recycled Paper Without Deinking	SFAEFL 1996 Newsprint
Energy	MMBtu/ton	19.1	20.0	10.4	15.4
NO_x	lb/ton	10.0	5.3	1.8	3.2
NMVOC*	lb/ton	3.4	1.8	0.6	1.0
COD	lb/ton	2.5	16.7	0.02	15.1

*Non-methane volatile organic compounds.

The boundaries for the textbook paper LCI profiles include harvesting of trees, transporting of logs (or chips) to the mill, debarking and chipping, and manufacture of pulp and paper using primary fiber. This inventory data for the production of primary textbook paper was collected and published by the EDF, according to their agreed methodology (EDF, 1995c). With the addition of precombustion energy and emissions data taken from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of primary textbook paper. Figure 5.5-1 shows a simplified process flow diagram for processing primary textbook pulp.

5.5.2 Textbook Paper Production

The data included in the primary textbook paper LCI profile represent primary, uncoated groundwood textbook paper, which consists of 94 percent pulp and 6 percent moisture. Groundwood pulp is a low-grade pulp used for printed text. The data in this profile were primarily developed through the use of the EDF's White Paper 10A on business and writing paper (EDF, 1995c). EDF's Table 4, Environmental Parameters for an uncoated groundwood paper with 0% secondary content, which presents a cradle-to-gate LCI data profile for 1 short ton of primary textbooks, was used along with precombustion energy and emissions data published by Franklin Associates (1998). The following steps outline the procedure used to calculate inventory data for virgin textbooks.

1. The EDF primary textbook data profile was converted from kilograms per metric ton to pounds per ton for emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels used in the process were not included in the EDF publication; hence, the appropriate emissions and precombustion energies from the Franklin report were added to make it a cradle-to-gate profile.

3. To account for the regeneration of wood (from the forest) that accompanies its removal as a a result of forest management, this profile assumes that, for every pound of wood used in the paper-making process, an equivalent is regenerated.

For every pound of wood consumed in the paper-making process (approximately 94 percent of paper weight is wood fiber), 2.2 lb of CO_2 is subtracted from the biomass material balance.

Table 5.5-1 summarizes the cradle-to-gate LCI data for primary textbook paper. Table 5.5-1 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

See Sections 5.2 and 5.3 for a brief description of the sequence of production for paper from primary sources, including forest management and wood procurement, wood residues production, and pulp production (mechanical).

5.5.3 Secondary Textbook Production

This section contains an LCI profile for secondary text book paper production. The data in this profile represents secondary, uncoated groundwood textbook paper made from 15 percent deinked recovered pulp (DIP) and 85 percent groundwood pulp. This section contains process flow diagrams and descriptions for production processes, LCI data tables for 1 short ton of product. Data quality information for the secondary textbook paper production LCI profile is included in Section 5.5.4.

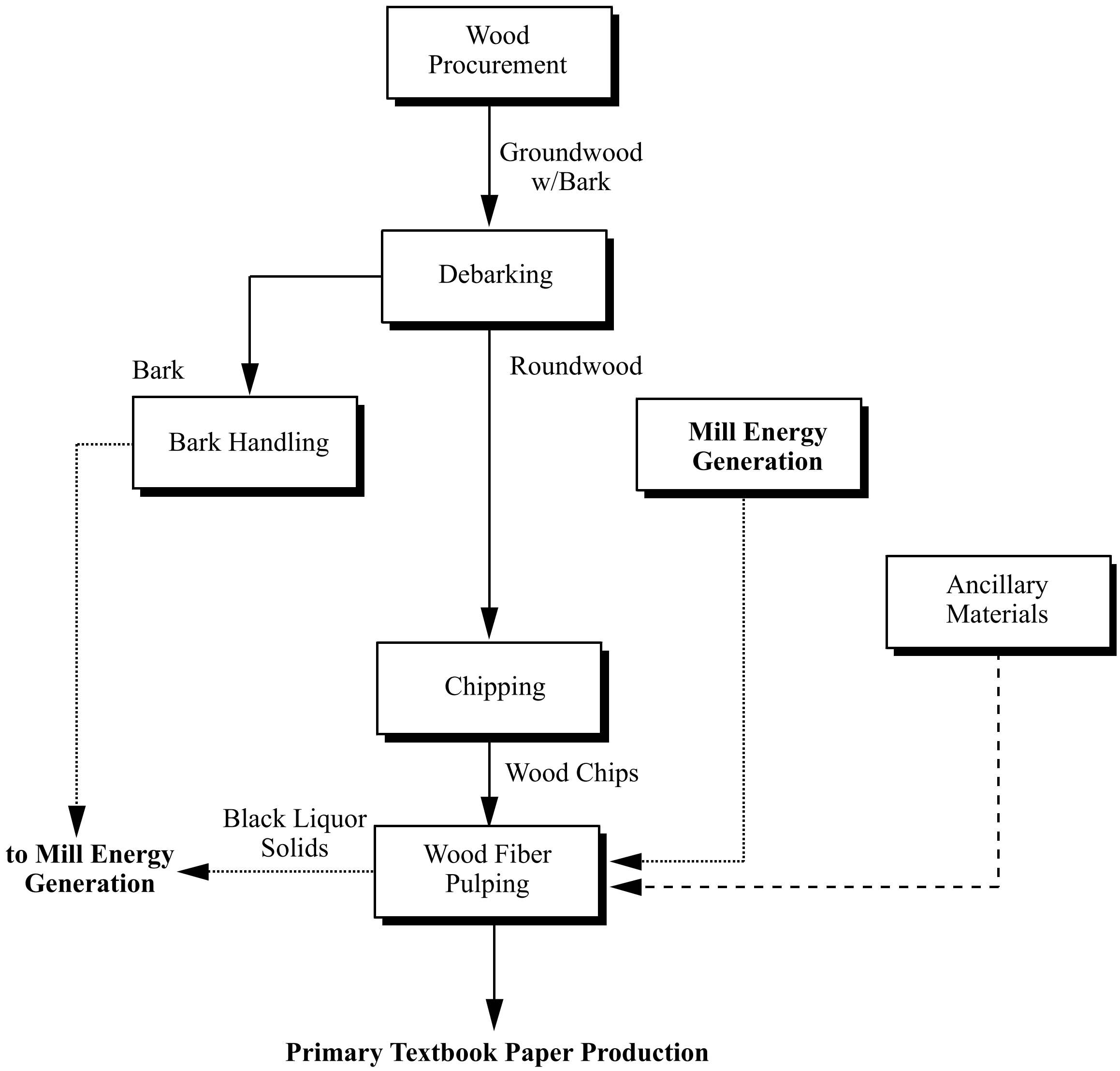


Figure 5.5-1. Simplified process flow diagram for primary textbook paper production.

Table 5.5-1. Data for Production of 1 Ton of Primary Textbook Paper[a]

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	1.02E+03	1.07E+01	1.05E-02
Natural Gas	cu ft	7.78E+03	9.03E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	6.17E+02	7.07E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	1.94E+01	3.31E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu	3.20E+06	3.20E+00	1.00E-06
Black Liquor	Btu	0.00E+00	0.00E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.04E+03	1.21E+00	1.16E-03
Residual Oil	gal	1.06E+00	1.81E-01	1.71E-01
Distillate oil	gal	8.44E-01	1.34E-01	1.58E-01
Gasoline	gal	4.57E-01	6.46E-02	1.41E-01
LPG	gal	2.90E-02	3.12E-03	1.08E-01
Coal	lb	1.08E+01	1.24E-01	1.15E-02
Nuclear	lb U238	4.30E-05	4.45E-02	1.04E+03
Hydropower	Btu	6.81E+03	6.81E-03	1.00E-06
Other	Btu	6.03E+03	6.03E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	3.76E-07		3.76E-07
Ammonia	lb	9.80E-04		9.80E-04
Antimony	lb	2.10E-06		2.10E-06
Arsenic	lb	4.81E-06		4.81E-06
Benzene	lb	1.41E-06		1.41E-06
Beryllium	lb	3.61E-07		3.61E-07
Cadmium	lb	6.66E-06		6.66E-06
Carbon Dioxide-fossil	lb	5.00E+03	4.80E+03	2.03E+02
Carbon Dioxide-nonfossil (1)	lb	6.01E+02	6.00E+02	5.32E-01
Carbon Dioxide-nonfossil (2)	lb	-3.54E+03	-3.54E+03	5.32E-01
Carbon Monoxide	lb	2.04E+00		2.04E+00
Carbon Tetrachloride	lb	2.68E-06		2.68E-06
Chlorine	lb	3.57E-05		3.57E-05
Chromium	lb	5.85E-06		5.85E-06

(continued)

Table 5.5-1. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	6.06E-06		6.06E-06
Dioxins	lb	2.08E-12		2.08E-12
Formaldehyde	lb	1.72E-06		1.72E-06
Hydrocarbons (non CH_4)	lb	1.04E+01	5.19E+00	5.24E+00
Hydrochloric Acid	lb	1.96E-03		1.96E-03
Hydrogen Fluoride	lb	2.62E-04		2.62E-04
Kerosene	lb	8.95E-06		8.95E-06
Lead	lb	6.75E-06		6.75E-06
Manganese	lb	8.46E-06		8.46E-06
Mercury	lb	1.64E-06		1.64E-06
Metals	lb	2.12E-04		2.12E-04
Methane	lb	5.94E+00		5.94E+00
Methylene Chloride	lb	1.73E-06		1.73E-06
Naphthalene	lb	6.06E-07		6.06E-07
Nickel	lb	9.28E-05		9.28E-05
Nitrogen Oxides	lb	2.06E+01	1.93E+01	1.25E+00
Nitrous Oxide	lb	2.58E-04		2.58E-04
n-nitrodimethylamine	lb	8.04E-08		8.04E-08
Other Aldehydes	lb	1.48E-02		1.48E-02
Other Organics	lb	1.71E-02		1.71E-02
Particulate	lb	1.38E+01	1.22E+01	1.64E+00
Perchloroethylene	lb	3.94E-07		3.94E-07
Phenols	lb	1.05E-05		1.05E-05
Radionuclides (Ci)	lb	7.05E-06		7.05E-06
Selenium	lb	4.79E-06		4.79E-06
Sulfur Oxides	lb	5.37E+01	3.77E+01	1.60E+01
Trichloroethylene	lb	3.57E-07		3.57E-07
Solid Wastes	lb	3.43E+02	8.18E+01	2.61E+02
Waterborne Emissions				
Acid	lb	1.83E-07		1.83E-07
Ammonia	lb	3.37E-04		3.37E-04
Boron	lb	1.85E-03		1.85E-03
BOD	lb	1.66E+00	1.64E+00	2.38E-02
COD	lb	1.52E+01	1.50E+01	1.67E-01
Cadmium	lb	1.12E-03		1.12E-03
Calcium	lb	7.72E-06		7.72E-06
Chlorides	lb	1.12E+00		1.12E+00
Chromates	lb	5.45E-06		5.45E-06
Chromium	lb	1.12E-03		1.12E-03
Cyanide	lb	1.68E-06		1.68E-06
Dissolved Solids	lb	2.44E+01		2.44E+01

(continued)

Table 5.5-1. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	3.58E-05		3.58E-05
Iron	lb	7.50E-02		7.50E-02
Lead	lb	3.22E-07		3.22E-07
Manganese	lb	4.87E-02		4.87E-02
Mercury	lb	8.79E-08		8.79E-08
Metal Ion	lb	3.83E-03		3.83E-03
Nitrates	lb	3.41E-06		3.41E-06
Oil	lb	4.39E-01		4.39E-01
Other Organics	lb	7.06E-02		7.06E-02
Phenol	lb	1.27E-05		1.27E-05
Phosphate	lb	2.33E-04		2.33E-04
Sodium	lb	1.43E-05		1.43E-05
Sulfates	lb	8.81E-01		8.81E-01
Sulfuric Acid	lb	4.63E-04		4.63E-04
Suspended Solids	lb	3.97E+00	3.05E+00	9.29E-01
Zinc	lb	3.88E-04		3.88E-04

[a] The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

The boundaries for this profile include the reprocessing of pulp and paper using recovered fiber and manufacture of primary pulp. The processes of collecting, baling, and transporting recovered paper to the repulping facility are included in other modules of the MSW-DST. The LCI data for the production of recovered textbook pulp were collected and published by EDF (1995c), according to their agreed methodology. With the addition of precombustion energy and emission data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of secondary textbook. Figure 5.5-2 shows a simplified process flow diagram for processing secondary textbook. The three main processing operations—deinking, pulping, and sheet formation—are described in Section 5.3. Refer to that section for details on these processes.

The data in this profile were primarily developed through the use of EDF's White Paper 10A on business and writing paper (EDF, 1995c). EDF's Table 4, Environmental Parameters for an uncoated groundwood paper with 15 percent secondary content, which presents a cradle-to-gate environmental data profile for 1 short ton of secondary office paper (EDF, 1995c), was used along with precombustion energy and emission data from the Franklin report (1998). The following steps outline the procedure used to calculate LCI data for secondary office paper:

1. The EDF secondary office paper profile was converted from kilograms per ton to pounds per ton for water emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels and electricity used in the process were not included in the EDF published data sets. Hence the appropriate emissions and precombustion energies from the Franklin Associates report (1998) were added to make it a cradle-to-gate profile.

3. To account for the regeneration of wood (from the forest) that accompanies its removal as a a result of forest management, this profile assumes that, for every pound of wood used in the paper-making process, an equivalent is regenerated. For every pound of wood consumed in the paper-making process (approximately 58 percent of paper weight is wood fiber), 2.2 lb of CO_2 is subtracted from the CO_2 biomass material balance.

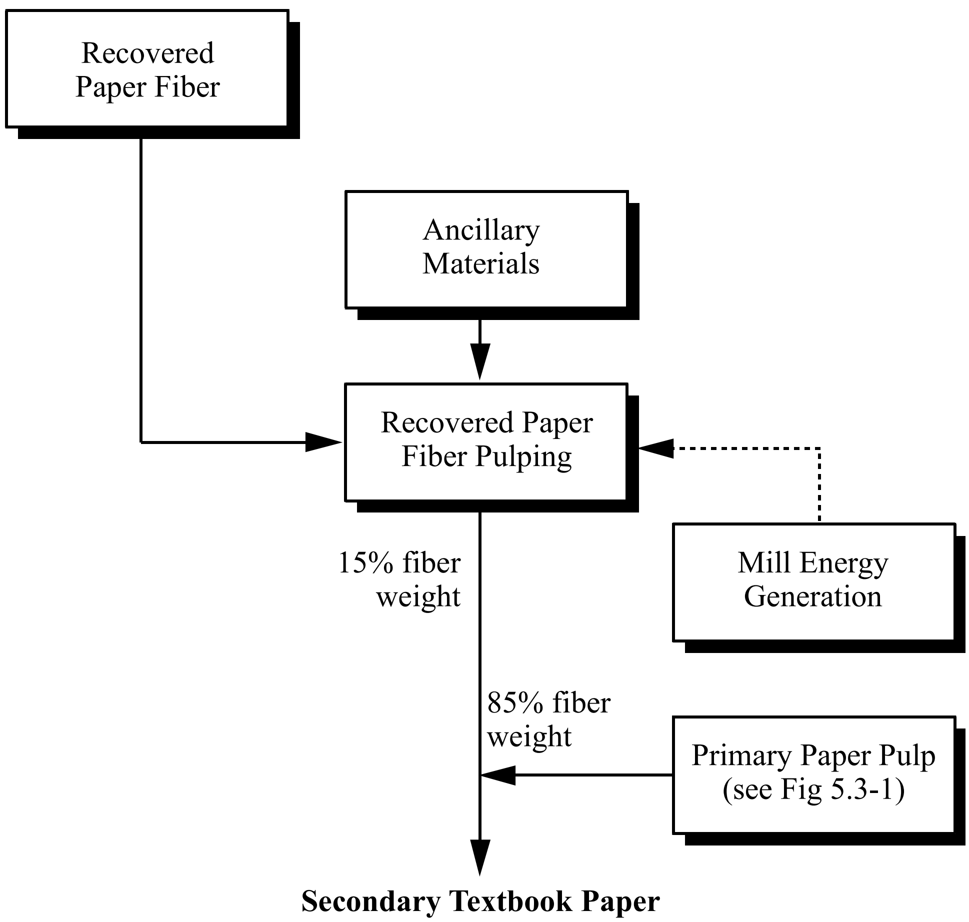


Figure 5-5.2. Simplified process flow diagram for secondary textbook paper production.

Table 5.5-2 summarizes the cradle-to-gate LCI data for secondary textbook paper production. Table 5.5-2 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

5.5.4 Data Quality

Table 5.5-3 summarizes data quality for primary and secondary textbook paper. EDF data were based on a thorough survey of North American paper mills. The results determined here are thought to be representative of U.S. production. Because secondary data were used to construct the textbook paper LCI profiles, measures of precision, consistency, and completeness of information are not available.

Table 5.5-4 shows how certain data in the primary textbook paper LCI profile compare with data from other public sources, and thus provides a measure of representativeness. In 1992 the World Energy Council estimated that, world wide, the pulp and paper industry consumed between 17 and 26 million Btu per ton of output (IIED, 1996). That range takes into account all products produced by the pulp and paper industry globally, from products such as newsprint, which require comparatively smaller amounts of processing energy and which is quite a different paper grade, to primary bleached kraft paper. Table 5.5-4 compares the gross energy data (the simple sum of combustion process energy and precombustion energy) from this EPA work and European data for different grades of paper. Gross energy can vary by more than 50 percent depending on the grade of paper compared. Furthermore, there is great variation in emissions among the different paper grades compared in Table 5.5-4.

Table 5.5-5 shows how the data in the secondary textbook paper LCI profile compare with data from other public sources, and thus provides a measure of representativeness. As with primary paper, there is great variation in inventory data for the different grades of secondary paper. The main source of data on paper is the SFAEFL database, which profiles many different paper grades, among them 100 percent secondary deinked paper and 100 percent secondary nondeinked paper (SFAEFL, 1996). Also shown in Table 5.5-5 are data for newsprint, which is a low-grade paper containing secondary content. Again here, as with primary paper, it must be emphasized that the wide range of different paper grades available will account for large variations in energy requirements and emissions. Gross energy data (the simple sum of combustion process energy and precombustion energy) from the current work is 40 percent higher than 100 percent secondary deinked paper. This larger variation is likely due to the fact that these two papers differ more significantly than the other papers (secondary office and telephone book paper) in this study compared with the SFAEFL data. There is greater variation in other emissions, such as CO_2.

The data in the primary and secondary textbook paper profiles are considered to be of average quality.

Table 5.5-2. Data for Production of 1 Ton of Secondary Textbook Paper[a]

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	9.70E+02	1.02E+01	1.05E-02
Natural Gas	cu ft	7.42E+03	8.61E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	5.89E+02	6.74E+00	1.15E-02
Distillate Oil	gal			1.58E-01
Residual Oil	gal	1.85E+01	3.16E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu	2.80E+06	2.80E+00	1.00E-06
Black Liquor	Btu	0.00E+00	0.00E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.12E+03	1.30E+00	1.16E-03
Residual Oil	gal	1.18E+00	2.02E-01	1.71E-01
Distillate oil	gal	1.26E+00	2.00E-01	1.58E-01
Gasoline	gal	4.97E-01	7.02E-02	1.41E-01
LPG	gal	3.19E-02	3.43E-03	1.08E-01
Coal	lb	1.42E+01	1.63E-01	1.15E-02
Nuclear	lb U238	5.61E-05	5.81E-02	1.04E+03
Hydropower	Btu	8.87E+03	8.87E-03	1.00E-06
Other	Btu	7.86E+03	7.86E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	4.91E-07		4.91E-07
Ammonia	lb	1.09E-03		1.09E-03
Antimony	lb	2.68E-06		2.68E-06
Arsenic	lb	6.29E-06		6.29E-06
Benzene	lb	1.90E-06		1.90E-06
Beryllium	lb	4.79E-07		4.79E-07
Cadmium	lb	8.53E-06		8.53E-06
Carbon Dioxide-fossil	lb	4.83E+03	4.60E+03	2.34E+02
Carbon Dioxide-nonfossil (1)	lb	6.87E+02	6.86E+02	6.95E-01
Carbon Dioxide-nonfossil (2)	lb	-2.31E+03	-2.31E+03	6.95E-01
Carbon Monoxide	lb	2.24E+00		2.24E+00
Carbon Tetrachloride	lb	3.84E-06		3.84E-06
Chlorine	lb	3.93E-05		3.93E-05
Chromium	lb	7.74E-06		7.74E-06

(continued)

Table 5.5-2. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	7.72E-06		7.72E-06
Dioxins	lb	2.69E-12		2.69E-12
Formaldehyde	lb	2.25E-06		2.25E-06
Hydrocarbons (non CH_4)	lb	1.07E+01	5.10E+00	5.62E+00
Hydrochloric Acid	lb	2.57E-03		2.57E-03
Hydrogen Fluoride	lb	3.43E-04		3.43E-04
Kerosene	lb	1.17E-05		1.17E-05
Lead	lb	8.38E-06		8.38E-06
Manganese	lb	1.13E-05		1.13E-05
Mercury	lb	2.12E-06		2.12E-06
Metals	lb	2.77E-04		2.77E-04
Methane	lb	8.31E+00		8.31E+00
Methylene Chloride	lb	2.27E-06		2.27E-06
Naphthalene	lb	7.91E-07		7.91E-07
Nickel	lb	1.19E-04		1.19E-04
Nitrogen Oxides	lb	1.98E+01	1.84E+01	1.43E+00
Nitrous Oxide	lb	3.48E-04		3.48E-04
n-nitrodimethylamine	lb	1.05E-07		1.05E-07
Other Aldehydes	lb	1.74E-02		1.74E-02
Other Organics	lb	2.09E-02		2.09E-02
Particulate	lb	1.43E+01	1.15E+01	2.84E+00
Perchloroethylene	lb	5.19E-07		5.19E-07
Phenols	lb	1.37E-05		1.37E-05
Radionuclides (Ci)	lb	9.18E-06		9.18E-06
Selenium	lb	6.18E-06		6.18E-06
Sulfur Oxides	lb	5.31E+01	3.60E+01	1.71E+01
Trichloroethylene	lb	4.66E-07		4.66E-07
Solid Wastes	lb	5.20E+02	9.55E+01	4.24E+02
Waterborne Emissions				
Acid	lb	2.00E-07		2.00E-07
Ammonia	lb	3.70E-04		3.70E-04
Boron	lb	2.40E-03		2.40E-03
BOD	lb	1.93E+00	1.91E+00	2.53E-02
COD	lb	1.40E+01	1.39E+01	1.78E-01
Cadmium	lb	1.19E-03		1.19E-03
Calcium	lb	1.01E-05		1.01E-05
Chlorides	lb	1.19E+00		1.19E+00
Chromates	lb	6.94E-06		6.94E-06
Chromium	lb	1.19E-03		1.19E-03
Cyanide	lb	1.78E-06		1.78E-06
Dissolved Solids	lb	2.60E+01		2.60E+01

(continued)

Table 5.5-2. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	4.68E-05		4.68E-05
Iron	lb	1.31E-01		1.31E-01
Lead	lb	3.51E-07		3.51E-07
Manganese	lb	8.50E-02		8.50E-02
Mercury	lb	9.33E-08		9.33E-08
Metal Ion	lb	4.17E-03		4.17E-03
Nitrates	lb	4.44E-06		4.44E-06
Oil	lb	4.66E-01		4.66E-01
Other Organics	lb	7.50E-02		7.50E-02
Phenol	lb	1.38E-05		1.38E-05
Phosphate	lb	3.00E-04		3.00E-04
Sodium	lb	1.87E-05		1.87E-05
Sulfates	lb	9.37E-01		9.37E-01
Sulfuric Acid	lb	6.01E-04		6.01E-04
Suspended Solids	lb	4.91E+00	3.32E+00	1.59E+00
Zinc	lb	4.12E-04		4.12E-04

[a] The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

Table 5.5-3. Data Quality Summary for Primary and Secondary Textbook Paper

Data Quality Indicator	Textbook Paper: Primary	Textbook Paper: Secondary
Geographic Coverage	The data represent North American paper mills producing coated freesheet and lightweight coated groundwood pulp	The data represent North American paper mills producing uncoated free sheet paper using deinked recovered pulp.
Time Period Coverage	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996.
Technology Coverage	No significant variations in technology were outlined by EDF	No significant variations in technology were outlined by EDF.
Precision	Information not available	Information not available
Consistency	Information not available	Information not available
Completeness	Information not available	Information not available
Representativeness	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.
Reproducibility	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.5.3 at the product level.	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.6.3 at the product level.
Sources of Data	EDF's reports 3 and 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.	EDF's reports 3 and 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.

(continued)

Table 5.5-3. (concluded)

Data Quality Indicator	Textbook Paper	
	Primary	**Secondary**
Uncertainty	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following ISO 14040 (1994), internal expert review was carried out for this data set.	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following ISO 14040, internal expert review was carried out for this data set.
Data Quality Rating	The data are considered to be of average quality.	The data are considered to be of average quality.

Table 5.5-4. Comparison to Literature of Key Inventory Data Values for Primary Textbook Paper

	Unit	EPA Primary Textbook Paper Profile	SFAEFL 1996 Kraft Bleached Uncoated	SFAEFL 1996 Graph Paper Woody Uncoated
Energy	MMBtu/ton	33.50	56.92	42.45
NOx	lb/ton	20.55	9.50	4.64
NMVOC*	lb/ton	6.01	3.70	1.464
COD	lb/ton	15.03	84.60	16.66

*Non-methane volatile organic compounds.

Table 5.5-5. Comparison to Literature of Key Inventory Data Values for Secondary Textbook Paper

	Unit	EPA Secondary Textbook Paper Profile	SFAEFL 1996 Recycled (Deinked) Paper	SFAEFL 1996 Recycled Paper Without Deinking	SFAEFL 1996 Newsprint
Energy	MMBtu/ton	31.7	20.0	10.4	15.4
NOx	lb/ton	19.8	5.3	1.8	3.2
NMVOC*	lb/ton	6.0	1.8	0.6	1.0
COD	lb/ton	13.9	16.7	0.02	15.1

*Non-methane volatile organic compounds.

5.6 Magazine Paper

5.6.1 Introduction

This section contains an LCI profile for primary and secondary magazine paper production, including process flow diagrams and descriptions for production processes and LCI data tables for 1 short ton of product. Data quality information is provided in Section 5.6.4

5.6.2 Primary Magazine Paper Production

The LCI profile for primary magazine paper production includes the harvesting of trees, transporting of logs (or chips) to the mill, debarking and chipping, and manufacture of pulp and paper using primary fiber. This LCI data for the production of primary magazine paper pulp was collected and published EDF, according to their agreed methodology (EDF, 1995c). With the addition of precombustion energy and emissions data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of primary magazine paper pulp. Figure 5.6-1 shows a simplified process flow diagram for processing primary magazine paper pulp.

The data profile represents primary magazine paper made using lightweight coated groundwood primary pulp. The clay coating accounts for 30 percent of the weight; the pulp furnish, 64 percent, and the remaining 6 percent is moisture (EDF, 1995c). Coated freesheet paper contains a mix of softwood and hardwood bleached kraft pulp, while the furnish of lightweight coated groundwood papers (LWC) contains an equal mix of bleached softwood kraft and mechanical pulps, which varies with basis weight. The softwood kraft pulp provides strength; the mechanical pulps impart opacity at low basis weights. The mechanical component

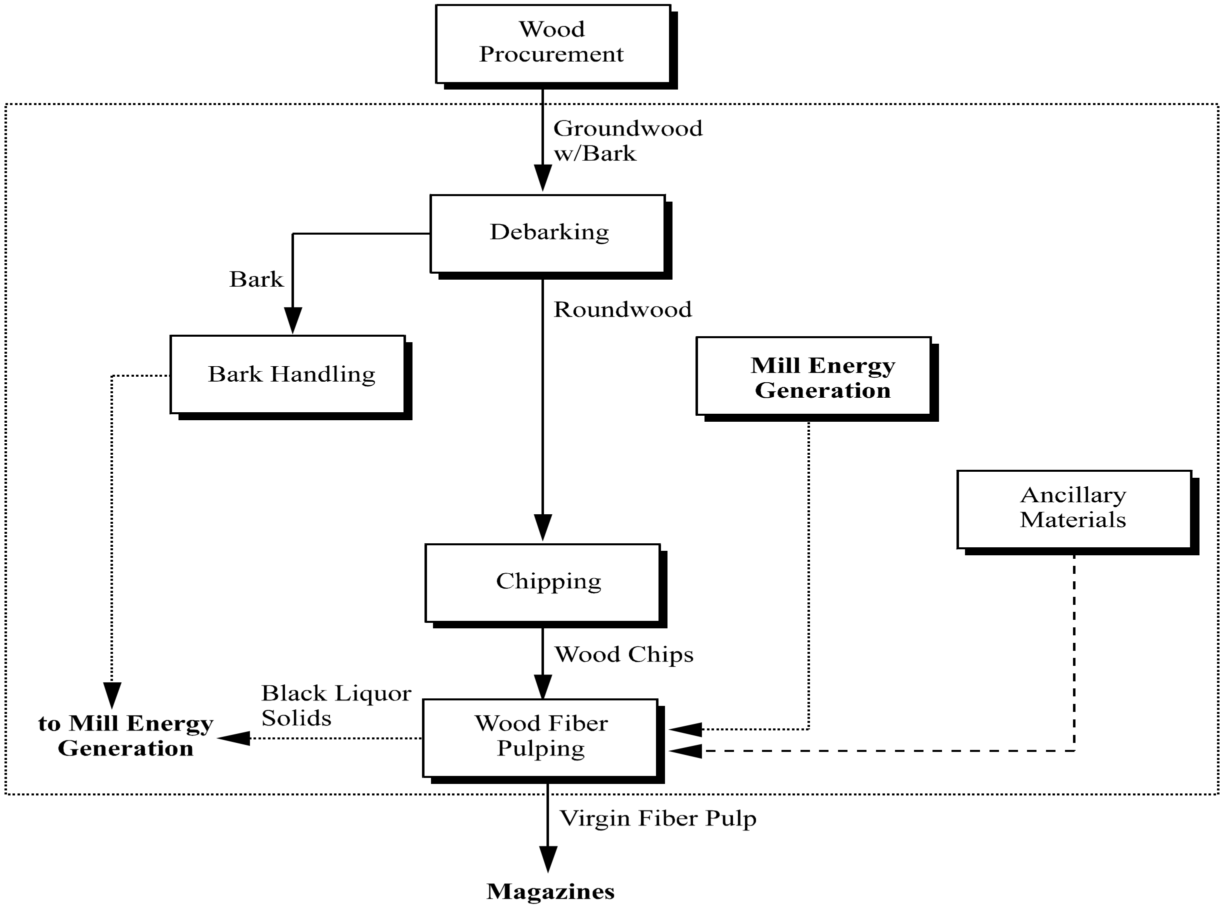


Figure 5.6-1. Simplified process flow diagram for primary magazine paper production.

of the furnish may contain stone groundwood pulp (SGP), pressurized groundwood pulp (PGW), TMP, or a combination of the three.

The groundwood and TMP processes use mechanical energy to separate the wood into fibers. Pressurized groundwood produces a stronger groundwood pulp by grinding the wood in a pressurized chamber. These mechanical pulping processes typically have pulp yields above 88 percent; thus, most of the lignin remains with the fibers. The yield loss includes small bundles of fibers and water soluble extractives such as resin and fatty acids.

See Sections 5.2 and 5.3 for brief descriptions of the sequence of paper production for primary systems, including forest management and wood procurement, wood residues production, pulping and paper formation. The production of primary magazine paper is identical.

The data in this profile were primarily developed through the use of EDF's White Paper 10A on business and writing paper (EDF, 1995c). EDF's Table 4, Environmental Parameters for lightweight coated groundwood primary paper with 0 percent secondary content, which presents a cradle-to-gate environmental data profile for 1 short ton of primary magazine paper, was used along with precombustion energy and emissions data published by Franklin Associates (1998). The following steps outline the procedure used to calculate inventory data for primary textbooks

1. The lightweight coated groundwood paper data profile (EDF, 1995c) was converted from kilograms per metric ton to pounds per ton for emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels used in the process were not included in the EDF publication; hence, the appropriate emissions and precombustion energies from the Franklin report were added to make it a cradle-to-gate profile.

3. To account for the regeneration of wood (from the forest) that accompanies its removal as a result of forest management, this profile assumes that, for every pound of wood used in the paper-making process, an equivalent is regenerated. For every pound of wood consumed in the paper-making process (approximately 64 percent of paper weight is wood fiber), 2.2 lb of CO_2 is subtracted from the biomass material balance.

Tables 5.6-1 summarizes the cradle-to-gate LCI data for primary magazine paper production. Table 5.6-1 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

5.6.3 Secondary Magazine Paper Production

The LCI profile for secondary magazine paper production represents coated groundwood magazine paper made using 10 percent DIP and 90 percent primary groundwood fiber. It contains process flow diagrams and descriptions for production processes, LCI data tables for 1 short ton of product, and a description of data quality.

The boundaries for this profile include the reprocessing of pulp and paper using recovered fiber and manufacture of primary pulp. The processes of collecting, baling, and transporting recovered paper to the repulping facility are included in other modules of the MSW-DST. The LCI data for the production of recovered magazine paper pulp were collected and published by EDF (1995c), according to their agreed methodology. With the addition of precombustion energy and emission data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of secondary magazine paper. Figure 5.6-2 shows a simplified process flow diagram for processing secondary magazine paper.

The data in this profile were primarily developed through the use of EDF's White Paper 10A on business and writing paper (EDF, 1995c). EDF's Table 4, Environmental Parameters for lightweight coated groundwood paper with 10 percent secondary content, which presents a cradle-to-gate environmental data profile for 1 short ton of secondary office paper, was used along with precombustion energy and emission data from the Franklin report (1998). The following steps outline the procedure used to calculate inventory data for secondary office paper.

1. The EDF lightweight coated groundwood paper with 10 percent secondary content paper profile was converted from kilograms per ton to pounds per ton for water emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels and electricity used in the process were not included in the EDF published data sets. Hence the appropriate emissions and precombustion energies from the Franklin Associates report (1998) were added to make it a cradle-to-gate profile.

3. To account for the regeneration of wood (from the forest) that accompanies its removal as a a result of forest management, this profile assumes that, for every pound of wood used in the paper-making process, an equivalent is regenerated. For every pound of wood consumed in the paper-making process (approximately 58 percent of paper weight is wood fiber), 2.2 lb of CO_2 is subtracted from the biomass material balance.

Table 5.6-2 summarizes the cradle-to-gate LCI data for secondary magazine paper production. Table 5.6-2 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

5.6.4 Data Quality

Table 5.6-3 summarizes data quality for primary and secondary magazine paper production. EDF data were based on a thorough survey of North American paper mills. The results determined here are thought to be representative of U.S. production. Because secondary data were used in this study, precision, consistency, and completeness of information are not available. The various data quality measures are defined below

Table 5.6-4 shows how certain data in the primary magazine paper profile compare with data from other public sources, and thus provides a measure of representativeness. In 1992, the World Energy Council estimated that, world wide, the pulp and paper industry consumed between 17 and 26 million Btu per ton of output (IIED, 1996). That range takes into account all products produced by the pulp and paper industry globally, from products such as newsprint, which is quite a different grade of paper and requires comparatively smaller amounts of processing energy, to primary bleached kraft paper. Table 5.6-4 compares the gross energy data

Table 5.6-1. Data for Producing 1 Ton of Primary Magazine Paper[a]

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	7.98E+02	8.38E+00	1.05E-02
Natural Gas	cu ft	6.10E+03	7.08E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	4.84E+02	5.55E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	1.52E+01	2.60E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu	8.00E+06	8.00E+00	1.00E-06
Black Liquor	Btu	0.00E+00	0.00E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	8.16E+02	9.47E-01	1.16E-03
Residual Oil	gal	8.28E-01	1.42E-01	1.71E-01
Distillate oil	gal	6.61E-01	1.05E-01	1.58E-01
Gasoline	gal	3.58E-01	5.07E-02	1.41E-01
LPG	gal	2.27E-02	2.45E-03	1.08E-01
Coal	lb	8.49E+00	9.72E-02	1.15E-02
Nuclear	lb U238	3.37E-05	3.49E-02	1.04E+03
Hydropower	Btu	5.34E+03	5.34E-03	1.00E-06
Other	Btu	4.73E+03	4.73E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	2.95E-07		2.95E-07
Ammonia	lb	7.68E-04		7.68E-04
Antimony	lb	1.65E-06		1.65E-06
Arsenic	lb	3.77E-06		3.77E-06
Benzene	lb	1.11E-06		1.11E-06
Beryllium	lb	2.83E-07		2.83E-07
Cadmium	lb	5.22E-06		5.22E-06
Carbon Dioxide-fossil	lb	4.04E+03	3.88E+03	1.59E+02
Carbon Dioxide-nonfossil (1)	lb	3.32E+03	3.32E+03	4.17E-01
Carbon Dioxide-nonfossil (2)	lb	5.03E+02	5.03E+02	4.17E-01
Carbon Monoxide	lb	1.60E+00		1.60E+00
Carbon Tetrachloride	lb	2.10E-06		2.10E-06
Chlorine	lb	2.80E-05		2.80E-05
Chromium	lb	4.59E-06		4.59E-06

(continued)

Table 5.6-1. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	4.75E-06		4.75E-06
Dioxins	lb	1.63E-12		1.63E-12
Formaldehyde	lb	1.35E-06		1.35E-06
Hydrocarbons (non CH_4)	lb	9.34E+00	5.23E+00	4.11E+00
Hydrochloric Acid	lb	1.54E-03		1.54E-03
Hydrogen Fluoride	lb	2.05E-04		2.05E-04
Kerosene	lb	7.02E-06		7.02E-06
Lead	lb	5.29E-06		5.29E-06
Manganese	lb	6.63E-06		6.63E-06
Mercury	lb	1.29E-06		1.29E-06
Metals	lb	1.66E-04		1.66E-04
Methane	lb	4.66E+00		4.66E+00
Methylene Chloride	lb	1.36E-06		1.36E-06
Naphthalene	lb	4.75E-07		4.75E-07
Nickel	lb	7.28E-05		7.28E-05
Nitrogen Oxides	lb	1.68E+01	1.58E+01	9.83E-01
Nitrous Oxide	lb	2.03E-04		2.03E-04
n-nitrodimethylamine	lb	6.30E-08		6.30E-08
Other Aldehydes	lb	1.16E-02		1.16E-02
Other Organics	lb	1.34E-02		1.34E-02
Particulate	lb	1.18E+01	1.05E+01	1.29E+00
Perchloroethylene	lb	3.09E-07		3.09E-07
Phenols	lb	8.25E-06		8.25E-06
Radionuclides (Ci)	lb	5.53E-06		5.53E-06
Selenium	lb	3.75E-06		3.75E-06
Sulfur Oxides	lb	4.42E+01	3.16E+01	1.26E+01
Trichloroethylene	lb	2.80E-07		2.80E-07
Solid Waste	lb	2.91E+02	8.64E+01	2.05E+02
Waterborne Emissions				
Acid	lb	1.44E-07		1.44E-07
Ammonia	lb	2.64E-04		2.64E-04
Boron	lb	1.45E-03		1.45E-03
BOD	lb	2.34E+00	2.32E+00	1.87E-02
COD	lb	1.89E+01	1.88E+01	1.31E-01
Cadmium	lb	8.77E-04		8.77E-04
Calcium	lb	6.06E-06		6.06E-06
Chlorides	lb	8.77E-01		8.77E-01
Chromates	lb	4.27E-06		4.27E-06
Chromium	lb	8.77E-04		8.77E-04
Cyanide	lb	1.31E-06		1.31E-06
Dissolved Solids	lb	1.95E+01	3.18E-01	1.92E+01

(continued)

Table 5.6-1. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	2.81E-05		2.81E-05
Iron	lb	5.88E-02		5.88E-02
Lead	lb	2.52E-07		2.52E-07
Manganese	lb	3.82E-02		3.82E-02
Mercury	lb	6.89E-08		6.89E-08
Metal Ion	lb	3.00E-03		3.00E-03
Nitrates	lb	2.67E-06		2.67E-06
Oil	lb	3.44E-01		3.44E-01
Other Organics	lb	5.53E-02		5.53E-02
Phenol	lb	9.94E-06		9.94E-06
Phosphate	lb	1.83E-04		1.83E-04
Sodium	lb	1.12E-05		1.12E-05
Sulfates	lb	6.91E-01		6.91E-01
Sulfuric Acid	lb	3.63E-04		3.63E-04
Suspended Solids	lb	4.09E+00	3.36E+00	7.28E-01
Zinc	lb	3.04E-04		3.04E-04

[a] The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

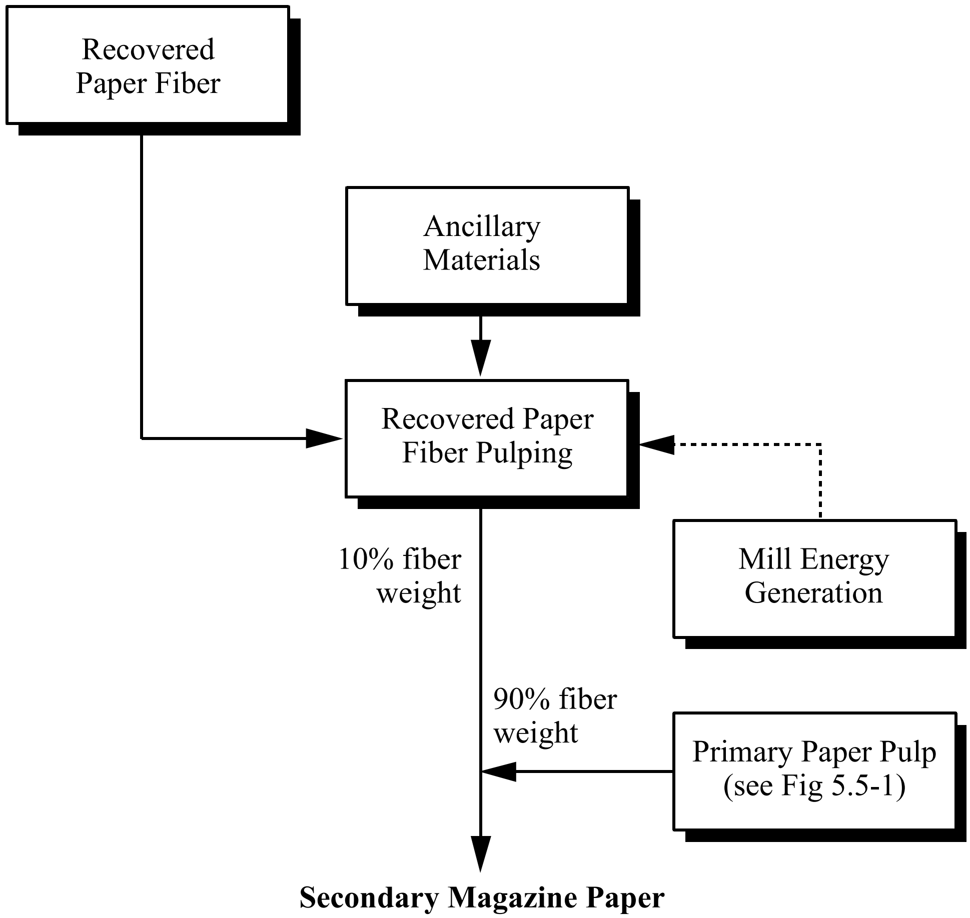


Figure 5.6-2. Simplified process flow diagram for secondary magazine paper production.

Table 5.6-2. Data for Producing 1 Ton of Secondary Magazine Paper[a]

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	7.88E+02	8.27E+00	1.05E-02
Natural Gas	cu ft	6.03E+03	6.99E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	4.78E+02	5.48E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	1.50E+01	2.56E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu	7.30E+06	7.30E+00	1.00E-06
Black Liquor	Btu	0.00E+00	0.00E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	8.06E+02	9.35E-01	1.16E-03
Residual Oil	gal	8.18E-01	1.40E-01	1.71E-01
Distillate oil	gal	6.53E-01	1.03E-01	1.58E-01
Gasoline	gal	3.54E-01	5.00E-02	1.41E-01
LPG	gal	2.24E-02	2.42E-03	1.08E-01
Coal	lb	8.38E+00	9.60E-02	1.15E-02
Nuclear	lb U238	3.33E-05	3.45E-02	1.04E+03
Hydropower	Btu	5.27E+03	5.27E-03	1.00E-06
Other	Btu	4.67E+03	4.67E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	2.91E-07		2.91E-07
Ammonia	lb	7.58E-04		7.58E-04
Antimony	lb	1.63E-06		1.63E-06
Arsenic	lb	3.72E-06		3.72E-06
Benzene	lb	1.09E-06		1.09E-06
Beryllium	lb	2.79E-07		2.79E-07
Cadmium	lb	5.15E-06		5.15E-06
Carbon Dioxide-fossil	lb	3.99E+03	3.83E+03	1.57E+02
Carbon Dioxide-nonfossil (1)	lb	2.97E+03	2.97E+03	4.12E-01
Carbon Dioxide-nonfossil (2)	lb	4.34E+02	4.33E+02	4.12E-01
Carbon Monoxide	lb	1.58E+00		1.58E+00
Carbon Tetrachloride	lb	2.08E-06		2.08E-06
Chlorine	lb	2.76E-05		2.76E-05
Chromium	lb	4.53E-06		4.53E-06

(continued)

Table 5.6-2. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	4.69E-06		4.69E-06
Dioxins	lb	1.61E-12		1.61E-12
Formaldehyde	lb	1.33E-06		1.33E-06
Hydrocarbons (non CH_4)	lb	9.05E+00	4.99E+00	4.06E+00
Hydrochloric Acid	lb	1.52E-03		1.52E-03
Hydrogen Fluoride	lb	2.02E-04		2.02E-04
Kerosene	lb	6.93E-06		6.93E-06
Lead	lb	5.23E-06		5.23E-06
Manganese	lb	6.55E-06		6.55E-06
Mercury	lb	1.27E-06		1.27E-06
Metals	lb	1.64E-04		1.64E-04
Methane	lb	4.60E+00		4.60E+00
Methylene Chloride	lb	1.34E-06		1.34E-06
Naphthalene	lb	4.69E-07		4.69E-07
Nickel	lb	7.19E-05		7.19E-05
Nitrogen Oxides	lb	1.65E+01	1.55E+01	9.71E-01
Nitrous Oxide	lb	2.00E-04		2.00E-04
n-nitrodimethylamine	lb	6.22E-08		6.22E-08
Other Aldehydes	lb	1.14E-02		1.14E-02
Other Organics	lb	1.32E-02		1.32E-02
Particulate	lb	1.14E+01	1.01E+01	1.27E+00
Perchloroethylene	lb	3.05E-07		3.05E-07
Phenols	lb	8.14E-06		8.14E-06
Radionuclides (Ci)	lb	5.46E-06		5.46E-06
Selenium	lb	3.70E-06		3.70E-06
Sulfur Oxides	lb	4.34E+01	3.10E+01	1.24E+01
Trichloroethylene	lb	2.76E-07		2.76E-07
Solid Wastes	lb	2.97E+02	9.55E+01	2.02E+02
Waterborne Emissions				
Acid	lb	1.42E-07		1.42E-07
Ammonia	lb	2.61E-04		2.61E-04
Boron	lb	1.43E-03		1.43E-03
BOD	lb	2.47E+00	2.45E+00	1.84E-02
COD	lb	2.38E+01	2.36E+01	1.29E-01
Cadmium	lb	8.66E-04		8.66E-04
Calcium	lb	5.98E-06		5.98E-06
Chlorides	lb	8.66E-01		8.66E-01
Chromates	lb	4.22E-06		4.22E-06
Chromium	lb	8.66E-04		8.66E-04
Cyanide	lb	1.30E-06		1.30E-06
Dissolved Solids	lb	1.92E+01	2.73E-01	1.89E+01

(continued)

Table 5.6-2. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	2.77E-05		2.77E-05
Iron	lb	5.81E-02		5.81E-02
Lead	lb	2.49E-07		2.49E-07
Manganese	lb	3.77E-02		3.77E-02
Mercury	lb	6.81E-08		6.81E-08
Metal Ion	lb	2.97E-03		2.97E-03
Nitrates	lb	2.64E-06		2.64E-06
Oil	lb	3.39E-01		3.39E-01
Other Organics	lb	5.46E-02		5.46E-02
Phenol	lb	9.81E-06		9.81E-06
Phosphate	lb	1.81E-04		1.81E-04
Sodium	lb	1.11E-05		1.11E-05
Sulfates	lb	6.82E-01		6.82E-01
Sulfuric Acid	lb	3.58E-04		3.58E-04
Suspended Solids	lb	5.17E+00	4.45E+00	7.19E-01
Zinc	lb	3.01E-04		3.01E-04

[a] The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

Table 5.6-3. Data Quality Summary for Primary and Secondary Magazine Paper

Data Quality Indicator	Magazine Paper: Primary	Magazine Paper: Secondary
Geographic Coverage	The data represent North American paper mills producing uncoated free sheet paper using bleached Kraft pulp.	The data represent North American paper mills producing newsprint using deinked recovered pulp.
Time Period Coverage	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996.	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996.
Technology Coverage	No significant variations in technology were outlined by EDF	No significant variations in technology were outlined by EDF.
Precision	Information not available	Information not available
Consistency	Information not available	Information not available
Completeness	Information not available	Information not available
Representativeness	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.
Reproducibility	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.6.3 at the product level.	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.6.3 at the product level.
Sources of Data	EDF’s reports 3 and 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.	EDF’s reports 3 and 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.
Uncertainty	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following IS0 14040 (1994), internal expert review was carried out for this data set.	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following IS0 14040, internal expert review was carried out for this data set.
Data Quality Rating	The data are considered to be of average quality.	The data are considered to be of average quality.

Table 5.6-4. Comparison to Literature of Key Inventory Data Values for Primary Magazine Paper

	Unit	EPA Primary Magazine Paper Profile	SFAEFL 1990 Kraft Standard Coated	SFAEFL 1996 Primary Paper Coated	SFAEFL 1996 Graph Paper Woody Uncoated
Energy	MMBtu/ton	31.76	42.65	47.06	42.45
NOx	lb/ton	16.47	11.25	8.24	4.64
NMVOC*	lb/ton	5.76	12.97	3.38	1.464
COD	lb/ton	18.84	41.69	61.40	16.66

*Non-methane volatile organic compounds.

(the simple sum of combustion process energy and precombustion energy) from this EPA work and European data for different grades of paper. Gross energy can vary by more than 50 percent depending on the grade of paper compared. Furthermore, there is great variation in emissions among the different paper grades compared in Table 5.6-4.

Table 5.6-5 shows how the data in the secondary magazine paper profile compares with data from other public sources, and thus provides a measure of representativeness. As with primary paper, there is great variation in LCI data for the different grades of secondary paper. The main source of data for paper is SFAEFL (1996) database, which profiles many different paper grades, among them 100 percent secondary deinked paper and 100 percent secondary nondeinked paper. Also shown in Table 5.6-5 are data for newsprint, which is a low-grade paper containing secondary fibers. Again here, as with primary paper, it must be emphasized that the wide range of different paper grades available will account for large variations in energy requirements and emissions. Gross energy data (the simple sum of combustion process energy and precombustion energy) for recycled magazine paper from the current work is 35 percent higher than that for 100 percent secondary deinked paper. This larger variation is likely due to the fact that these two papers differ more significantly than the other papers (secondary office and telephone book paper) in this study compared with the SFAEFL data. There is greater variation in other emissions, such as CO_2.

The data in the primary and secondary magazine paper profiles are considered to be of average quality.

Table 5.6-5. Comparison to Literature of Key Inventory Data Values for Secondary Magazine Paper

	Unit	EPA Secondary Magazine Paper Profile	SFAEFL 1996 Secondary (Deinked) Paper	SFAEFL 1996 Secondary Paper Without Deinking	SFAEFL 1996 Newsprint
Energy	MMBtu/ton	30.8	20.0	10.4	15.4
NOx	lb/ton	16.5	5.3	1.8	3.2
NMVOC*	lb/ton	5.8	1.8	0.6	1.0
COD	lb/ton	23.7	16.7	0.02	15.1

*Non-methane volatile organic compounds.

5.7 Telephone Book Paper

5.7.1 Introduction

This section contains LCI profiles for the production of primary and secondary rolls of telephone book paper and includes process flow diagrams and descriptions for production processes, description of data quality followed by LCI data tables for one short ton of primary and secondary paper rolls.

5.7.2 Primary Telephone Book Paper Production

The data profile represents primary telephone book paper made using thermomechanical pulp (TMP). The boundaries for this study include the harvesting of trees, transporting of logs (or chips) to the mill, debarking and chipping, and manufacture of pulp and paper using primary and secondary fiber. The LCI data for the production of primary telephone book pulp was collected and published by EDF, according to their agreed methodology (EDF, 1995a). With the addition of pre-combustion energy and emissions data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of primary telephone book pulp. Figure 5.7-1 shows a simplified process flow diagram for processing primary telephone book pulp.

See Sections 5.2 and 5.3 for a brief description of the sequence of production for primary office paper, including forest management and wood procurement, wood residues production, pulp production, and paper formation. The production of primary telephone book paper is identical.

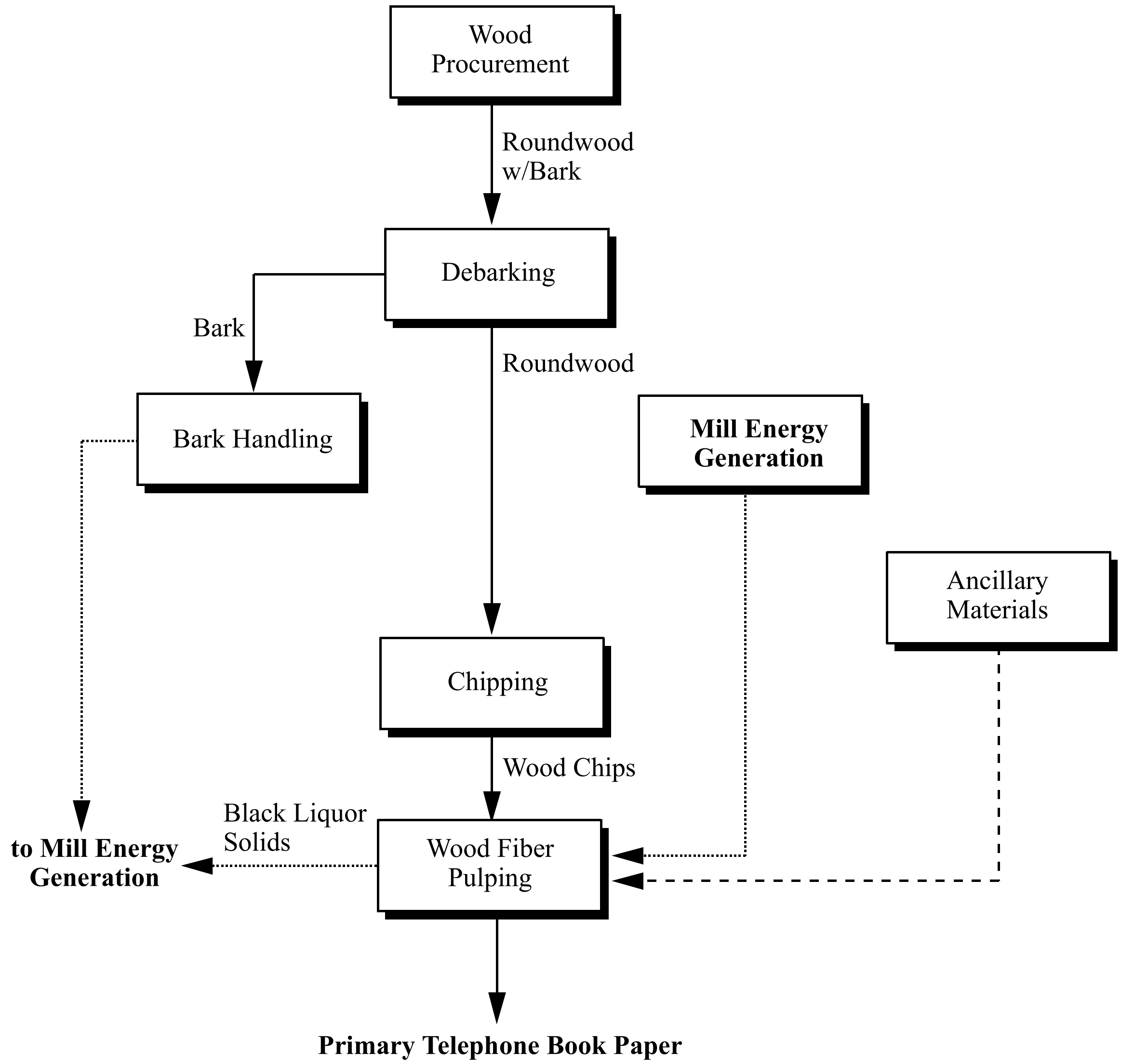


Figure 5.7-1. Simplified process flow diagram for primary telephone book paper production.

The data in this profile were primarily developed through the use of EDF's White Paper 3 on Virgin Paper and Recycled Paper-Based Systems (EDF, 1995a). The EDF White Paper 3,[1]

[1] From White paper 3, this data profile was incorporated: Figure S1 – Average Energy Use and Environmental Releases for Managing Newsprint; Figure 1 - Solid Waste Outputs from Component Activities of Discarded Paper Production and Management; Figure 2 - Solid Waste Output for Discarded Paper Production and Management; Figure 3 - Total, Purchased and Fossil Fuel Energy Use for Component Activities of Paper Production and Management; Figure 4 - Energy Use for Discarded Paper Production and Management; Figure 5 - NEWSPRINT: Air Emissions from Production and Management; and Figure 10 - NEWSPRINT: Waterborne Wastes from Production and Management.

which presents a cradle-to-gate environmental data profile for 1 short ton of primary telephone book paper, was used along with precombustion energy and emissions data published by Franklin Associates (1998). The following steps outline the procedure used to calculate LCI data for primary telephone book paper:

1. The primary telephone book data profile (EDF) was converted from kilograms per metric ton to pounds per ton for water emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) for the fuels used in the process were not included in the EDF publication; hence, the appropriate emissions and precombustion energies from the Franklin report were added to make it a cradle-to-gate profile.

3. To account for the regeneration of wood (from the forest) that accompanies its removal as a result of forest management, this profile assumes that, for every pound of wood used in the paper making process, an equivalent is regenerated. For every pound of wood consumed in the paper-making process (approximately 88 percent of paper weight is wood fiber), 2.2 lb of CO_2 is subtracted from the biomass material balance.

Table 5.7-1 summarizes the cradle-to-gate LCI data for primary telephone book paper production. Table 5.7-1 breaks down the individual fuels that make up precombustion energy related to process fuels and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and pre-combustion activities.

5.7.3 Secondary Telephone Book Paper Production

This sections contains an LCI profile for the production of secondary telephone book paper, representing 100 percent recovered fiber. It contains process flow diagrams and descriptions for production processes, description of data quality followed by LCI data tables for one short ton of product. The data in this profile represents secondary telephone book paper made using 100 percent DIP. See Section 5.3.5 for a description of the DIP process.

The boundaries for this profile include remanufacturing of pulp and paper using recovered fiber. The processes of collecting, baling, and transporting recovered paper to the repulping facility are included in other modules of the MSW-DST. The LCI data for the production of secondary telephone book pulp were collected and published by EDF (1995a), according to their agreed methodology. With the addition of precombustion energy and emission data from Franklin Associates (1998), the profile used in this study represents boundaries for the aggregated cradle-to-gate processing of one ton of secondary telephone book. Figure 5.7-2 shows a simplified process flow diagram for processing secondary telephone book.

Table 5.7-1. Data for Producing 1 Ton of Primary Telephone Book Paper[a]

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	1.15E+03	1.21E+01	1.05E-02
Natural Gas	cu ft	8.82E+03	1.02E+01	1.16E-03
LPG	gal			1.08E-01
Coal	gal	6.99E+02	8.01E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	2.19E+01	3.75E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu	9.45E+05	9.45E-01	1.00E-06
Black Liquor	Btu	2.56E+06	2.56E+00	1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.18E+03	1.37E+00	1.16E-03
Residual Oil	gal	1.20E+00	2.05E-01	1.71E-01
Distillate oil	gal	9.56E-01	1.51E-01	1.58E-01
Gasoline	gal	5.18E-01	7.32E-02	1.41E-01
LPG	gal	3.29E-02	3.54E-03	1.08E-01
Coal	lb	1.23E+01	1.41E-01	1.15E-02
Nuclear	lb U238	4.87E-05	5.04E-02	1.04E+03
Hydropower	Btu	7.71E+03	7.71E-03	1.00E-06
Other	Btu	6.83E+03	6.83E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	4.26E-07		4.26E-07
Ammonia	lb	1.11E-03		1.11E-03
Antimony	lb	2.38E-06		2.38E-06
Arsenic	lb	5.45E-06		5.45E-06
Benzene	lb	1.60E-06		1.60E-06
Beryllium	lb	4.09E-07		4.09E-07
Cadmium	lb	7.54E-06		7.54E-06
Carbon Dioxide-fossil	lb	4.07E+03	3.84E+03	2.30E+02
Carbon Dioxide-nonfossil (1)	lb	1.78E+03	1.78E+03	6.02E-01
Carbon Dioxide-nonfossil (2)	lb	-2.09E+03	-2.09E+03	6.02E-01
Carbon Monoxide	lb	2.31E+00		2.31E+00
Carbon Tetrachloride	lb	3.04E-06		3.04E-06
Chlorine	lb	4.04E-05		4.04E-05
Chromium	lb	6.63E-06		6.63E-06

(continued)

Table 5.7-1. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	6.86E-06		6.86E-06
Dioxins	lb	2.35E-12		2.35E-12
Formaldehyde	lb	1.95E-06		1.95E-06
Hydrocarbons (non CH_4)	lb	1.17E+01	5.79E+00	5.94E+00
Hydrochloric Acid	lb	2.23E-03		2.23E-03
Hydrogen Fluoride	lb	2.96E-04		2.96E-04
Kerosene	lb	1.01E-05		1.01E-05
Lead	lb	7.65E-06		7.65E-06
Manganese	lb	9.58E-06		9.58E-06
Mercury	lb	1.86E-06		1.86E-06
Metals	lb	2.40E-04		2.40E-04
Methane	lb	6.73E+00		6.73E+00
Methylene Chloride	lb	1.96E-06		1.96E-06
Naphthalene	lb	6.87E-07		6.87E-07
Nickel	lb	1.05E-04		1.05E-04
Nitrogen Oxides	lb	2.47E+01	2.33E+01	1.42E+00
Nitrous Oxide	lb	2.93E-04		2.93E-04
n-nitrodimethylamine	lb	9.11E-08		9.11E-08
Other Aldehydes	lb	1.67E-02		1.67E-02
Other Organics	lb	1.93E-02		1.93E-02
Particulate	lb	1.55E+01	1.36E+01	1.86E+00
Perchloroethylene	lb	4.47E-07		4.47E-07
Phenols	lb	1.19E-05		1.19E-05
Radionuclides (Ci)	lb	7.99E-06		7.99E-06
Selenium	lb	5.42E-06		5.42E-06
Sulfur Oxides	lb	6.00E+01	4.18E+01	1.82E+01
Trichloroethylene	lb	4.04E-07		4.04E-07
Solid Wastes	lb	6.62E+02	3.67E+02	2.96E+02
Waterborne Emissions				
Acid	lb	2.07E-07		2.07E-07
Ammonia	lb	3.82E-04		3.82E-04
Boron	lb	2.10E-03		2.10E-03
BOD	lb	1.16E+00	1.14E+00	2.70E-02
COD	lb	1.67E+01	1.65E+01	1.89E-01
Cadmium	lb	1.27E-03		1.27E-03
Calcium	lb	8.75E-06		8.75E-06
Chlorides	lb	1.27E+00		1.27E+00
Chromates	lb	6.17E-06		6.17E-06
Chromium	lb	1.27E-03		1.27E-03
Cyanide	lb	1.90E-06		1.90E-06
Dissolved Solids	lb	2.77E+01		2.77E+01

(continued)

Table 5.7-1. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	4.06E-05		4.06E-05
Iron	lb	8.50E-02		8.50E-02
Lead	lb	3.65E-07		3.65E-07
Manganese	lb	5.51E-02		5.51E-02
Mercury	lb	9.96E-08		9.96E-08
Metal Ion	lb	4.34E-03		4.34E-03
Nitrates	lb	3.86E-06		3.86E-06
Oil	lb	4.97E-01		4.97E-01
Other Organics	lb	7.99E-02		7.99E-02
Phenol	lb	1.44E-05		1.44E-05
Phosphate	lb	2.64E-04		2.64E-04
Sodium	lb	1.62E-05		1.62E-05
Sulfates	lb	9.99E-01		9.99E-01
Sulfuric Acid	lb	5.25E-04		5.25E-04
Suspended Solids	lb	3.23E+00	2.18E+00	1.05E+00
Zinc	lb	4.40E-04		4.40E-04

[a] The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

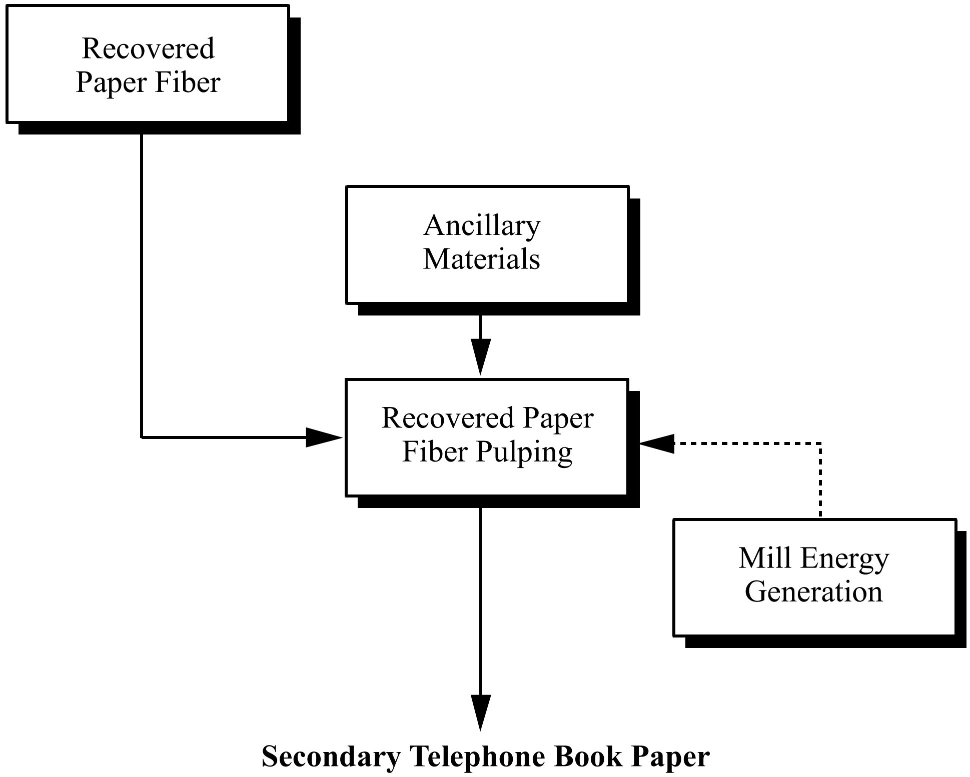


Figure 5.7-2. Simplified process flow diagram for secondary telephone book paper production.

The profile used in this study is composed mostly of paper recovered from offices. As a result, deinked recovered fiber pulps produced from recovered office paper contain a high percentage of bleached hardwood Kraft pulp. The three main processing operations—deinking, pulping, and sheet formation—are described in Sections 5.2 and 5.3. Refer to those section for details on these processes.

The data in this profile were primarily developed through the use of EDF's White Paper 3 on Virgin Paper And Recycled Paper-Based Systems (EDF, 1995a). The EDF white paper 3,[2] which presents a cradle-to-gate environmental data profile for 1 short ton of secondary telephone book paper, was used along with precombustion energy and emission data from the Franklin

[2] From White Paper 3, the following data were used: Figure S1 – Average Energy Use and Environmental Releases for Managing Newsprint; Figure 1 - Solid Waste Outputs from Component Activities of Discarded Paper Production and Management; Figure 2 - Solid Waste Output for Discarded Paper Production and Management; Figure 3 - Total, Purchased and Fossil Fuel Energy Use for Component Activities of Paper Production and Management; Figure 4 - Energy Use for Discarded Paper Production and Management; Figure 5 - NEWSPRINT: Air Emissions from Production and Management; and Figure 10 - NEWSPRINT: Waterborne Wastes from Production and Management.

report (1998). The following steps outline the procedure used to calculate LCI data from secondary office paper.

1. The EDF recycled office paper profile was converted from kilograms per ton to pounds per ton for water emissions and solid waste.

2. The precombustion energy and environmental emissions (air emissions, water emissions, and solid waste emissions) for the fuels and electricity used in the process were not included in the EDF published data sets. Hence the appropriate emissions and precombustion energies from the Franklin Associates report (1998) were added to make it a cradle-to-gate profile.

Table 5.7-2 summarizes the cradle-to-gate LCI data for secondary telephone book paper production. Table 5.7-2 breaks down the individual fuels that make up pre-combustion energy related to process fuels, and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

5.7.4 Data Quality

Table 5.7-3 summarizes data quality information for primary and secondary telephone book paper. EDF data were based on a thorough survey of North American paper mills. The results determined here are thought to be representative of U.S. production. Because secondary data were used in this study, precision, consistency, and completeness of information are not available.

Table 5.7-4 shows how certain data in the primary profile compare with data from other public sources, and thus provides a measure of representativeness. In 1992, the World Energy Council estimated that, world wide, the pulp and paper industry consumed between 17 and 26 million Btu per ton of output (IIED, 1996). That range takes into account all products produced by the pulp and paper industry globally, from products such as newsprint, which is quite a different grade of paper and requires comparatively smaller amounts of processing energy, to primary bleached kraft paper. Table compares the gross energy data (the simple sum of combustion process energy and precombustion energy) from this EPA work and European data for different grades of paper. Gross energy can vary by more than 50 percent depending on the grade of paper compared. There is greater variation in emissions among the different paper grades compared in Table 5.7-4.

Table 5.7-5 shows how the data in the secondary profile compare with data from other public sources, and thus provides a measure of representativeness. As with primary paper, there is great variation in inventory data for the different grades of secondary paper. The main source of data on paper is the SFAEFL database, which profiles many different paper grades, among them 100 percent secondary deinked paper and 100 percent secondary nondeinked paper (SFAEFL). Also shown in Table 5.7-5 are data for newsprint, which is a low-grade paper containing secondary fibers. Again here, as with primary paper, it must be emphasized that the wide range of different paper grades available will account for large variations in energy

Table 5.7-2. Data for Producing 1 Ton of Secondary Telephone Book Paper

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	7.03E+02	7.38E+00	1.05E-02
Natural Gas	cu ft	5.38E+03	6.24E+00	1.16E-03
LPG	gal			1.08E-01
Coal	gal	4.27E+02	4.89E+00	1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	1.34E+01	2.29E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu			1.00E-06
Black Liquor	Btu			1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	7.19E+02	8.35E-01	1.16E-03
Residual Oil	gal	7.30E-01	1.25E-01	1.71E-01
Distillate oil	gal	5.83E-01	9.23E-02	1.58E-01
Gasoline	gal	3.16E-01	4.47E-02	1.41E-01
LPG	gal	2.00E-02	2.16E-03	1.08E-01
Coal	lb	7.48E+00	8.57E-02	1.15E-02
Nuclear	lb U238	2.97E-05	3.08E-02	1.04E+03
Hydropower	Btu	4.70E+03	4.70E-03	1.00E-06
Other	Btu	4.17E+03	4.17E-03	1.00E-06

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Acreolin	lb	2.60E-07		2.60E-07
Ammonia	lb	6.77E-04		6.77E-04
Antimony	lb	1.45E-06		1.45E-06
Arsenic	lb	3.32E-06		3.32E-06
Benzene	lb	9.77E-07		9.77E-07
Beryllium	lb	2.49E-07		2.49E-07
Cadmium	lb	4.60E-06		4.60E-06
Carbon Dioxide-fossil	lb	3.60E+03	3.46E+03	1.40E+02
Carbon Dioxide-nonfossil (1)	lb	3.67E-01		3.67E-01
Carbon Dioxide-nonfossil (2)	lb	3.67E-01		3.67E-01
Carbon Monoxide	lb	1.41E+00		1.41E+00
Carbon Tetrachloride	lb	1.85E-06		1.85E-06
Chlorine	lb	2.47E-05		2.47E-05
Chromium	lb	4.04E-06		4.04E-06

(continued)

Table 5.7-2. (continued)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Cobalt	lb	4.19E-06		4.19E-06
Dioxins	lb	1.44E-12		1.44E-12
Formaldehyde	lb	1.19E-06		1.19E-06
Hydrocarbons (non CH_4)	lb	6.34E+00	2.72E+00	3.62E+00
Hydrochloric Acid	lb	1.36E-03		1.36E-03
Hydrogen Fluoride	lb	1.81E-04		1.81E-04
Kerosene	lb	6.19E-06		6.19E-06
Lead	lb	4.66E-06		4.66E-06
Manganese	lb	5.85E-06		5.85E-06
Mercury	lb	1.14E-06		1.14E-06
Metals	lb	1.46E-04		1.46E-04
Methane	lb	4.10E+00		4.10E+00
Methylene Chloride	lb	1.19E-06		1.19E-06
Naphthalene	lb	4.19E-07		4.19E-07
Nickel	lb	6.41E-05		6.41E-05
Nitrogen Oxides	lb	1.58E+01	1.49E+01	8.67E-01
Nitrous Oxide	lb	1.79E-04		1.79E-04
n-nitrodimethylamine	lb	5.55E-08		5.55E-08
Other Aldehydes	lb	1.02E-02		1.02E-02
Other Organics	lb	1.18E-02		1.18E-02
Particulate	lb	8.34E+00	7.20E+00	1.14E+00
Perchloroethylene	lb	2.73E-07		2.73E-07
Phenols	lb	7.27E-06		7.27E-06
Radionuclides (Ci)	lb	4.87E-06		4.87E-06
Selenium	lb	3.31E-06		3.31E-06
Sulfur Oxides	lb	3.58E+01	2.47E+01	1.11E+01
Trichloroethylene	lb	2.46E-07		2.46E-07
Solid Wastes	lb	4.21E+02	2.41E+02	1.80E+02
Waterborne Emissions				
Acid	lb	1.27E-07		1.27E-07
Ammonia	lb	2.33E-04		2.33E-04
Boron	lb	1.28E-03		1.28E-03
BOD	lb	1.15E+00	1.14E+00	1.64E-02
COD	lb	1.26E+01	1.25E+01	1.15E-01
Cadmium	lb	7.73E-04		7.73E-04
Calcium	lb	5.34E-06		5.34E-06
Chlorides	lb	7.73E-01		7.73E-01
Chromates	lb	3.76E-06		3.76E-06
Chromium	lb	7.73E-04		7.73E-04
Cyanide	lb	1.16E-06		1.16E-06
Dissolved Solids	lb	1.69E+01		1.69E+01

(continued)

Table 5.7-2. (concluded)[a]

Environmental Releases	Units	Total	Process	Fuel Related
Fluorides	lb	2.48E-05		2.48E-05
Iron	lb	5.19E-02		5.19E-02
Lead	lb	2.22E-07		2.22E-07
Manganese	lb	3.36E-02		3.36E-02
Mercury	lb	6.08E-08		6.08E-08
Metal Ion	lb	2.65E-03		2.65E-03
Nitrates	lb	2.35E-06		2.35E-06
Oil	lb	3.03E-01		3.03E-01
Other Organics	lb	4.88E-02		4.88E-02
Phenol	lb	8.76E-06		8.76E-06
Phosphate	lb	1.61E-04		1.61E-04
Sodium	lb	9.91E-06		9.91E-06
Sulfates	lb	6.09E-01		6.09E-01
Sulfuric Acid	lb	3.20E-04		3.20E-04
Suspended Solids	lb	3.77E+00	3.13E+00	6.42E-01
Zinc	lb	2.68E-04		2.68E-04

[a] The EDF report did not publish process-related emissions for many of the data categories such as CO emissions to air and other water emissions.

Source: EDF, 1995c; Franklin Associates, 1998.

Table 5.7-3. Data Quality Summary for Primary and Secondary Telephone Book Paper

Data Quality Indicator	**Telephone Book Paper**	
	Primary	**Secondary**
Geographic Coverage	The data represent North American paper mills producing uncoated groundwood book paper.	The data represent North American paper mills producing uncoated free sheet paper using deinked recovered pulp.
Time Period Coverage	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996.	EDF collected information from several sources (primary and published) since 1980. All pre-combustion energy and fuel data were from 1996.
Technology Coverage	No significant variations in technology were outlined by EDF.	No significant variations in technology were outlined by EDF.
Precision	Information not available	Information not available
Consistency	Information not available	Information not available
Completeness	Information not available	Information not available
Representativeness	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.	The pulp fibers and processes used to profile this paper grade are representative of North American practices according to the EDF report.
Reproducibility	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.3.3 at the product level.	Since the major sources of data for this profile are publicly available (EDF, Franklin), the process (combustion and pre-combustion) energy and emissions can be calculated or reproduced from the secondary data using steps described in Section 5.4.3 at the product level.
Sources of Data	EDF's reports 3 and 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.	EDF's reports 3 and 10A data on process energy and electricity along with data from Franklin Associates on pre-combustion energy and emissions associated with process fuels and electricity.
Uncertainty	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following IS0 14040 (1994), internal expert review was carried out for this data set.	■ Secondary sources cited in this profile did not publish measures of uncertainty in the data. ■ The EDF data and methodology was peer reviewed. Also, following IS0 14040, internal expert review was carried out for this data set.
Data Quality Rating	The data are considered to be of average quality.	The data are considered to be of average quality.

Table 5.7-4. Comparison to Literature of Key Inventory Data Values for Primary Telephone Book Paper

	Unit	EPA Primary Telephone Book Paper Profile	SFAEFL 1996 Kraft Bleached Uncoated	SFAEFL 1996 Graph Paper Woody Uncoated
Energy	MMBtu/ton	37.83	56.92	42.45
NO_x	lb/ton	24.72	9.50	4.64
NMVOC*	lb/ton	6.62	3.70	1.464
COD	lb/ton	16.53	84.60	16.66

*Non-methane volatile organic compounds.

Table 5.7-5. Comparison to Literature of Key Inventory Data Values for Secondary Telephone Book Paper

	Unit	EPA Secondary Telephone Book Paper Profile	SFAEFL 1996 Secondary (Deinked) Paper	SFAEFL 1996 Secondary Paper Without Deinking	SFAEFL 1996 Newsprint
Energy	MMBtu/ton	20.9	20.0	10.4	15.4
NO_x	lb/ton	3461.9	5.3	1.8	3.2
NMVOC*	lb/ton	0.5	1.8	0.6	1.0
COD	lb/ton	12.5	16.7	0.02	15.1

*Non-methane volatile organic compounds.

requirements and emissions. Gross energy data (the simple sum of combustion process energy and precombustion energy) from the current work is only 5 percent higher than 100 percent secondary deinked paper, the paper grade closest in composition to secondary telephone book paper. There is greater variation in other emissions, such as CO_2.

The LCI data for primary and secondary telephone book paper are considered to be of average quality.

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6.0 Summary LCI of Plastic Products

6.1 Introduction

This chapter presents cradle-to-gate LCI results for HDPE, LDPE, PET and Secondary Plastics (PET and HDPE bottles). The LCI results include energy and emissions from raw materials extraction through production of the final product but do not include the use or disposal portions of a traditional LCI. In addition, data for the collection, processing, and transportation of discarded plastics to a reprocessing facility are not included in the data sets for the secondary systems. Data for these activities is included in other modules of the MSW-DST and included in any scenario including recycling.

Data from the Association of Plastics Manufacturers in Europe (APME) and the Swiss Agency for the Environment, Forests,0 and Landscapes (SFAEFL) were used but were modified to include U.S. electrical energy and related emissions[1] (EIA, 1998; Franklin Associates, 1998). The profiles for HDPE, and LDPE were put together from data presented in APME reports 3 and 10 (APME, 1993, 1997). The profiles for PET and secondary PET were put together using data from APME Report 8 and SFAEFL, respectively (APME, 1995, SFAEFL, 1996). The data presented follow standard LCI methodology, to the extent possible, as outlined in ISO 14040 and ISO 14041. Each profile includes a discussion of data quality. Because the data profiles were compiled from secondary sources, many of the data quality indicators reflected this secondary source of data.

This chapter contains the LCI results for HDPE (Section 6.2), LDPE (Section 6.3), PET (Section 6.4) and Secondary Plastics (Section 6.5). Each section presents the functional unit, system boundaries (including description of unit processes), data sources and calculation procedures, LCI results, and data quality assessment. For all of the profiles, the functional unit is 1 ton (2,000 lb) of material produced.

All material and water consumption, as well as environmental emissions, are presented as mass in pounds (lb), volume in U.S. gallons (gal), gaseous volume in cubic feet (ft^3), and energy in British thermal units (Btu).

[1] The **Western European** electrical energy mix data from 1992 were used to backcalculate fuels and emissions related to electrical energy consumption for the U.S. scenario. The Western European electrical grid mix is divided down into: Coal (36.4%), Natural gas (8.7%), Residual Oil (9.8%), Nuclear (34.1%), Hydro (9.9%), and Other (1.1%). The **U.S. National Electric Grid** mix is divided into: Coal (56.45%), Natural gas (9.75%), Residual Oil (2.62%), Distillate Oil (.23%), Nuclear (22.13%), Hydro (8.59%), and Wood (0.24%). (EIA, 1998)

Because the data used in this study are from secondary sources, the allocation approach was defined by APME (1992). Coproduct allocation was based on the calorific content for all stages of oil refining, gas extraction/processing, and cracking.

This study assumes that fuels used in Europe are characteristically the same as those extracted in the U.S. (i.e., calorific values of fuels in the U.S. and Europe are assumed to be the same). The model for combustion and precombustion fuel and electrical energy-related environmental releases was developed by Franklin Associates (1998).

6.2 High-Density Polyethylene (HDPE)

6.2.1 Introduction

This section contains an LCI profile for the production of primary HDPE. It contains process flow diagrams and descriptions for production processes, LCI data tables for 1 short ton of product, and a discussion of data quality. Section 6.3.1 describes the typical process for producing polyethylene.

The boundaries for this material system depend on plastic production data (secondary) from a series of papers on "eco-profiles of the European plastics industry." The LCI data for the production of commodity thermoplastics was collected and published by APME member companies, according to their agreed methodology (APME methods). Thus, the boundaries for the current product system include extraction of raw material (crude oil, natural gas, LPG, etc.), processing crude oil and natural gas, petroleum refining, and ethylene polymerization and separation of HDPE.

To maintain consistency in boundaries, calculations and presentation, and confidentiality of data, the data were aggregated by APME at the product system level. With the addition of U.S. combustion and precombustion energy, the data set used in this study represents boundaries for the aggregated cradle-to-gate processing of 1 ton of HDPE as described in APME Report 3 and adjusted based on clarification outlined in Report 10 (APME, 1993, 1997). There are differences between the U.S. precombustion model and the model used to generate the APME data. Although care was taken to "Americanize" the electrical energy related, differences between the U.S. and APME precombustion models may have resulted in some errors.

6.2.2 Ethylene Production

Figure 6-1 shows a simplified process flow diagram for processing ethylene. The manufacture of polyethylene includes production and transport of processed crude oil and natural gas (both domestic and imported), petroleum refining, and ethylene polymerization and separation.

Because the APME Report 3 does not include specific descriptions of the unit processes, the following descriptions are general descriptions.

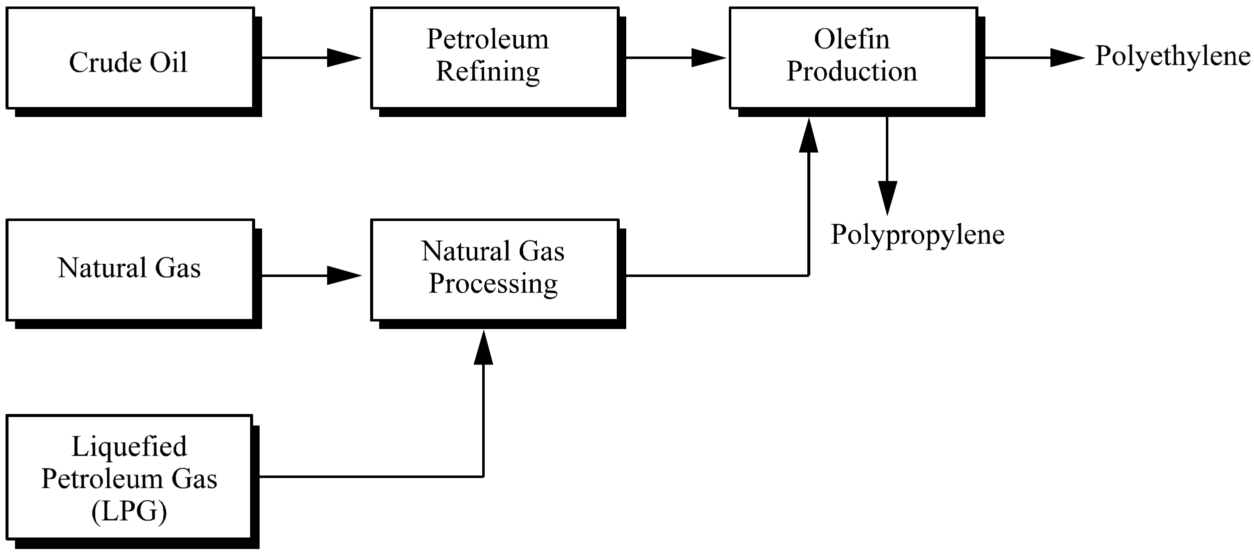

Figure 6-1. Simplified process flow diagram for ethylene (modified from APME, 1993)

6.2.2.1 <u>Crude Oil Production</u>. Oil is produced by drilling into porous rock structures generally located several thousand feet underground. Once an oil deposit is located, numerous holes are drilled and lined with steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although most oil requires some energy to drive pumps that lift oil to the surface. Once oil is on the surface, it is stored in tanks to await transportation to a refinery. In some cases, it is immediately transferred to a pipeline, which transports the oil to a larger terminal.

There are two primary sources of waste from crude oil production. The first source is the "oil field brine," or water that is extracted with the oil. The brine goes through a separator at or near the well head to remove the oil from the water. These separators are very efficient and leave minimal oil in the water. The second source of waste is the gas produced from oil wells. While most of this is recovered for sale, some is not. Atmospheric emissions from crude oil production are primarily hydrocarbons.

6.2.2.2 <u>Natural Gas (Kent, 1974; Elvers et al., 1991; Standen, 1968)</u>. Natural gas occurs in three principal forms: associated gas, nonassociated gas, and gas condensate. Associated gas is found in crude oil reservoirs, either dissolved in the crude oil or in conjunction with crude deposits. Dissolved gases are extracted from oil wells along with the oil and are separated from it at the well head. Much of the very large gas reserves of some Persian Gulf countries and the Prudhoe Bay reserves of Alaska are associated gas.

Nonassociated gas occurs in reservoirs separate from those of crude oil. It is called gas well gas and it contains much less of the heavier, or condensable, hydrocarbons found in associated gas. Nonassociated gas is the most commonly used gas today.

The third form is neither a true gas nor a true liquid. It occurs as a two-phase liquid. These reservoirs, called "gas condensate" reservoirs, usually are found in moderately deep formations, have very high pressures and pose special problems in production and processing.

Several nonhydrocarbon gases are also found in natural gas mixtures. Nitrogen and carbon dioxide are noncombustible and may be found in substantial proportions. These, if present in significant amounts, are removed to raise the heating value, reduce volume, and sustain combustion properties. Hydrogen sulfide is generally removed by treatment with ethanolamine in a process similar to that used in petroleum refining.

Natural gas pipelines normally operate at elevated pressures. In many instances, the gas is available at low pressures; in such cases, it must be pumped or compressed to higher pressures. Usually, water-barge transport is used for importing natural gas.

6.2.2.3 Liquefied Petroleum Gas (Kent, 1974; Elvers et al., 1991; Standen, 1968). The turbo-expander process allows for the recovery of liquid ethane as well as heavier hydrocarbon components to produce liquefied petroleum gas (LPG). The process extracts work from the gas during expansion from a high pressure to a lower pressure, and cools it to a low temperature by means of heat exchange. When the gas stream from a liquid-gas separator is either cooled or compressed, phase change occurs in the gas, and a liquid forms.

The liquid product from this facility can be introduced into either a pipeline or a container for shipment.

6.2.2.4 Petroleum Refining. Only the major processes within the petroleum refining unit process are described below.

Crude Desalting. This is a water-washing process. This process allows for inmate mixing between the crude oil and water, followed by sufficient separation so that water does not enter subsequent crude-oil distillation heaters. The unrefined crude oil is treated with heat to allow for improved fluid properties. Elevated temperatures reduce oil viscosity for better mixing, and elevated pressure suppresses vaporization. The wash water can be added either before or after heating. Mixing between the water and crude oil is assured by passing the mixture through a throttling valve or emulsifier orifice. Trace quantities of caustic agents, acid, or other chemicals are sometimes added to promote treating. Then the water-in-oil emulsion is introduced into a high voltage electrostatic field inside a gravity settler. The electrostatic field encourages the agglomeration of water droplets for easier settling. Salts, minerals, and other water-soluble impurities in the crude oil are carried off with the water discharge from the settler. Clean desalted crude oil flows from the top of the settler and is ready for subsequent refining.

Crude Distillation. Single or multiple distillation columns are used to separate crude oil into fractions determined by their boiling range. The crude oil is heated by exchange with various hot products coming from the system before it passes through a fired heater. The temperature of the crude oil entering the first column is high enough to vaporize the heavy gas oil and all lighter fractions. Because light products must pass from the feed point up to their respective draw-off point, any intermediate stream will contain some of these lighter materials. Stream stripping is used to reintroduce these light materials back into the tower to continue their passage up through the column. The various products are then collected through ports installed along the column.

Hydrotreating. This is a catalytic hydrogenation process that reduces the concentration of sulfur, nitrogen, oxygen, metals, and other contaminants in a hydrocarbon feed. The feed is pumped to operating pressure and mixed with a hydrogen-rich gas, either before or after being heated to the proper reactor inlet temperature. The heated mixture passes through a fixed bed of catalyst where exothermic hydrogenation reactions occur. The effluent from the reactor is then cooled and sent through two separation stages. In the first, the high-pressure scrubber removes hydrogen sulfide; the cleaned hydrogen is then recycled. In the second, the lower-pressure separator takes off the remaining gases and light hydrocarbons from the liquid product. Hydrotreating for sulfur removal is called hydrodesulfurization, and the catalyst used is cobalt and molybdenum oxides on an alumina support.

Catalytic Cracking. This unit is characterized by two huge vessels, one to react the feed with hot catalyst and the other to regenerate the spent catalyst by burning off carbon with air. The contact time takes place in a transfer line that connects the regenerator and the reaction vessels, where most of the reaction occurs. Products are quickly taken overhead. There are several configurations of reactors and regenerators. In most designs, one vessel is stacked on top of the other. All are big structures. Better regeneration of spent catalyst is obtained by operating at high temperatures. Heavier feedstocks are put into catalytic crackers. The catalysts prevent sulfur, which is contained in heavier feeds, from exhausting into the atmosphere prior to entering the reactor. Ordinary gas-treating methods are used to capture the hydrogen sulfide coming from the sulfur in the feedstock.

Coking. Coking is an extreme form of thermal cracking that uses high temperatures and a long residence time to break down heavy crude residues to get lighter liquids (Kent, 1974). Coking takes place in a series of ovens in the absence of oxygen. After a typical coking time of 12 to 20 hours, most of the volatile matter is driven from the crude residue, and the coke is formed. The desired products of the coking process are actually the volatile products. The petroleum coke itself is considered a byproduct. The coke is collected in a coke drum, while the lighter products go overhead as vapors.

Hydrocracking. Prior to the late 1960s, most hydrogen used in processing crude oil was for pretreating catalytic reformer feed naphtha and for desulfurizing middle-distillate products. Soon thereafter, requirements to lower sulfur content in most fuels became an important consideration. Process flow is similar to hydrotreating in that feed is pumped to operating pressure, mixed with a hydrogen-rich gas, heated, passed through a catalytic reactor, and distributed among various fractions. Operating pressures are very high and hydrogen consumption is also high. Under mild conditions, the process functions as a hydrotreater. Under more severe conditions of cracking, the process produces a varying ratio of motor fuels and middle distillates, depending on the feedstock and operating variables.

Production of Ethylene. Ethylene is one of the principal products derived from petroleum cracking. In this process, a feed of raw hydrocarbon from the refinery, which is composed of many different hydrocarbon fractions, is fed into a furnace. Cracker feeds often consist of naphtha or natural gas. At the appropriate reaction temperature, the following reaction occurs.

$$\text{Ethane} \rightarrow \text{Ethylene} + H_2$$

When the product gases leave the furnace (reactor), they are quenched and cooled to inhibit further reactions. The products are then separated.

Other reaction products include propylene and a mixture of butene isomers. Reaction products depend on feed composition, temperature, and reactant resident time. The cracker temperature and feed residence time can be set to optimize the product mix from a given feed (APME, 1993).

6.2.2.5 Natural Gas Processing (Berger and Anderson, 1992; Hobson, 1984; Meyers, 1986; McKetta, 1992; Gary and Handwork, 1994; Beggs, 1984). Natural gas is often found in close association with crude oil. In many instances it is the pressure of natural gas exerted upon the subterranean oil reservoir that drives oil up to the surface. Natural gas components are mostly saturated light paraffins such as methane, ethane, and propane that exist in the gaseous phase, depending on the pressure in the reservoir. When pentane and heavier compounds coexist, they are usually found as liquids. When a natural gas reserve contains substantial amounts of ethane and the higher paraffinic compounds, these are usually extracted at the production site and produced as natural gas liquids (NGLs). This source of light hydrocarbons is especially prominent in the U.S., where natural gas processing provides a major portion of the ethane feedstock for olefin manufacture and the LPG for heating and commercial purposes.

Field-production gas is often available at very low pressures, 14 pounds per square inch (psi) or less being common. Most end uses of gas require pressures in the range of 500 to 1,000 psi. Hence, the gas is processed through multiple stages of compression. In a simple compression gas-processing plant, field gas is charged to an inlet scrubber, where entrained liquids are removed. The gas is then successively compressed and cooled to remove condensed liquids and to reduce the temperature of the fluid in order to conserve compressor power requirements. The heavier liquids from the gas stream are separated using a more complex refrigerated absorption and fractionation plant. The compressed raw gas is processed in admixture with a liquid hydrocarbon, called lean oil, in an absorber column, where heavier components in the gas are absorbed in the lean oil. The bulk of the gas is discharged from the top of the absorber as residue gas (usually containing 95 percent methane) for subsequent treatment to remove sulfur and other impurities. The heavier components leave with the bottoms liquid stream, now called rich oil, for further processing to remove ethane for plant fuel or petrochemical feedstock and to recover the lean oil. Some gas-processing plants may contain additional distilling columns for further separation of the gas liquids into propane, butanes, and heavier NGLs. Many older gas-absorption plants were designed to operate at ambient temperature, but newer facilities usually employ refrigeration to lower processing temperatures and increase the absorption efficiency.

6.2.2.6 <u>Olefin (Polymerization of Ethylene) (Smith, 1990)</u>. Chain-growth polymerization is used to synthesize polyethylene. Three steps describe the reaction— initiation, propagation, and termination.

Catalysts, such as organic peroxides, are used to initiate the polymerization of ethylene by decomposing into free radicals upon heating. The peroxide free radical reacts with ethylene to form a longer chain free radical. It is propagation that occurs as successive ethylene reactants react with the initiator free radical. Termination then occurs by the addition of a terminator free radical or when two chains come together

Experiments and analysis have shown that the molecular structure of polyethylene is composed of both crystalline and amorphous regions. Until 1940, polyethylene was regarded as a linear long-chain hydrocarbon, but the advent of infrared spectroscopy has revealed more methyl groups than could previously be accounted for as terminal groups. Side chains account for the weaker mechanical properties of the polymer. Further work has shown that, if polymerization techniques were altered to favor the side-chain branching reaction, then the physical properties of the polymer would reflect those of a less crystalline, low-density material having highly branched side chains.

Plastic films and fibers made from hydrocarbon olefins use ethylene gas and high-pressure polyethylene to produce polyethylene and polypropylene. The polymerization of light olefins emphasizes a combination of only two or three molecules so that the resulting liquid will be in the gasoline boiling range.

6.2.3 HDPE Production

Figure 6-2 shows a simplified process flow diagram for processing high-density polyethylene. The manufacture of HDPE includes: production and transport of processed crude oil and natural gas (both domestic and imported), petroleum refining, and ethylene polymerization and separation (Kent, 1974; Elvers et al., 1991; Standen, 1968).

Many of the material production operations for HDPE were described for polyethylene in Section 6.2. Please refer to Section 6.2.2 for a detailed description of crude oil production, natural gas production, LPG production, petroleum refining, natural gas processing, ethylene production, and olefin (ethylene) polymerization.

6.2.3.1 <u>Comonomer</u>. Polymerization entails copolymerizing ethylene and a chosen monomer (olefin feed) in the presence of a catalyst. Comonomers are fed continuously into the reactor, which operates at high pressure and a chosen temperature. Either aluminum trialkyl titanium tetrachloride or chromium oxide on a silica/aluminum support is used as a catalyst system in the production of HDPE. The product resins are linear polymers in the density range of 0.94 to 0.96 when a comonomer is used with ethylene during polymerization. Most of the commercially available high-molecular-weight resins are copolymers of either butene-1 or hexene-1 with ethylene.

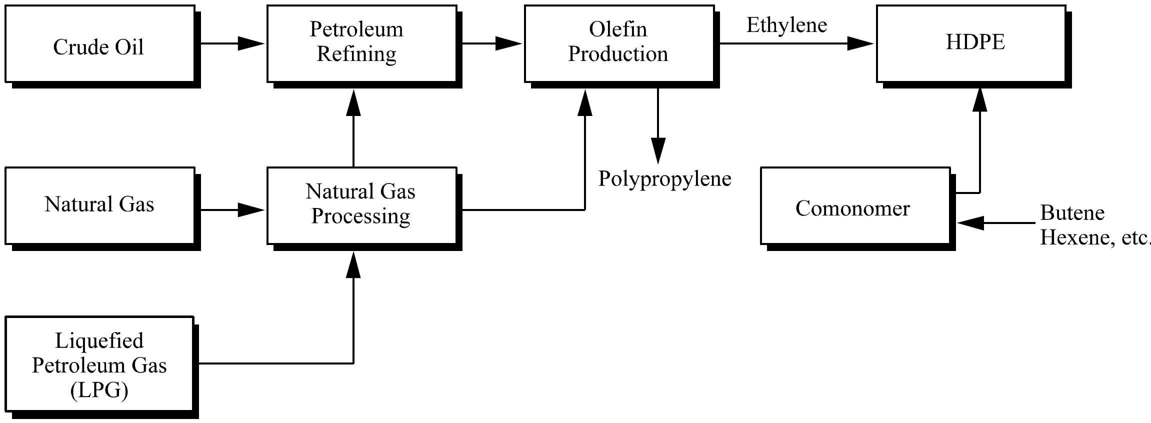

Figure 6-2. Simplified process flow diagram for high-density polyethylene

6.2.3.2 Polymerization of HDPE. The HDPE polymerization process requires copolymerizing ethylene and the monomer feed using a catalyst. Gaseous ethylene, hydrogen, a titanium-containing catalyst, and comonomer are continuously fed to this fluidized-bed reactor that operates at a preselected temperature and pressure. The polymer product and gas are intermittently discharged from the reactor; the gas is separated from the polymer. The polymer, in powder form, is then sent to storage or pelletizers (Kent, 1974).

6.2.4 Data Source and Calculation Procedures

The data were developed primarily using the European APME plastics data sets. Electrical energy[2] and the associated emissions from these APME data were replaced with data from the electrical energy module included as part of the overall decision support tool. APME Report 3, which presents a cradle-to-gate environmental data profile for 1 kilogram of HDPE, was used along with Western European electric grid data and U.S. electric grid data (EIA, 1998; Franklin Associates, 1998; APME, 1993, 1997). The following steps outline the procedure used to construct LCI data for PE:

1. The HDPE profile from APME was converted from SI units (energy in MJ, mass in milligrams per kilogram) to U.S. units (mass in lb, volume in U.S. gallons, gaseous volume in ft^3, and energy in Btu/1 ton (2,000 lb).[3] The electrical energy is converted from MJ to kWh using the appropriate efficiencies for each fuel in the electrical fuel mix (EIA, 1998).

[2] The average of the U.S. National Grid was used to calculate the electrical emissions (Franklin Associates, 1998).

[3] Energy conversion factors developed by Franklin Associates Ltd. (Table 9 in their 1998 report); Franklin data were used to calculate/convert to the appropriate units.

2. Based on the Western European Fuel Mix from 1992 and combustion and precombustion emissions from the Franklin Report,[4] an environmental profile for producing and delivering 1 (kWh) of the Western European electrical grid[5] was developed. A similar environmental profile for producing 1 kWh of the U.S. electrical grid was developed by Franklin (EIA, 1998; Franklin Associates, 1998).

3. The precombustion energy and environmental releases (air emissions, water emissions and solid waste emissions) from the European Electrical Fuel Mix were deducted using the profile developed in Step 2 for the appropriate kWh converted in Step 1. For the same kWh, the precombustion energies and environmental emissions for the U.S. electrical mix are added to the profile. The net electrical energy for the process is the same; however, the precombustion energy quantities and environmental emissions are different because of the different fuel mix from the two electrical grids.

Table 6-1 shows the original APME HDPE emissions profile. The first column shows the published APME data profile and the second column shows APME data with the European electrical emissions subtracted. The complete LCI data results are provided in Section 6.3.4.

6.2.5 LCI Results

Table 6-2 summarizes the cradle-to-gate LCI data for primary HDPE production. Table 6-2 breaks down the individual fuels that make up the energy of material resource, combustion process energy, and precombustion energy related to material resource feedstock, process fuels, and electric energy fuels. The emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

6.2.6 Data Quality

Table 6-3 summarizes data quality information for HDPE production. APME data were based on a thorough survey of European producers. APME data represent a cross section of poor, average and above average performance and technologies. The results determined here are thought to be representative of both global and U.S. production. Young (1996) expressed confidence that APME data used primary industry data collected from a nondiscriminating sample in a large population. Because secondary data were used in this study, precision, consistency, and completeness of information are not all available. The various data quality measures are defined below.

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[4] Energy consumption and emissions released from *Utility Boilers* developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to develop the appropriate pre-combustion energies and environmental emissions for 1 kWh of European electric grid.

[5] U.S. Electrical Energy and Emissions data developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to calculate the appropriate precombustion energies and environmental emissions for 1 kWh of U.S. electric grid.

Table 6-1. Environmental Emissions for Production of 1 Ton of HPDE With and Without European Electrical Emissions

		Original APME Data (lb/ton)	APME Data without European Electricity Emissions (lb/ton)
Atmospheric Emissions			
Particulates (PM_{10})	lb	0.00E+00	0.00E+00
Particulates (Total)	lb	4.00E+00	3.68E+00
Nitrogen Oxides	lb	2.00E+01	1.91E+01
Hydrocarbons (non CH_4)	lb	4.20E+01	4.16E+01
Sulfur Oxides	lb	1.20E+01	1.03E+01
Carbon Monoxide	lb	1.20E+00	9.25E+01
CO_2 (biomass)	lb	0.00E+00	0.00E+00
CO_2 (non biomass)	lb	3.80E+03	3.57E+03
Ammonia	lb	0.00E+00	0.00E+00
Lead	lb	0.00E+00	0.00E+00
Methane	lb	0.00E+00	0.00E+00
Hydrochloric Acid	lb	1.00E-01	1.00E+01
Solid Waste			
Solid Waste #1	lb	0.00E+00	0.00E+00
Ash	lb	1.00E+01	0.00E+00
Sludge	lb	0.00E+00	0.00E+00
Scrap	lb	0.00E+00	0.00E+00
Unspecified	lb	6.01E+01	6.01E+01
Waterborne Emissions			
Dissolved Solids	lb	1.00E+00	8.25E-01
Suspended Solids	lb	4.00E-01	4.00E-01
BOD	lb	2.00E-01	2.00E-01
COD	lb	4.00E-01	3.99E-02
Oil	lb	6.00E-02	5.76E-02
Sulfuric Acid	lb	2.00E-01	6.61E-02
Iron	lb	0.00E+00	0.00E+00
Ammonia	lb	2.00E-02	2.00E-02
Copper	lb	0.00E+00	0.00E+00
Cadmium	lb	0.00E+00	0.00E+00
Arsenic	lb	0.00E+00	0.00E+00
Mercury	lb	0.00E+00	0.00E+00
Phosphate	lb	2.00E-03	2.00E-03
Selenium	lb	0.00E+00	0.00E+00
Chromium	lb	0.00E+00	0.00E+00
Lead	lb	0.00E+00	0.00E+00
Zinc	lb	0.00E+00	0.00E+00

Source: EIA, 1998; APME, 1993, 1997; Franklin Associates. 1998.

Table 6-2. Data for Production of 1 Ton of Primary HDPE

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Energy of Material Resource				
Petroleum	MMBtu	4.11E+01	4.11E+01	1.00E+00
Coal	MMBtu	8.60E-03	8.60E-03	1.00E+00
Combustion Process Energy				
Electricity	kWh	1.80E+02	1.62E+00	8.97E-03
Natural Gas	cu ft	1.21E+04	1.40E+01	1.03E-03
LPG	gal			9.55E-02
Coal	lb			1.12E-02
Distillate oil	gal			1.39E-01
Residual Oil	gal	5.13E+01	8.76E+00	1.50E-01
Gasoline	gal			1.25E-01
Diesel	gal			1.39E-01
Wood	Btu			1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	6.30E+02	7.31E-01	1.30E-04
Residual Oil	gal	4.34E+00	7.42E-01	2.10E-02
Distillate oil	gal			1.93E-02
Gasoline	gal			1.64E-02
LPG	gal			1.21E-02
Coal	lb	1.15E+02	1.32E+00	2.60E-04
Nuclear	lb U238	1.11E-03	1.15E+00	5.06E+01
Hydropower	Btu	3.33E+05	3.33E-01	1.00E-06
Other	Btu	3.70E+04	3.70E-02	1.00E-06

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Atmospheric Emissions				
Acreolin	lb	3.76E-06		3.76E-06
Ammonia	lb	1.18E-03		1.18E-03
Antimony	lb	1.70E-06		1.70E-06
Arsenic	lb	8.27E-06		8.27E-06
Benzene	lb	4.30E-06		4.30E-06
Beryllium	lb	9.60E-07		9.60E-07
Cadmium	lb	1.20E-06		1.20E-06
Carbon Dioxide-fossil	lb	3.84E+03	3.57E+03	2.61E+02
Carbon Dioxide-nonfossil	lb	6.51E-01		6.51E-01
Carbon Monoxide	lb	1.03E+00	9.25E-01	1.09E-01
Carbon Tetrachloride	lb	6.35E-06		6.35E-06
Chlorine	lb	3.12E-06		3.12E-06

(continued)

Table 6-2. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Chromium	lb	1.07E-05		1.07E-05
Cobalt	lb	2.12E-04		2.12E-04
Dioxins	lb	1.16E-06		1.16E-06
Formaldehyde	lb	1.15E-05		1.15E-05
Hydrocarbons (non CH_4)	lb	4.17E+01	4.16E+01	1.35E-01
Hydrochloric acid	lb	1.19E-01	1.00E-01	1.91E-02
Hydrogen Fluoride	lb	2.63E-03		2.63E-03
Kerosene	lb	9.92E-05		9.92E-05
Lead	lb	1.25E-05		1.25E-05
Manganese	lb	2.81E-05		2.81E-05
Mercury	lb	7.04E-06		7.04E-06
Metals	lb	5.62E-05		5.62E-05
Methane	lb	5.64E-01		5.64E-01
Methylene Chloride	lb	1.63E-05		1.63E-05
Naphthalene	lb	7.62E-07		7.62E-07
Nickel	lb	4.93E-05		4.93E-05
Nitrogen Oxides	lb	2.01E+01	1.91E+01	9.74E-01
Nitrous Oxide	lb	2.14E-03		2.14E-03
n-nitrodimethylamine	lb	7.95E-07		7.95E-07
Other Aldehydes	lb	6.42E-04		6.42E-04
Other Organics	lb	1.01E-03		1.01E-03
Particulate	lb	3.99E+00	3.68E+00	3.17E-01
Perchloroethylene	lb	3.59E-06		3.59E-06
Phenols	lb	2.06E-05		2.06E-05
Radionuclides (Ci)	lb	7.05E-05		7.05E-05
Selenium	lb	2.67E-05		2.67E-05
Sulfur Oxides	lb	1.22E+01	1.03E+01	1.93E+00
Trichloroethylene	lb	3.56E-06		3.56E-06
Solid Wastes	lb	9.33E+01	4.56E+01	4.77E+01
Waterborne Emissions				
Acid	lb	3.82E-09		3.82E-09
Ammonia	lb	2.01E-02	2.00E-02	1.65E-04
BOD	lb	2.00E-01	2.00E-01	6.37E-04
COD	lb	4.08E-01	3.99E-01	8.75E-03
Boron	lb	9.71E-03		9.71E-03
Cadmium	lb	2.78E-05		2.78E-05
Calcium	lb	8.52E-05		8.52E-05
Chlorides	lb	2.90E-02		2.90E-02
Chromates	lb	3.04E-06		3.04E-06
Chromium	lb	2.78E-05		2.78E-05
Cyanide	lb	4.16E-08		4.16E-08

(continued)

Table 6-2. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Dissolved Solids	lb	1.44E+00	8.25E-01	6.16E-01
Fluorides	lb	3.94E-04		3.94E-04
Iron	lb	1.43E-02		1.43E-02
Lead	lb	6.74E-09		6.74E-09
Manganese	lb	8.20E-03		8.20E-03
Mercury	lb	2.18E-09		2.18E-09
Metal Ion	lb	8.04E-05		8.04E-05
Nitrates	lb	3.72E-05		3.72E-05
Oil	lb	6.85E-02	5.76E-02	1.09E-02
Other Organics	lb	3.62E-03		3.62E-03
Phenol	lb	2.64E-07		2.64E-07
Phosphate	lb	3.21E-03	2.00E-03	1.21E-03
Sodium	lb	1.57E-04		1.57E-04
Sulfates	lb	7.10E-02		7.10E-02
Sulfuric Acid	lb	2.33E-03		2.33E-03
Suspended Solids	lb	5.71E-01	4.00E-01	1.72E-01
Zinc	lb	9.62E-06		9.62E-06

Source: APME 1992, 1997; Franklin Associates, 1998.

Table 6-3. Data Quality Summary for HDPE

Data Quality Indicator	HDPE
Geographic coverage	Data represent 10 European polymerization plants producing approximately1.4 million short tons of HDPE. European electrical emissions were replaced with U.S. electricity-related emissions
Time Period coverage	APME data were collected between 1991 and 1992 and published in 1993. EIA data on the 1992 European grid were published in 1998. Franklin data on U.S. national grid electrical emissions were published in 1998.
Technology coverage	The data represent 10 European ethylene polymerization plants producing approximately 1.4 million short tons of HDPE.
Precision	APME noted a range in variability for gross energy of 59 – 88 Btu per short ton.
Consistency	Information not available
Completeness	Information not available

(continued)

Table 6-3. (continued)

Data Quality Indicator	HDPE
Representativeness	Gross energy is 10% lower than a small sample of other public data sources. CO_2 is within ±10% of this sample; NO_x is 5% higher, and solid waste is 25% higher than this sample of public data.
Reproducibility	Process energy and emissions can be calculated or reproduced from all secondary sources since the major sources of data are publicly available.
Sources of data	HDPE profile data are from APME reports 3 and 10. EIA data on the Western European electricity grid were used to backcalculate fuels and emissions related to electrical energy consumption and were replaced with the U.S. national grid mix. Franklin data were used for electrical emissions from the U.S. grid.
Uncertainty	A direct analysis of uncertainty was not possible because the data were based on secondary sources, which did not publish uncertainty ranges. However, based on review from public sources, comments on data variation, indicate: ± 30% for energy, ± 100% for emissions.
Data Quality Rating	The HDPE data are considered to be of average quality.

Table 6-4 shows how the data in the current study compare with data from other public sources, and thus provides a measure of representativeness. Gross energy data (the simple sum of energy of material resource, combustion process energy, and precombustion energy) is 10 percent lower than that of the other public sources cited. CO_2 is within ±10 percent of this sample of public sources, NO_x is 5 percent higher, and solid waste is 25 percent higher than those public sources.

The APME energy profile was modified in 1997 since the publication of the original report from 1993. In the 1997 publication feedstock energy and fuel have changed in the proportion of oil and gas reported; however, the total energy did not change. This was due to the fact that they had not previously accounted for feedstock waste that was used as fuel. The EPA profile used feedstock and fuel energy from both reports to determine the total primary energy of polyethylene.

A direct analysis of uncertainty was not possible because the study was based on secondary data. The secondary sources cited in this profile did not publish measures of uncertainty in the data. However, some comment on the limitations of the results is possible. Young examined the relevance and limitations of the APME data to the North American context. He noted the potential for variation in feedstock energy related to the proportion of oil versus

Table 6-4. Comparison to Literature of Key Inventory Data Values for HDPE

	Unit	EPA HDPE Profile	APME[a]	SFAEFL[b]	Young [c]
Energy	MMBtu/ton	64.04	69.63	69.6	69.6
CO_2	lb/ton	3861	3800	4120	4100
NO_x	lb/ton	20.38	20	20	20
Solid Waste	lb/ton	74.1	64.08	63.8	64

[a] APME, 1993, 1997
[b] SFAEFL, 1996
[c] Young, 1996

natural gas used as feedstock. He further examined uncertainty in the APME data and noted that the range for both energy and CO_2 due to variation in practice is on the order of ±20 to 30 percent. For other emissions and solid wastes, it is reasonable to expect variations on the order of ±100 percent.

Four independent experts in the field developed the APME methodology. Additionally, following IS0 14040, internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review. In accordance with the ISO standards, the internal experts are familiar with the requirements of ISO 14040 and 14041 and have the necessary technical and scientific expertise. However, a report detailing the findings by the internal experts was not prepared.

The HDPE data are considered to be of average quality.

6.3 Low-Density Polyethylene (LDPE)

6.3.1 Introduction

This section contains an LCI profile for the production of primary (virgin) LDPE. It contains process flow diagrams and descriptions for production processes, LCI data tables for 1 short ton of product, and a discussion of data quality. Section 6.2 describes the typical process for producing polyethylene. This section describes only the unit operations for LDPE that differ from those of polyethylene.

The boundaries for this material system depend on plastic production data (secondary) from a series of papers on "eco-profiles of the European plastics industry.” These inventory data for the production of commodity thermoplastics were collected and published by APME member companies, according to their agreed methodology. Thus, the boundaries for the current product system include extraction of raw material (crude oil, natural gas, LPG, etc.), processing crude oil and natural gas, petroleum refining, and ethylene polymerization and separation of LDPE. To maintain consistency in boundaries, calculations and presentation, and confidentiality of data, the data were aggregated by APME at the product system level. With the addition of U.S.

combustion and precombustion energy, the data set used in this study represents boundaries for the aggregated cradle to gate processing of 1 ton of LDPE as described in APME Report 3 and modified according to clarifications outlined in APME Report 10 (APME, 1993, 1997).

6.3.2 LDPE Production

Figure 6-3 shows a simplified process flow diagram for processing low-density polyethylene. The manufacture of LDPE includes: production and transport of processed crude oil and natural gas (both domestic and imported), petroleum refining, and ethylene polymerization and separation (Kent, 1974; Elvers et al., 1991; Standen, 1968).

Many of the material production operations for LDPE were described for polyethylene in Section 6.2. Please refer to Section 6.2.2 for a detailed description of crude oil production, natural gas production, LPG production, petroleum refining, natural gas processing, ethylene production, and olefin (ethylene) polymerization. This section describes the steps in LDPE production that were not included in the description of polyethylene production.

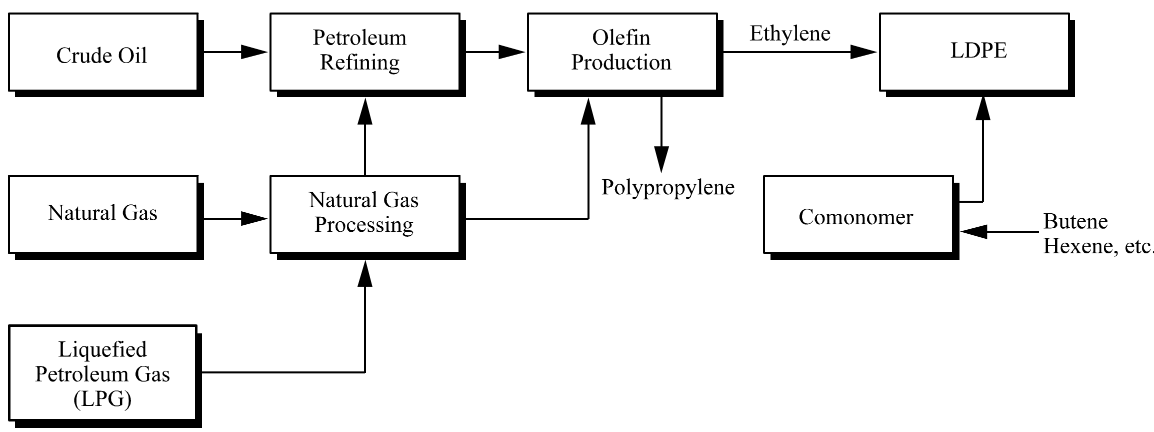

Figure 6-3. Simplified process flow diagram for low-density polyethlene (modified from APME, 1993)

LDPE is produced by the free-radical polymerization of ethylene at high temperature and high pressure. Temperatures vary from 150°to 300°C, and pressures range from 103-345 MPa. The polymerization process involves three basic steps: initiation, propagation, and termination.

Initiation uses a peroxide as an initiator that thermally decomposes into free radicals,

$$\text{Initiator } (R)2 \rightarrow 2R'$$

R' reacts with ethylene

$$R' + CH_2CH_2 \rightarrow RCH_2CH_2'$$

Propagation occurs as the chain reaction continues

$$R\ CH_2CH_2' + CH_2CH_2 \rightarrow R(CH_2)3CH_2'$$

Termination of a growing chain occurs when two free-radical groups combine

$$RCH_2CH_2' + 'CH_2CH_2 \rightarrow R(CH_2)3R$$

or when a hydrogen radical transfers from one chain to another.

$$R\ CH_2CH_2' + '\ CH_2CH_2R \rightarrow R\ CH_2CH_3 + R\ CH_2CH_2$$

The ethylene monomer and small amounts of oxygen peroxides or other free radical sources, which act as initiators, are used to polymerize LDPE. Reactions take place at pressures up to 50,000 psi and temperatures as high as 300°C. This leads to polymers with a high degree of branching and densities from about 0.910 to 0.935 g/cm^3.

Two commercial methods are used to polymerize ethylene to LDPE:

- autoclave process
- tubular process.

6.3.2.1 <u>Autoclave Process</u>. The autoclave process uses a continuous-flow stirred autoclave reactor with a length to diameter (L/D) ratio ranging from 2:1 to 20:1. Usually the reactor is divided by baffles that enhance mixing in the reaction zone. LDPE resins with a wide range of molecular weight distributions can be produced through this process.

6.3.2.2 <u>Tubular Process</u>. In the tubular process, the reactor consists of a long tube with L/D ratios greater than 12,000:1. Because there is no mechanical agitation, the reactor operates as a plug flow reactor. The molecular weight distribution produced through this process is generally between the extremes achievable by the autoclave.

In both processes, separators downstream from the reactor operate at lower pressures, separating unreacted ethylene from the polymer. Only 10 to 30 percent of the ethylene is converted to polyethylene per pass through the reactor. From the separator, molten polyethylene is extruded through an underwater pelletizer to form pellets. The pellets are then dried and stored in silos until they are loaded into railcars, boxes, or bags.

6.3.3 Data Source and Calculation Procedures

The data were developed primarily using the European APME plastics data sets. Electrical energy[6] and the associated emissions from these APME data were replaced with data from the electrical energy module included as part of the overall decision support tool. APME

[6] The average of the U.S. National Grid was used to calculate the electrical emissions (Franklin Associates, 1998).

Report 3, which presents a cradle-to-gate environmental data profile for 1 kilogram of LDPE, was used along with Western European electric grid data and U.S. electric grid data (EIA, 1998; Franklin Associates, 1998; APME, 1993, 1997). The following steps outline the procedure used to construct LCI data for PE:

1. The LDPE profile from APME was converted from SI units (energy in MJ, mass in milligrams per kilogram) to U.S. units (mass in lb, volume in U.S. gallons, gaseous volume in ft^3, and energy in Btu/1 ton (2,000 lb).[7] The electrical energy is converted from MJ to kWh using the appropriate efficiencies for each fuel in the electrical fuel mix (EIA, 1998).

2. Based on the Western European Fuel Mix from 1992 and combustion and precombustion emissions from the Franklin Report,[8] an environmental profile for producing and delivering 1 (kWh) of the Western European electrical grid[9] was developed. A similar environmental profile for producing 1 kWh of the U.S. electrical grid was developed by Franklin (EIA, 1998; Franklin Associates, 1998).

3. The precombustion energy and environmental releases (air emissions, water emissions and solid waste emissions) from the European Electrical Fuel Mix were deducted using the profile developed in Step 2 for the appropriate kWh converted in Step 1. For the same kWh, the precombustion energies and environmental emissions for the U.S. electrical mix are added to the profile. The net electrical energy for the process is the same; however, the precombustion energy quantities and environmental emissions are different because of the different fuel mix from the two electrical grids.

Table 6-5 shows the original APME LDPE emissions profile. The first column shows the published APME data profile and the second column shows APME data with the European electrical emissions subtracted. The complete LCI data results are shown in Section 6.3.4.

6.3.4 LCI Results

Tables 6-6 summarizes the LCI data for virgin LDPE production. The table breaks down the individual fuels that make up the energy of material resource, combustion process energy, and precombustion energy related to material resource feedstock, process fuels, and electric

[7] Energy conversion factors developed by Franklin Associates Ltd. (Table 9 in their 1998 report); Franklin data were used to calculate/convert to the appropriate units.

[8] Energy consumption and emissions released from *Utility Boilers* developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to develop the appropriate pre-combustion energies and environmental emissions for 1 kWh of European electric grid.

[9] U.S. Electrical Energy and Emissions data developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to calculate the appropriate precombustion energies and environmental emissions for 1 kWh of U.S. electric grid.

Table 6-5. Environmental Emissions for Production of 1 Ton of LDPE With and Without European Electrical Emissions

		Original APME Data (lb/ton)	APME Data without European Electricity Emissions (lb/ton)
Atmospheric Emissions			
Particulates (PM_{10})	lb	0.00E+00	0.00E+00
Particulates (Total)	lb	6.00E+00	5.46E+00
Nitrogen Oxides	lb	2.40E+01	2.26 E+01
Hydrocarbons (non CH_4)	lb	4.20E+01	4.14E+01
Sulfur Oxides	lb	1.80E+01	1.52E+01
Carbon Monoxide	lb	1.80E+00	1.34E+00
CO_2 (biomass)	lb	0.00E+00	0.00E+00
CO_2 (non biomass)	lb	4.80E+03	4.42E+03
Ammonia	lb	0.00E+00	0.00E+00
Lead	lb	0.00E+00	0.00E+00
Methane	lb	0.00E+00	0.00E+00
Hydrochloric Acid	lb	1.40E-01	1.40E-01
Solid Waste			
Solid Waste #1	lb	0.00E+00	0.00E+00
Ash	lb	1.80E+01	0.00E+00
Sludge	lb	0.00E+00	0.00E+00
Scrap	lb	0.00E+00	0.00E+00
Unspecified	lb	6.08E+01	6.08E+01
Waterborne Emissions			
Dissolved Solids	lb	6.00E-01	3.08E-01
Suspended Solids	lb	1.00E+00	1.00E+00
BOD	lb	4.00E-01	4.00E-01
COD	lb	3.00E+00	3.00E+00
Oil	lb	4.00E-01	3.96E-01
Sulfuric Acid	lb	1.20E-01	0.00E+00
Iron	lb	0.00E+00	0.00E+00
Ammonia	lb	1.00E-02	9.96E-03
Cooper	lb	0.00E+00	0.00E+00
Cadmium	lb	0.00E+00	0.00E+00
Arsenic	lb	0.00E+00	0.00E+00
Mercury	lb	0.00E-00	0.00E+00
Phosphate	lb	1.00E-02	1.00E-02
Selenium	lb	0.00E+00	0.00E+00
Chromium	lb	0.00E+00	0.00E+00
Lead	lb	0.00E+00	0.00E+00
Zinc	lb	0.00E+00	0.00E+00

Source: EIA (1998), APME (1993, 1997), Franklin Associates (1998).

Table 6-6. Data for Production of 1 Ton of Primary LDPE

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Energy of Material Resource				
Petroleum	MMBtu	4.11E+01	4.11E+01	1.00E+00
Coal	MMBtu	8.60E-03	8.60E-03	1.00E+00
Combustion Process Energy				
Electricity	kWh	3.01E+02	2.70E+00	8.97E-03
Natural Gas	cu ft	1.34E+04	1.55E+01	1.03E-03
LPG	gal			9.55E-02
Coal	lb			1.12E-02
Distillate Oil	gal			1.39E-01
Residual Oil	gal	6.11E+01	1.04E+01	1.50E-01
Gasoline	gal			1.25E-01
Diesel	gal			1.39E-01
Wood	Btu			1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	7.56E+02	8.78E-01	1.30E-04
Residual Oil	gal	6.14E+00	1.05E+00	2.10E-02
Distillate Oil	gal			1.93E-02
Gasoline	gal			1.64E-02
LPG	gal			1.21E-02
Coal	lb	1.89E+02	2.17E+00	2.60E-04
Nuclear	lb U238	1.82E-03	1.89E+00	5.06E+01
Hydropower	Btu	5.48E+05	5.48E-01	1.00E-06
Other	Btu	6.09E+04	6.09E-02	1.00E-06

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Atmospheric Emissions				
Acreolin	lb	6.29E-06		6.29E-06
Ammonia	lb	1.97E-03		1.97E-03
Antimony	lb	2.84E-06		2.84E-06
Arsenic	lb	1.38E-05		1.38E-05
Benzene	lb	7.18E-06		7.18E-06
Beryllium	lb	1.60E-06		1.60E-06
Cadmium	lb	2.01E-06		2.01E-06
Carbon Dioxide-fossil	lb	4.86E+03	4.42E+03	4.36E+02
Carbon Dioxide-nonfossil	lb	1.09E+00		1.09E+00
Carbon Monoxide	lb	1.52E+00	1.34E+00	1.83E-01
Carbon Tetrachloride	lb	1.06E-05		1.06E-05
Chlorine	lb	5.21E-06		5.21E-06
Chromium	lb	1.78E-05		1.78E-05
Cobalt	lb	3.53E-04		3.53E-04
Dioxins	lb	1.95E-06		1.95E-06

(continued)

Table 6-6. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Formaldehyde	lb	1.93E-05		1.93E-05
Hydrocarbons (non CH_4)	lb	4.16E+01	4.14E+01	2.26E-01
Hydrochloric acid	lb	1.72E-01	1.40E-01	3.18E-02
Hydrogen Fluoride	lb	4.39E-03		4.39E-03
Kerosene	lb	1.66E-04		1.66E-04
Lead	lb	2.09E-05		2.09E-05
Manganese	lb	4.70E-05		4.70E-05
Mercury	lb	1.18E-05		1.18E-05
Metals	lb	9.38E-05		9.38E-05
Methane	lb	9.42E-01		9.42E-01
Methylene Chloride	lb	2.72E-05		2.72E-05
Naphthalene	lb	1.27E-06		1.27E-06
Nickel	lb	8.23E-05		8.23E-05
Nitrogen Oxides	lb	2.42E+01	2.26E+01	1.63E+00
Nitrous Oxide	lb	3.57E-03		3.57E-03
n-nitrodimethylamine	lb	1.33E-06		1.33E-06
Other Aldehydes	lb	1.07E-03		1.07E-03
Other Organics	lb	1.69E-03		1.69E-03
Particulate	lb	5.99E+00	5.46E+00	5.29E-01
Perchloroethylene	lb	6.00E-06		6.00E-06
Phenols	lb	3.43E-05		3.43E-05
Radionuclides (Ci)	lb	1.18E-04		1.18E-04
Selenium	lb	4.46E-05		4.46E-05
Sulfur Oxides	lb	1.84E+01	1.52E+01	3.22E+00
Trichloroethylene	lb	5.94E-06		5.94E-06
Solid Wastes	lb	1.18E+02	3.79E+01	7.97E+01
Waterborne Emissions				
Acid	lb	6.39E-09		6.39E-09
Ammonia	lb	1.02E-02	9.96E-03	2.76E-04
BOD	lb	4.01E-01	4.00E-01	1.06E-03
COD	lb	3.01E+00	3.00E+00	1.46E-02
Boron	lb	1.62E-02		1.62E-02
Cadmium	lb	4.64E-05		4.64E-05
Calcium	lb	1.42E-04		1.42E-04
Chlorides	lb	4.84E-02		4.84E-02
Chromates	lb	5.08E-06		5.08E-06
Chromium	lb	4.64E-05		4.64E-05
Cyanide	lb	6.95E-08		6.95E-08
Dissolved Solids	lb	1.34E+00	3.08E-01	1.03E+00
Fluorides	lb	6.59E-04		6.59E-04
Iron	lb	2.39E-02		2.39E-02
Lead	lb	1.13E-08		1.13E-08
Manganese	lb	1.37E-02		1.37E-02
Mercury	lb	3.65E-09		3.65E-09
Metal Ion	lb	1.34E-04		1.34E-04
Nitrates	lb	6.21E-05		6.21E-05
Oil	lb	4.14E-01	3.96E-01	1.81E-02
Other Organics	lb	6.05E-03		6.05E-03

(continued)

Table 6-6. (concluded)

Environmental Releases	Units	Total	Process	Fuel Related
Phenol	lb	4.42E-07		4.42E-07
Phosphate	lb	1.20E-02	1.00E-02	2.03E-03
Sodium	lb	2.62E-04		2.62E-04
Sulfates	lb	1.19E-01		1.19E-01
Sulfuric Acid	lb	3.89E-03		3.89E-03
Suspended Solids	lb	1.29E+00	1.00E+00	2.86E-01
Zinc	lb	1.61E-05		1.61E-05

Source: EIA, 1998; APME, 1993, 1997; Franklin Associates, 1998.

energy fuels. The emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

6.3.5 Data Quality

Table 6-7 summarizes data quality information for LDPE production. APME data were based on a thorough survey of European producers. APME data represent a cross-section of poor, average and above average performance and technologies. The results determined here are thought to be representative of both global and U.S. production. Young (1996) expressed confidence that APME data used primary industry data collected from a nondiscriminating sample in a large population. Because secondary data were used in this study, precision, consistency, and completeness of information are not all available.

Table 6-8 shows how the data in the current study compare with data from other public sources, and thus provides a measure of representativeness. Gross energy data (the simple sum of energy of material resource, combustion process energy, and precombustion energy) from the current work is 10 percent lower than that of other public sources. CO_2 is 10 percent lower than this sample of public sources, NO_x is approximately 3 percent higher, and solid waste is up to 20 percent higher than this sample of public data.

A direct analysis of uncertainty is not possible because the study was based on secondary data. The secondary sources cited in this profile did not publish measures of uncertainty in the data. However, some comment on the limitations of the results is possible. Young examined the relevance and limitations of the APME data to the North American context. He noted the potential for variation in feedstock energy related to the proportion of oil versus natural gas used as feedstock. He further examined uncertainty in the APME data and noted that the range for both energy and CO^2 due to variation in practice is on the order of ±20 to 30 percent. For other emissions and solid wastes, it is reasonable to expect variations on the order of ±100 percent.

Four independent experts in the field developed the APME methodology. Additionally, following IS0 14040, internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review. In accordance with the ISO standards, the internal experts are familiar with the requirements of ISO 14040 and 14041 and

Table 6-7. Data Quality Summary for LDPE

Data Quality Indicator	LDPE
Geographic coverage	Data represent 22 European ethylene polymerization plants producing 3.1 million short tons of LDPE. European electrical emissions were replaced with U.S. electricity-related emissions.
Time period coverage	APME data were collected between 1991 and 1992 and published in 1993. EIA data on the 1992 European grid were published in 1998. Franklin data on U.S. national grid electrical emissions were published in 1998.
Technology coverage	The data represent 22 European ethylene polymerization plants producing approx. 3.1 million short tons of LDPE.
Precision	APME noted a range in variability for gross energy of 63 – 92 Btu per short ton.
Consistency	Information not available.
Completeness	Information not available.
Representativeness	Gross energy is 10% lower than a small sample of other public data sources. CO_2 is 10% higher, NO_x is approximately 3% higher, and SW is up to 20% higher than this sample of public data.
Reproducibility	Process energy and emissions can be calculated or reproduced from all secondary sources since the major sources of data are publicly available.
Sources of data	LDPE profile data are from APME reports 3 and 10. EIA data on the Western European electricity grid were used to backcalculate fuels and emissions related to electrical energy consumption and were replaced with the U.S. national grid mix. Franklin data were used for electrical emissions from the U.S. grid.
Uncertainty	A direct analysis of uncertainty was not possible because the data were based on secondary sources, which did not publish uncertainty ranges. However, based on review from public sources, comments on data variation, indicate: ± 30% for energy, ± 100% for emissions.
Data Quality Rating	The LDPE data are considered to be of average quality.

Table 6-8. Comparison to Literature of Key Inventory Data Values for LDPE

	Unit	EPA LDPE Profile	APME[a]	SFAEFL[b]
Energy	MMBtu/ton	67.38	71.35	71.4
CO_2	lb/ton	4,892.00	4,800.00	4,640.00
NO_x	lb/ton	24.62	24.00	24.00
Solid Waste	lb/ton	95.26	78.8	78.2

[a] APME, 1993, 1997
[b] SFAEFL, 1996.

have the necessary technical and scientific expertise. However, a report detailing the findings by the internal experts was not prepared.

The LDPE data are considered to be of average quality.

6.4 Polyethylene Terephthalate (PET)

6.4.1 Introduction

This section contains an LCI profile for the production of primary (virgin) PET. It contains process flow diagrams and descriptions for production processes, LCI data tables for 1 short ton of product, and a discussion of data quality. Section 6.2 describes many of the upstream processes, such as petroleum extraction and processing, that also apply to the production of PET. This section describes only the unit operations for PET production that occur after ethylene production.

The boundaries for this material system depend on plastic production data (secondary) from a series of papers on "eco-profiles of the European plastics industry." The LCI data for the production of commodity thermoplastics were collected and published by APME member companies, according to their agreed methodology (APME methods). Thus, the boundaries for the current product system include extraction of raw material (crude oil, natural gas, LPG, etc.), processing crude oil and natural gas, petroleum refining, and ethylene polymerization and separation of PET. To maintain consistency in boundaries, calculations and presentation, and confidentiality of data, the data were aggregated by APME at the product system level. With the addition of U.S. combustion and precombustion energy, the data set used in this study represents boundaries for the aggregated cradle-to-gate processing of one ton of PET as described in APME Report 8 (APME, 1995).

6.4.2 PET Production

Figure 6-4 shows a simplified process flow diagram for processing PET. The manufacture of PET includes: production and transport of processed crude oil and natural gas (both domestic and imported), petroleum refining, and ethylene polymerization and separation (Kent, 1974; Elvers et al., 1991; Standen, 1968, APME, 1995).

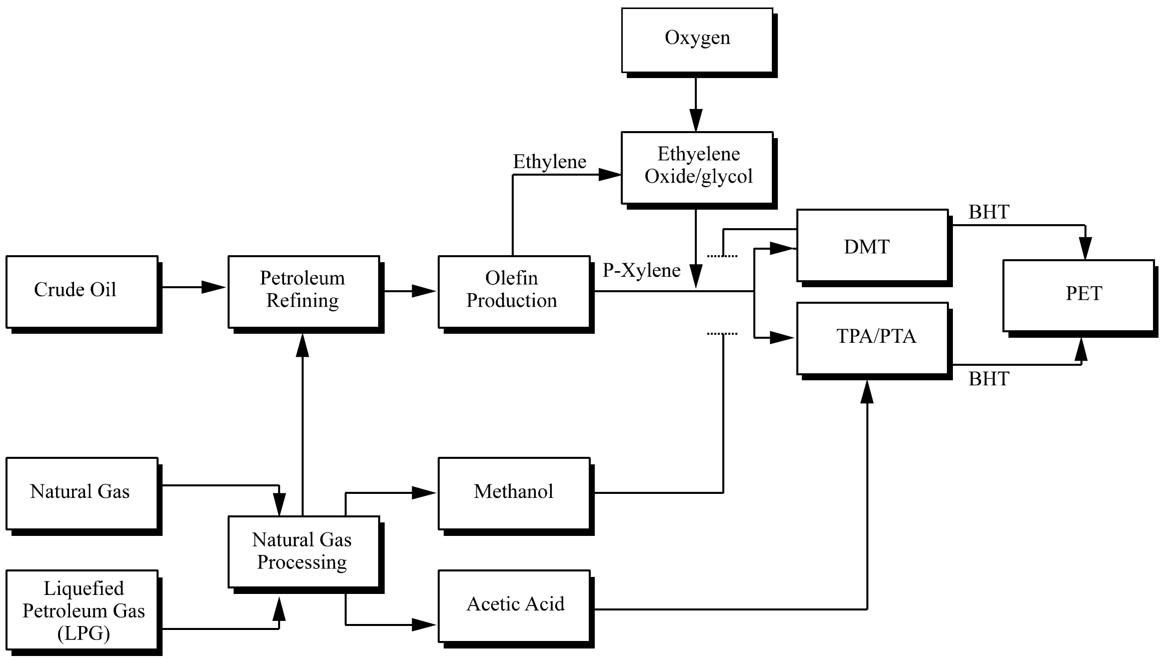

Figure 6-4. Simplified process flow diagram for polyethylene terephthalate (PET) (modified from APME, 1995)

Many of the material production operations for PET were described for polyethylene in Section 6.2. Please refer to Section 6.2.2.1 for a detailed description of crude oil production, natural gas production, LPG production, petroleum refining, natural gas processing, ethylene production, and olefin (ethylene) polymerization. This section describes the steps in PET production that follow the aforementioned processes.

Polyethylene terephthalate is produced by melt polymerizing bishydroxyethyl terephthalate (BHET) to amorphous PET using a continuous melt-phase polymerization process, followed by a solid-state polymerization process that yields a highly crystalline pellet and provides the final molecular weight and final intrinsic viscosity. This solid state process yields a polymer with a low acetaldehyde content. Typical commercial PET resins melt at approximately 250°C. On the other hand, highly crystalline PET melts at approximately 270°C.

BHET is produced using one of two possible precursors: via terephthalic acid (TPA) or via dimethyl terephthalate (DMT). These two techniques are described briefly below.

In the TPA route, also known as the direct esterification route, PET is manufactured by oxidizing para-xylene and reacting it with acetic acid, which is produced from natural gas, to make terephthalic acid. TPA is then purified and combined with ethylene glycol in a reaction that produces BHT. BHT is then used to produce PET.

In the DMT route, also known as the ester interchange reaction, PET is produced by reacting para-xylene and methanol to form DMT, which then reacts with ethylene glycol in the ester interchange reaction to produce BHET. BHET is then used to produce PET.

6.4.3 Data Source and Calculation Procedures

The data were developed primarily using the European APME plastics data sets. Electrical energy[10] and the associated emissions from these APME data were replaced with data from the electrical energy module included as part of the overall decision support tool. APME Report 8, which presents a cradle-to-gate environmental data profile for 1 kilogram of PET, was used along with Western European electric grid data and U.S. electric grid data (EIA, 1998; Franklin Associates, 1998; APME, 1993, 1997). The following steps outline the procedure used to construct LCI data for PET:

1. The TPA profile from APME was converted from SI units (energy in MJ, mass in milligrams per kilogram) to U.S. units (mass in lb, volume in U.S. gallons, gaseous volume in ft^3, and energy in Btu/1 ton (2,000 lb).[11] The electrical energy is converted from MJ to kWh using the appropriate efficiencies for each fuel in the electrical fuel mix (EIA, 1998).

2. Based on the Western European Fuel Mix from 1992 and combustion and precombustion emissions from the Franklin Report,[12] an environmental profile for producing and delivering 1 (kWh) of the Western European electrical grid[13] was developed. A similar environmental profile for producing 1 kWh of the U.S. electrical grid was developed by Franklin (EIA, 1998; Franklin Associates, 1998).

3. The precombustion energy and environmental releases (air emissions, water emissions and solid waste emissions) from the European Electrical Fuel Mix were deducted using the profile developed in Step 2 for the appropriate kWh converted

[10] The average of the U.S. National Grid was used to calculate the electrical emissions (Franklin Associates, 1998).

[11] Energy conversion factors developed by Franklin Associates Ltd. (Table 9 in their 1998 report); Franklin data were used to calculate/convert to the appropriate units.

[12] Energy consumption and emissions released from *Utility Boilers* developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to develop the appropriate pre-combustion energies and environmental emissions for 1 kWh of European electric grid.

[13] U.S. Electrical Energy and Emissions data developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to calculate the appropriate precombustion energies and environmental emissions for 1 kWh of U.S. electric grid.

in Step 1. For the same kWh, the precombustion energies and environmental emissions for the U.S. electrical mix are added to the profile. The net electrical energy for the process is the same; however, the precombustion energy quantities and environmental emissions are different because of the different fuel mix from the two electrical grids.

Table 6-9 shows the original APME PET emissions profile. The first column shows the published APME data profile and the second column shows APME data with the European electrical emissions subtracted. The complete LCI results are provided in Section 6.4.4.

6.4.4 LCI Results

Table 6-10 summarizes the cradle-to-gate LCI data for virgin PET production. The table breaks down the individual fuels that make up the energy of material resource, combustion process energy, and precombustion energy related to material resource feedstock, process fuels, and electric energy fuels. The emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

6.4.5 Data Quality

Table 6-11 summarizes data quality information for virgin PET production. APME data were based on a thorough survey of European producers. APME data represent a cross-section of poor, average and above average performance and technologies. The results determined here are thought to be representative of both global and U.S. production. Young (1996) expressed confidence that APME data used primary industry data collected from a nondiscriminating sample in a large population. Because secondary data were used in this study, precision, consistency, and completeness of information is not all available. The various data quality measures are defined below.

Table 6-12 shows how the data in the current study compare with data from other public sources, and thus provides a measure of representativeness. Gross energy data (the simple sum of energy of material resource, combustion process energy, and precombustion energy) from the current work is up to 10 percent lower than that of other public sources. CO_2 is up to 10 percent higher than this sample of public data, NO_x is up to 8 percent higher, and solid waste is up to 25 percent higher than this sample.

A direct analysis of uncertainty was not possible because the study was based on secondary data. The secondary sources cited in this profile did not publish measures of uncertainty in the data. However, some comment on the limitations of the results is possible. Young (1996) examined the relevance and limitations of the APME data to the North American context. He noted the potential for variation in feedstock energy related to the proportion of oil versus natural gas used as feedstock. He further examined uncertainty in the APME data and noted that the range for both energy and CO^2 due to variation in practice is in the order of ±20 to 30 percent. For other emissions and solid wastes, it is reasonable to expect variations on the order of ±100 percent.

Table 6-9. Environmental Emissions for Production of 1 Ton of PET With and Without European Electrical Emissions

		Original APME Data (lb/ton)	APME Data without European Electricity Emissions (lb/ton)
Atmospheric Emissions			
Particulates (PM_{10})	lb	0.00E+00	0.00E+00
Particulates (Total)	lb	7.60E+00	5.46E+00
Nitrogen Oxides	lb	4.04E+01	2.26 E+01
Hydrocarbons (non CH_4)	lb	8.00E+01	4.14E+01
Sulfur Oxides	lb	5.00E+01	1.52E+01
Carbon Monoxide	lb	3.60E+01	1.34E+01
CO_2 (biomass)	lb	0.00E+00	0.00E+00
CO_2 (non biomass)	lb	4.66E+03	4.42E+03
Ammonia	lb	0.00E+00	0.00E+00
Lead	lb	0.00E+00	0.00E+00
Methane	lb	0.00E+00	0.00E+00
Hydrochloric Acid	lb	2.20E-01	1.40E-01
Solid Waste			
Solid Waste #1	lb	0.00E+00	0.00E+00
Ash	lb	1.92E+01	0.00E+00
Sludge	lb	0.00E+00	0.00E+00
Scrap	lb	0.00E+00	0.00E+00
Unspecified	lb	7.11E+01	6.08E+01
Waterborne Emissions			
Dissolved Solids	lb	1.16E-00	9.08E-01
Suspended Solids	lb	1.20E+00	1.20E+00
BOD	lb	2.00E-00	2.00E-00
COD	lb	6.60E+00	6.60E+00
Oil	lb	4.00E-02	3.65E-02
Sulfuric Acid	lb	3.60E-01	1.67E-01
Iron	lb	0.00E+00	0.00E+00
Ammonia	lb	0.00E+00	0.00E+00
Cooper		0.00E+00	0.00E+00
Cadmium	lb	0.00E+00	0.00E+00
Arsenic	lb	0.00E+00	0.00E+00
Mercury	lb	0.00E+00	0.00E+00
Phosphate	lb	2.00E-02	2.00E-02
Selenium	lb	0.00E+00	0.00E+00
Chromium	lb	0.00E+00	0.00E+00
Lead	lb	0.00E+00	0.00E+00
Zinc	lb	0.00E+00	0.00E+00

Table 6-10. Data for Production of 1 Ton of Primary PET

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Energy of Material Resource				
Petroleum	MMBtu	3.94E+01	3.94E+01	1.00E+00
Coal	MMBtu	8.60E-03	8.60E-03	1.00E+00
Combustion Process Energy				
Electricity	kWh	2.60E+02	2.33E+00	8.97E-03
Natural Gas	cu ft	1.05E+04	1.22E+01	1.16E-03
LPG	gal			1.08E-01
Coal	lb			1.15E-02
Distillate oil	gal			1.58E-01
Residual Oil	gal	5.71E+01	9.76E+00	1.71E-01
Gasoline	gal			1.41E-01
Diesel	gal			1.58E-01
Wood	Btu			1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.46E+03	1.70E+00	1.16E-03
Residual Oil	gal	1.33E+01	2.27E+00	1.71E-01
Distillate oil	gal			1.58E-01
Gasoline	gal			1.41E-01
LPG	gal			1.08E-01
Coal	lb	1.84E+02	2.11E+00	1.15E-02
Nuclear	lb U238	1.77E-03	1.84E+00	1.04E+03
Hydropower	Btu	5.33E+05	5.33E-01	1.00E-06
Other	Btu	5.92E+04	5.92E-02	1.00E-06

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Atmospheric Emissions				
Acreolin	lb	5.43E-06		5.43E-06
Ammonia	lb	1.70E-03		1.70E-03
Antimony	lb	2.45E-06		2.45E-06
Arsenic	lb	1.19E-05		1.19E-05
Benzene	lb	6.19E-06		6.19E-06
Beryllium	lb	1.38E-06		1.38E-06
Cadmium	lb	1.73E-06		1.73E-06
Carbon Dioxide-fossil	lb	4.71E+03	4.33E+03	3.76E+02
Carbon Dioxide-nonfossil	lb	9.39E-01		9.39E-01
Carbon Monoxide	lb	3.58E+01	3.56E+01	1.58E-01
Carbon Tetrachloride	lb	9.16E-06		9.16E-06
Chlorine	lb	4.50E-06		4.50E-06

(continued)

Table 6-10. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Chromium	lb	1.54E-05		1.54E-05
Cobalt	lb	3.05E-04		3.05E-04
Dioxins	lb	1.68E-06		1.68E-06
Formaldehyde	lb	1.66E-05		1.66E-05
Hydrocarbons (non CH_4)	lb	7.96E+01	7.94E+01	1.95E-01
Hydrochloric acid	lb	2.47E-01	2.20E-01	2.75E-02
Hydrogen Fluoride	lb	3.79E-03		3.79E-03
Kerosene	lb	1.43E-04		1.43E-04
Lead	lb	1.80E-05		1.80E-05
Manganese	lb	4.06E-05		4.06E-05
Mercury	lb	1.01E-05		1.01E-05
Metals	lb	8.10E-05		8.10E-05
Methane	lb	8.13E-01		8.13E-01
Methylene Chloride	lb	2.35E-05		2.35E-05
Naphthalene	lb	1.10E-06		1.10E-06
Nickel	lb	7.10E-05		7.10E-05
Nitrogen Oxides	lb	4.06E+01	3.92E+01	1.40E+00
Nitrous Oxide	lb	3.08E-03		3.08E-03
n-nitrodimethylamine	lb	1.15E-06		1.15E-06
Other Aldehydes	lb	9.25E-04		9.25E-04
Other Organics	lb	1.46E-03		1.46E-03
Particulate	lb	7.59E+00	7.13E+00	4.56E-01
Perchloroethylene	lb	5.18E-06		5.18E-06
Phenols	lb	2.96E-05		2.96E-05
Radionuclides (Ci)	lb	1.02E-04		1.02E-04
Selenium	lb	3.85E-05		3.85E-05
Sulfur Oxides	lb	5.04E+01	4.76E+01	2.78E+00
Trichloroethylene	lb	5.13E-06		5.13E-06
Solid Wastes	lb	1.24E+02	5.50E+01	6.88E+01
Waterborne Emissions				
Acid	lb	5.51E-09		5.51E-09
Ammonia	lb	2.04E-04	-3.44E-05	2.38E-04
BOD	lb	2.00E+00	2.00E+00	9.18E-04
COD	lb	6.61E+00	6.60E+00	1.26E-02
Boron	lb	1.40E-02		1.40E-02
Cadmium	lb	4.01E-05		4.01E-05
Calcium	lb	1.23E-04		1.23E-04
Chlorides	lb	4.18E-02		4.18E-02
Chromates	lb	4.38E-06		4.38E-06
Chromium	lb	4.01E-05		4.01E-05
Cyanide	lb	6.00E-08		6.00E-08

(continued)

Table 6-10. (continued)

Environmental Releases	Units	Total	Process	Fuel Related
Dissolved Solids	lb	1.80E+00	9.08E-01	8.87E-01
Fluorides	lb	5.68E-04		5.68E-04
Iron	lb	2.06E-02		2.06E-02
Lead	lb	9.71E-09		9.71E-09
Manganese	lb	1.18E-02		1.18E-02
Mercury	lb	3.15E-09		3.15E-09
Metal Ion	lb	1.16E-04		1.16E-04
Nitrates	lb	5.36E-05		5.36E-05
Oil	lb	5.22E-02	3.65E-02	1.57E-02
Other Organics	lb	5.22E-03		5.22E-03
Phenol	lb	3.81E-07		3.81E-07
Phosphate	lb	2.17E-02	2.00E-02	1.75E-03
Sodium	lb	2.26E-04		2.26E-04
Sulfates	lb	1.02E-01		1.02E-01
Sulfuric Acid	lb	3.36E-03		3.36E-03
Suspended Solids	lb	1.45E+00	1.20E+00	2.47E-01
Zinc	lb	1.39E-05		1.39E-05

Source: EIA, 1998; APME, 1995; Franklin Associates, 1998.

Table 6-11. Data Quality Summary for PET

Data Quality Indicator	PET
Geographic Coverage	Data represent 12 European plants producing approximately 180,000 short tons of PET. European electrical emissions were replaced with U.S. electricity- related emissions.
Time Period Coverage	APME data refer to a time period between 1989 and 1991. EIA data on the 1992 European grid were published in 1998. Franklin data on U.S. national grid electrical emissions were published in1998.
Technology Coverage	Approximately 80% of the 180,000 short tons of PET is produced by the terephthalic acid (TPA) route and the remainder is produced from dimethyl terephthalate (DMA).
Precision	APME noted a range in variability for gross energy of 57 – 84 Btu per short ton.
Consistency	Information not available.

(continued)

Table 6-11. (continued)

Data Quality Indicator	PET
Completeness	Information not available.
Representativeness	Gross energy is up to 10% lower than a small sample of other public sources. CO_2 is up to10% higher, NO_x is up to 8% higher, and SW is up to 25% higher than this sample of public data.
Reproducibility	Process energy and emissions can be calculated or reproduced from all secondary sources since the major sources of data are publicly available.
Sources of Data	PET profile data are from APME report 8. EIA data on the Western European electricity grid were used to back-calculate fuels and emissions related to electrical energy consumption and were replaced with the U.S. national grid mix. Franklin data were used for electrical emissions from the U.S. grid.
Uncertainty	A direct analysis of uncertainty was not possible because the data were based on secondary sources, which did not publish uncertainty ranges. However, based on review from public sources, comments on data variation, indicate: ± 30% for energy, ± 100% for emissions.
Data Quality Rating	The PET data are considered to be of average quality.

Table 6-12. Comparison to Literature of Key Inventory Data Values for PET

	Unit	EPA PET Profile	APME[a]	STAEFL[b]
Energy	MMBtu/ton	66.50	72.05	70.20
CO_2	lb/ton	4,742.00	4,660.00	4,400.00
NO_x	lb/ton	40.90	40.40	38.00
Solid Waste	lb/ton	104.50	90.26	82.20

[a] APME, 1995
[b] SFAEFL, 1996

Four independent experts in the field developed the APME methodology. Additionally, following IS0 14040, internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review. In accordance with the ISO standards, the internal experts are familiar with the requirements of ISO 14040 and 14041 and have the necessary technical and scientific expertise. However, a report detailing the findings by the internal experts was not prepared.

The PET data are considered to be of average quality.

6.5 Secondary Plastics

6.5.1 Introduction

This section contains an LCI profile for the production of secondary plastic. Plastics account for 9.4 percent of MSW generation by weight behind paper and paperboard, which together accounted for 38.1 percent of the MSW for 1997 (U.S. EPA, 1998). The remaining MSW fractions include yard trimmings at 13.4 percent, food at 10.4 percent, and "other wastes" (e.g., rubber and leather, textiles, miscellaneous inorganic waste) at 9.9 percent. About 5 percent of LDPE from industrial waste is recycled in the U.S. (Beck, 1997a). The secondary plastic data set models only the most commonly collected and recycled plastic waste: HDPE and PET bottles (Beck, 1997b). The processes for recycling PET and HDPE bottles and the LCI are similar; therefore, only one Secondary Plastics profile is provided for both polymers as part of this study.

The boundaries for this study depend on secondary plastic production data from a series of papers on packaging materials published in Europe. These inventory data for the recycling of PET and HDPE were collected and published by SFAEFL, according to their agreed methodology. Thus, the boundaries for the current material system includes the reprocessing of PET bottles. The secondary data used in this study were part of a larger database developed by SFAEFL. To maintain consistency in calculations and presentation and confidentiality of data, the data were aggregated at the unit process level. With the addition of combustion and precombustion energy, the data set used in this study represents an aggregated cradle-to-gate processing of 1 ton of secondary plastic flakes.

6.5.2 Secondary Plastics Production

Sorted plastic bottle bales are delivered from a MRF to a reprocessing facility. The sorted plastics are passed across a shaker screen to remove small pieces of trash and dirt. The recyclable plastics are then put through a grinding process where they are cut into small pieces. These pieces then are combined with water to soften and remove contaminants from the newly formed plastic flakes. The flakes are then conveyed into a washing system where residual contents, dirt, and labels are removed. Because different types of plastics have different densities, a flotation tank is used to separate the mixed plastics and contaminants. Heated air is used to dry the cleaned and separated flakes. Figure 6-5 shows a simplified process flow diagram for processing secondary plastics.

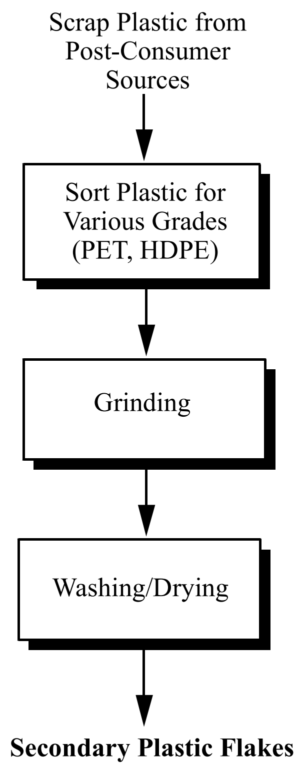

Figure 6-5. Process flow diagram for secondary plastics.

6.5.3 Data Source and Calculation Procedures

The primary source of data for this study is the SFAEFL report 250/11 on Plastics (SFAEFL, 1996). The SFAEFL data represent process energy and emissions only. The combustion and precombustion energy and emissions factors were added to complete the cradle-to-gate secondary plastic profile. An average U.S. grid was used to calculate the electrical emissions. The following steps outline the procedure taken to present inventory data for PET.

1. The secondary PET profile from SFAEFL was converted from SI units (energy in MJ, mass in milligrams per kilogram to U.S. units [mass in lb, volume in U.S. gallons, gaseous volume in ft^3, and energy in Btu/1 ton (2,000 lb)].[14] The electrical energy is converted from MJ to kWh using the appropriate efficiencies for each fuel in the electrical fuel mix (EIA, 1998).

2. Based on the Western European Fuel Mix from 1992 and combustion and precombustion emissions from the Franklin Report,[15] an environmental profile for

[14] Energy conversion factors developed by Franklin Associates Ltd. (Table 9 in their 1998 report), Franklin data were used to calculate/convert to the appropriate units.

[15] Energy consumption and emissions released from *Utility Boilers* developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to develop the appropriate pre-

producing and delivering 1 (kWh) of the Western European electrical grid[16] was developed. A similar environmental profile for producing 1 kWh of the U.S. electrical grid was developed by Franklin (EIA, 1998; Franklin Associates, 1998).

3. The precombustion energy and environmental emissions (air emissions, water emissions and solid waste emissions) from the European Electrical Fuel Mix were deducted using the profile developed in Step 2 for the appropriate kWh converted in Step 1. For the same kWh, the precombustion energies and environmental emissions for the U.S. electrical mix are added to the profile. The net electrical energy for the process is the same; however, the precombustion energy quantities and environmental emissions are different because of the different fuel mix from the two electrical grids. Because the data published in the SFAEFL report were for mechanical processing only, we have added the electrical[17] and fuel (natural gas[18]) precombustion energies and emissions. In addition we have assumed that the material inputs and solid wastes released are transported 70 miles on a single-unit diesel truck. Table 6-17 shows the breakdown of process-related and combustion and precombustion related emissions for the secondary plastics profile. The combustion and precombustion related emissions are further broken down into electrical, natural gas, and transport-related emissions.

6.5.4 LCI Results

Tables 6-13 summarizes the cradle-to-gate LCI data for Secondary Plastics. The table breaks down the individual fuels that make up precombustion energy related to material resource feedstock, process fuels, and electric energy fuels. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

6.5.5 Data Quality

Table 6-14 summarizes data quality information for Secondary Plastics production. Because secondary data were used in this study, precision, consistency, and completeness of information is not available.

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combustion energies and environmental emissions for 1 kWh of European electric grid.

[16] U.S. Electrical Energy and Emissions data developed by Franklin Associates (Tables 6, 7, 8, 14, 16, 18, 20, 26 in their 1998 report). Franklin data were used to calculate the appropriate precombustion energies and environmental emissions for 1 kWh of U.S. electric grid.

[17] U.S. Electrical Energy and Emissions developed by Franklin Associates Ltd. (Tables 6, 7, 8, 14, 16, 18, 20, 26) were used to add the appropriate precombustion energies and environmental emissions for 1kWh of U.S. Electric Grid.

[18] Precombustion Energy and Emissions for Natural Gas developed by Franklin Associates Ltd. (Table 11) was used to add the appropriate precombustion energies and environmental emissions.

Table 6-13. Data for Production of 1 Ton of Secondary Plastics

Energy Usage	Units	Total (Base Units)	Total (10^6 Btu)	Factor to Convert to 10^6 Btu
Combustion Process Energy				
Electricity	kWh	1.54E+02	1.38E+00	8.97E-03
Natural Gas	cu ft	7.09E+02	8.22E-01	1.16E-03
LPG	gal	1.27E-02	1.21E-03	9.55E-02
Coal	lb			1.12E-02
Distillate oil	gal			1.39E-01
Residual Oil	gal	1.09E-01	1.64E-02	1.50E-01
Gasoline	gal	7.00E-03	8.75E-04	1.25E-01
Diesel	gal	1.58E-02	2.19E-03	1.39E-01
Wood	Btu			1.00E-06
Precombustion Process Energy				
Natural Gas	cu ft	1.99E+02	2.59E-02	1.30E-04
Residual Oil	gal	1.68E+00	3.54E-02	2.10E-02
Distillate oil	gal	2.27E+00	4.39E-02	1.93E-02
Gasoline	gal	3.33E-02	5.46E-04	1.64E-02
LPG	gal	8.79E-05	1.06E-06	1.21E-02
Coal	lb	3.39E+00	8.80E-04	2.60E-04
Nuclear	lb U238	7.70E-05	3.90E-03	5.06E+01
Hydropower	Btu	5.20E+05	5.20E-01	1.00E-06
Other	Btu	1.31E+06	1.31E+00	1.00E-06
Combustion Transportation Energy				
Combination truck	1.15E+00	ton-miles		
Diesel	1.14E-02	gal	1.81E-03	1.58E-01
Rail	1.21E+00	ton-miles		
Diesel	3.39E-03	gal	5.36E-04	1.58E-01
Barge	4.02E-01	ton-miles		
Diesel	8.16E-04	gal	1.29E-04	1.58E-01
Residual Oil	3.26E-04	gal	5.58E-05	1.71E-01
Ocean Freighter	1.52E+02	ton-miles		
Diesel	1.52E-02	gal	2.41E-03	1.58E-01
Residual	2.74E-01	gal	4.68E-02	1.71E-01
Pipeline-natural gas	1.09E+01	ton-miles		
Natural gas	2.50E+01	cu ft	2.90E-02	1.16E-03
Pipeline-petroleum products	1.06E+01	ton-miles		
Electricity	2.34E-01	kWh	2.10E-03	8.97E-03

(continued)

Table 6.13. (continued)

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Atmospheric Emissions				
Acreolin	lb	3.18E-06		3.18E-06
Ammonia	lb	3.30E-03	2.30E-03	9.97E-04
Antimony	lb	1.44E-06		1.44E-06
Arsenic	lb	7.00E-06		7.00E-06
Benzene	lb	3.63E-06		3.63E-06
Beryllium	lb	8.12E-07		8.12E-07
Cadmium	lb	1.02E-06		1.02E-06
Carbon Dioxide-fossil	lb	5.67E+02	3.47E+02	2.21E+02
Carbon Dioxide-nonfossil	lb	6.31E-01	8.04E-02	5.51E-01
Carbon Monoxide	lb	3.41E+00	3.32E+00	9.25E-02
Carbon Tetrachloride	lb	5.37E-06		5.37E-06
Chlorine	lb	2.64E-06		2.64E-06
Chromium	lb	9.02E-06		9.02E-06
Cobalt	lb	1.79E-04		1.79E-04
Dioxins	lb	9.85E-07		9.85E-07
Formaldehyde	lb	9.75E-06		9.75E-06
Hydrocarbons (non CH_4)	lb	1.52E+00	1.41E+00	1.15E-01
Hydrochloric Acid	lb	1.64E-02	3.19E-04	1.61E-02
Hydrogen Fluoride	lb	2.22E-03		2.22E-03
Kerosene	lb	8.39E-05		8.39E-05
Lead	lb	1.24E-05	1.82E-06	1.06E-05
Manganese	lb	2.38E-05		2.38E-05
Mercury	lb	5.95E-06		5.95E-06
Metals	lb	4.75E-05		4.75E-05
Methane	lb	7.57E-01	2.80E-01	4.77E-01
Methylene Chloride	lb	1.38E-05		1.38E-05
Naphthalene	lb	6.44E-07		6.44E-07
Nickel	lb	4.17E-05		4.17E-05
Nitrogen Oxides	lb	4.44E+00	3.62E+00	8.24E-01
Nitrous Oxide	lb	1.81E-03		1.81E-03
n-nitrodimethylamine	lb	6.72E-07		6.72E-07
Other Aldehydes	lb	5.43E-04		5.43E-04
Other Organics	lb	8.54E-04		8.54E-04
Particulate	lb	9.99E-01	7.31E-01	2.68E-01
Perchloroethylene	lb	3.04E-06		3.04E-06
Phenols	lb	1.74E-05		1.74E-05
Radionuclides (Ci)	lb	5.96E-05		5.96E-05
Selenium	lb	2.26E-05		2.26E-05
Sulfur Oxides	lb	3.51E+00	1.88E+00	1.63E+00
Trichloroethylene	lb	3.01E-06		3.01E-06

(continued)

Table 6.13. (concluded)

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Solid Wastes	lb	3.69E+02	3.28E+02	4.04E+01
Waterborne Emissions				
Acid	lb	3.23E-09		3.23E-09
Ammonia	lb	3.21E-04	1.81E-04	1.40E-04
BOD	lb	1.08E-01	1.07E-01	5.39E-04
COD	lb	6.11E-01	6.04E-01	7.40E-03
Boron	lb	8.22E-03		8.22E-03
Cadmium	lb	1.25E-04	1.01E-04	2.35E-05
Calcium	lb	7.20E-05		7.20E-05
Chlorides	lb	2.45E-02		2.45E-02
Chromates	lb	2.57E-06		2.57E-06
Chromium	lb	1.25E-04	1.01E-04	2.35E-05
Cyanide	lb	3.52E-08		3.52E-08
Dissolved Solids	lb	2.81E+00	2.29E+00	5.21E-01
Fluorides	lb	3.33E-04		3.33E-04
Iron	lb	1.23E-02	2.41E-04	1.21E-02
Lead	lb	1.61E-07	1.55E-07	5.70E-09
Manganese	lb	6.93E-03		6.93E-03
Mercury	lb	9.76E-09	7.91E-09	1.85E-09
Metal Ion	lb	6.80E-05		6.80E-05
Nitrates	lb	3.14E-05		3.14E-05
Oil	lb	5.14E-02	4.22E-02	9.19E-03
Other Organics	lb	3.06E-03		3.06E-03
Phenol	lb	2.24E-07		2.24E-07
Phosphate	lb	1.07E-03	4.29E-05	1.03E-03
Sodium	lb	1.32E-04		1.32E-04
Sulfates	lb	6.01E-02		6.01E-02
Sulfuric Acid	lb	2.05E-03	8.42E-05	1.97E-03
Suspended Solids	lb	1.94E-01	4.87E-02	1.45E-01
Zinc	lb	4.50E-05	3.68E-05	8.14E-06

Source: EIA, 1998; SFAEFL, 1996; Franklin Associates, 1998.

Table 6-14 Data Quality Summary for Secondary Plastics

Data Quality Indicator	Secondary Plastic
Geographic Coverage	The data represent collection and processing of plastic bottles in Switzerland and Germany. http://www.snre.umich.edu./cemp/
Time Period Coverage	The secondary data (process-related energy emissions) were collected between 1989 and 1991 and published in 1997. EIA data on the 1992 European grid were published in 1998. Franklin data on U.S. national grid electrical emissions were published in1996.
Technology Coverage	Process data represent mechanical processing of PET and HDPE bottles (postconsumer) only.
Precision	Information not available.
Consistency	Information not available.
Completeness	Information not available.
Representativeness	Gross energy is approximately 40% higher than one other public data source.
Reproducibility	Process energy and emissions can be calculated or reproduced from all secondary sources since the major sources of data are publicly available.
Sources of Data	The secondary PET profile data are from the Swiss Eco-profiles of Packaging Materials, published by SFAEFL. EIA data on the Western European electricity grid were used to back-calculate fuels and emissions related to electrical energy consumption and were replaced with the U.S. national grid mix. Franklin data were used for electrical emissions from the U.S. grid.
Uncertainty	Information on data uncertainty was not available since the data collected in the secondary PET profile were compiled from secondary sources, which did not include an analysis of uncertainty.
Data Quality Rating	The secondary plastics data are considered to be of average quality.

Table 6-15 shows how the data in the current study compare with data from one other public source, and thus provides a measure of representativeness. Gross energy data (the simple sum of energy of material resource, combustion process energy, and precombustion energy) from the current work is 40 percent higher than that of the EPIC model (Canadian Plastics Industry Association). Data from other inventory categories such as CO_2 and NO_x were not available to compare for secondary PET (American Plastics Council, 1999a, b).

Table 6-15. Comparison to Literature of Key Inventory Data Values for Secondary Plastics

	EPA Secondary Plastics Profile	EPIC[a]
Total energy (MMBtu/ton)	7.96	6
Reprocessing (MMBtu/ton)	7.94	5
Transport (MMBtu/ton)	0.03	1

[a] Canadian Plastics Industry Association.

A direct analysis of uncertainty is not possible. The secondary sources cited in this profile did not publish measures of uncertainty. Furthermore, there are fewer publicly available data sources to compare secondary plastics than with primary plastic materials, as shown with the previous profiles. The EPIC model, developed by the Canadian Plastics Industry Association, is a publicly available model that allows one to estimate the reprocessing energy and transportation energy required for secondary plastics. The model does not, however, allow for the estimation of greenhouse gases or other emissions at this time.

However, some comment on the limitations of the results is possible. As noted earlier, the SFAEFL data set modeled a plant that reprocesses PET bottles. This data set was then supplemented with U.S. precombustion energy and emissions.

Four independent experts in the field developed the APME methodology. Additionally, following IS0 14040, internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review. In accordance with the ISO standards, the internal experts are familiar with the requirements of ISO 14040 and 14041 and have the necessary technical and scientific expertise. However, a report detailing the findings by the internal experts was not prepared.

The Secondary Plastics data are considered to be of average quality.

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7.0 Summary LCI of Steel Products[1]

7.1 Introduction

This chapter presents cradle-to-gate LCI profiles for two steel materials: primary hot rolled coil produced using the basic oxygen furnace (BOF) steel-making technology (Section 7.2) and secondary steel bars produced using the electric arc furnace (EAF) steel-making technology (Section 7.3). The data were collected by the American Iron and Steel Institute (AISI) and are intended for use in the MSW-DST (AISI, 1999). The intended audience for the steel data includes steel customers, consumers of steel and recycled steel, steel recyclers, and steel researchers. The LCI results include inputs and outputs from raw materials extraction through production of the final product but do not include the use or disposal portions of a traditional LCI.

The product system function is defined as the production of steel materials at the factory gate. The steel materials are later used in the manufacture of many types of goods, such as automobiles, food and beverage packaging, bridges, and housing, though these uses of steel are beyond the scope of this work. The functional unit, the unit by which the product inputs and outputs are referenced, is 1 ton (2,000 lb) of steel (BOF and EAF) product.

All material and water consumption, as well as environmental emissions, are presented as mass in pounds (lb), volume in U.S. gallons (gal), gaseous volume in cubic feet (ft^3), and energy in British thermal units (Btu).

The model uses combustion and precombustion fuel and electrical energy-related environmental releases developed by AISI (and their consultants) for the U.S. Automotive Material Partnership (USAMP) (AISI, 1999). AISI was not able to split out their fuel and electrical energy information from their steel profiles and thus we were not able to apply our common fuel and electrical energy model as was done for the other materials. A review of the AISI fuel and electrical energy data revealed no significant differences from our overall fuel and electrical energy model used for the other materials.

This chapter describes the function of each product system, the product system boundaries, allocation procedures, type of impact assessment employed, data requirements, assumptions, limitations, data quality, critical review, and the study report.

[1] AISI Report "Life Cycle Inventory of Steel" has been reformatted to suit EPA format for units and presentation.

7.2 Primary Steel Production (BOF Technology)

7.2.1 Introduction

This section contains an LCI profile for primary hot rolled coil produced using BOF steel-making technology (AISI, 1999). It contains process flow diagrams and descriptions for production processes, LCI data tables for 1 ton of product, and a discussion of allocation and data quality.

The LCI data for this profile were collected by AISI (1999) and models BOF steel (hot rolled steel) product from cradle-to-gate. The boundaries for the BOF steel data in this profile include all unit processes from acquisition of raw materials through production of the steel. Primary data were collected for the following unit processes: iron ore mining, limestone quarrying, coke production, iron production, BOF steel production, and hot rolling. Figure 7-1 shows a simplified process flow diagram for processing BOF steel. As indicated in Figure 7-1, data for coal mining were obtained from secondary sources.

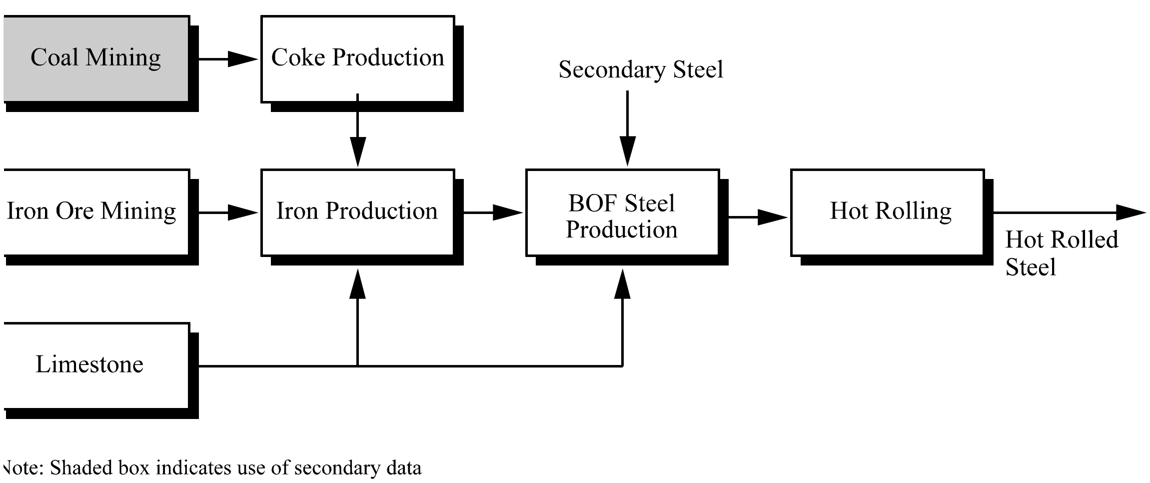

Figure 7-1. Simplified process flow diagram for BOF steel.

The following sections briefly describe the unit processes for mining and production activities associated with the production of steel.

7.2.2 Iron Ore Mining (Elvers et al., 1991; Honeycombe, 1981)

Most iron ores are extracted by surface mining techniques. Although some underground mines exist, surface mining is preferred by industry because there are abundant sources in surface mines and they are more economical to operate.

7.2.3 Limestone Quarrying

Limestone is quarried primarily from open pits. In the central and eastern United States, underground mining is becoming more common (Bureau of Mines, 1993). The most economical method of recovering the limestone has been through drilling, blasting, mechanical crushing, conveying, and screening (Bureau of Mines, 1993 and 1984). Airborne particulates are generated in the form of limestone dust throughout many of the operations. The limestone quarrying information used for the primary hot-rolled steel LCI is based upon one site in the United Kingdom. No further information about the recovery method used at this site was available.

7.2.4 Coke Production

Petroleum coking is an extreme form of thermal cracking that uses high temperatures and a long residence time to break down heavy crude residues to get lighter liquids (Kent, 1992). Coke production involves the reduction of coal in a series of ovens in the absence of oxygen. After a typical coking time of 12 to 20 hours, most of the volatile matter is driven from the crude residue and the coke is formed. The desired outputs of the coking process are actually the volatile products. The petroleum coke itself is considered a byproduct. The coke is collected in a coke drum, while the lighter products go overhead as vapors. Volatiles are captured for recovery of by-products.

7.2.5 Iron Production (Elvers et al., 1991)

Iron production involves the production of hot (iron) metal by removing oxygen from the iron ore. Almost all iron production in North America uses blast furnace technology, and it is this technology which is reflected in the steel data presented in this LCI profile. The blast furnace is a countercurrent heat and oxygen exchanger in which rising combustion gases exchange heat with descending iron oxides, which begins to convert to metallic iron at 1300°F.

7.2.6 BOF Steel Production (Lankford et al., 1985; Pehlke et al., 1974-77)

More than half the world's steel is produced in BOF, which uses pure oxygen to convert a charge of liquid blast-furnace iron and scrap into steel. The BOF is a refractory-lined, tiltable converter into which a vertically movable, water-cooled lance is inserted to blow oxygen through nozzles at supersonic velocity onto the charge. The use of pure oxygen at high flow rates results in fast oxidation of the elements contained in blast-furnace iron.

When oxygen contacts blast-furnace iron, a great amount of heat is released by the ensuing exothermic reactions, particularly the oxidation of silicon to silica, that, using only blast-furnace iron, would result in a liquid steel temperature too high for casting. Therefore, before the hot metal is added, a specific amount of scrap is charged into the furnace. Melting this scrap consumes approximately 340 kilocalories per kilogram, effectively cooling the process. A typical BOF charge, therefore, consists of about 75 percent liquid iron and 25 percent scrap. This requires a reliable supply of low-cost iron with a uniform chemical composition, which is attainable only by keeping the operating condition of the blast furnace as constant as possible;

this, in turn, requires a consistent iron consumer. There are also certain iron properties (e.g., for example, the silicon and sulfur content) that are selected to optimize the blast furnace and BOF operations and to produce steel at minimal cost. Such interdependence requires that blast furnaces and BOF facilities work within a well integrated operating system.

7.2.7 Hot Rolling (Lankford et al., 1985; Ginzburg, 1989)

Rolling is the most widely used method of shaping metals and is particularly important in the manufacture of steel for use in construction and other industries. Rolling may be done while the steel is hot (hot-rolling) or cold (cold-rolling). The process consists of passing the metal between pairs of rollers revolving at the same speed but in opposite directions and spaced so that the distance between them is slightly less than the thickness of the metal. The degree of change that can be made in the thickness of the steel depends on its temperature, with higher heat increasing the plasticity of the steel. The data included in the LCI profile reflect hot-rolling only.

7.2.8 Data Source and Calculation Procedures

Data were acquired from a combination of primary and secondary sources. Four North American steel companies provided primary data for the production of hot-rolled coil, while data were obtained from three sites for cold-rolled steel and hot dip galvanized steel. Two North American sites and one European site provided primary data for bar steel. Additional primary coke production data were obtained from 21 sites in Europe and Japan and used, along with the two North American sites, to calculate a global average value. This average value was used in two cases where data were not available from two North American BOF steel producers. Further primary data were collected for some upstream processes, such as iron ore mining and lime production. Secondary data were obtained from LCI databases and literature.

Sources of primary and secondary data include

- primary data from participating steel and mining companies
- BOF steelmaking: 2 in Canada, 2 in the United States
- coke production: 2 in Canada, 21 in Europe and Japan
- iron ore mining: 1 in Minnesota, 1 in Sweden
- limestone quarrying: 1 in the United Kingdom
- secondary data from Ecobalance database and literature source (AISI, 1999)

Table 7-1 summarizes the sources of secondary data and its quality.

The BOF (hot rolled steel) profile from AISI was converted from SI units (energy in MJ, mass in grams) per kilogram to U.S. units (mass in pounds [lb], volume in U.S. gallons [gal], gaseous volume in cubic feet [ft^3], and energy in British thermal units (Btu) per 1 ton [2,000 lb] of steel). Energy consumed was followed back to elementary flows from the earth and presented as materials inflows (e.g., coal, natural gas, oil) in the AISI profile. In the summary results, energy breakdowns for total process energy and transport energy are presented.

Table 7-1. Secondary Data Sources and Their Description

Material	Source	Data Quality
Aluminum (Al)	Swiss Federal Office of Environment, Forests, and Landscape (FOEFL or SFAEFL) Environment Series No. 132. Bern. February 1991.	Model based on aluminum slab production, 25% aluminum scrap and 75% primary aluminum.
Cast iron	Confidential source	Technology: Primary data from an iron casting plant supplying parts to the North American automotive industry. Averaged with North American secondary data on iron casting to preserve confidentiality. Temporal: Primary data collected for the year 1995. Secondary data are unknown. Geographical: North American data.
Chromium (Cr)	Swiss Federal Institute of Technology (ETH), Zurich, *Ecoprofiles for Energy Systems*, 1996. Page 58	Technology: Production of 1 kg chromium including mining, concentration, and reduction by electrolysis. Transport is not included. 99% in mass of ETH sources are taken into account. Chromium “ore” is reported as pure chromium; therefore, 1 kg of “ore” is used to produce 1 kg of material. Temporal: 1995 Geographical: Average of European sites.
Coal	SFAEFL 132 (1991) A11	Adapted by Ecobilan. Adaptation covers CO_2 emissions added for what SFAEFL calls precombustion for fuels production models; cross loop treatment for fuels production models; recalculation from process data when provided in SFAEFL; waste changed to 0.05 kg/kg representing greater dominance of open-pit mining.
Copper (Cu)	Swiss Federal Institute of Technology (ETH), Zurich, *Ecoprofiles for Energy Systems*, 1996. Page 60-69	Technology: Production of 1 kg Cu (ingot) with 60% primary copper + 40% secondary copper. Inputs of copper ore are 1 kg (for 1 kg Cu produced) because all flows are calculated up to the cradle (or gate) in ETH data (including Cu ore present in the secondary material). Also, Cu “ore” is reported as pure copper; therefore, 1 kg of “ore” is used to produce 1 kg of material. Transport is included for secondary copper (200 km rail, 100 km truck). 99% in mass of ETH sources are taken into account. Temporal: 1995 Geographical: Average of European sites.

(continued)

Table 7-1. (concluded)

Material	Source	Data Quality
Dolomite ($CaCO_3.MgCO_3$)	Swiss Federal Office of Environment, Forests, and Landscape (FOEFL or SFAEFL) Environment Series No. 132. Bern. February 1991.	Particulate emissions changed from 72 g/kg of dolomite to 0.11 g/kg due to primary data from one European limestone quarry.
Ferrite (Fe)	Confidential source.	Technology: Production of ferrite. Only 85% of inputs are accounted for. Site data have been aggregated with upstream processes to ensure confidentiality Temporal: Data collected in 1992 Geographical: European data
Lead (Pb)	Swiss Federal Institute of Technology (ETH), Zurich, *Ecoprofiles for Energy Systems*, 1996. Page 91	Technology: Production of lead including mining. Lead "ore" is reported as pure lead; therefore, 1 kg of "ore" is used to produce 1 kg of material. Temporal: 1995 Geographical: Average of European sites
Tin (Sn)	1) Metal resources and energy, Chapman, London 1983. 2) *Metals and Minerals Yearbook*, section Minerals 1989.	Technology: Production of 1 kg of tin. Both mining and recycling are taken into account. Tin "ore" is reported as pure tin; therefore, 1 kg of "ore" is used to produce 1 kg of material. Temporal: 1989 Geographical: Worldwide tin production Important producers are: Brazil (23%), Malaysia (14%), Indonesia (14%), and China (12%)
Zinc (Zn)	Swiss Federal Institute of Technology (ETH), Zurich, *Ecoprofiles for Energy Systems*, 1996. Page 107-108.	Technology: Mining, concentration, and refining. Transport included for 1 ton/km rail and 36 ton/km sea (per kg of Zn). Zinc ore is reported as pure zinc; therefore, 1 kg of ore is used to produce 1 kg of material. 99% in mass of ETH sources are taken into account. Temporal: 1995 Geographical average of several European sites

Source: AISI, 1999

7.2.9 Allocation Procedures

The steel LCI study includes consideration of several approaches to co-product allocation. Steel materials can be modeled by allocating inputs and outputs based on a mass, energy, or economics basis. Two other options are available, these being no allocation and avoiding allocation by using system expansion. The last option is not allocation, but is included here for convenience. AISI decided to pursue multiple approaches to co-product allocation because it is an issue of some debate and flexibility was a part of the study goals. For the data reported here, AISI used allocation for five co-products. Four co-products are generated in the coke production unit process—coal tar, ammonia, ammonium sulfate, and light oil. These co-products were allocated on the basis of mass. One co-product is generated in the iron production unit process: blast furnace slag. This co-product was allocated based on economic value. Within the system boundary, allocation was based on a physical parameter or, if more appropriate, economic value. An example of a physical allocation is water flow into a common wastewater treatment plant that has multiple inputs. The inputs and outputs of the wastewater treatment plant were allocated to a product based on the water flow from the unit process associated with the product. The only exception to allocation based on a physical parameter was economic allocation used for blast furnace gas. The blast furnace gas was allocated at the iron production unit process within the product system boundary.

7.2.10 LCI Results

Table 7-2 summarizes the cradle-to-gate LCI data for primary (BOF) steel (hot-rolled steel) production. Energy consumed was followed back to elementary flows from the earth and presented as materials inflows (e.g., coal, natural gas, oil) in the AISI profile. In the summary results, energy reminders for total process energy and transport energy are presented. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and pre-combustion activities.

7.2.11 Data Quality

The Canadian and American steel data were derived from a world-wide LCI study commissioned by the International Iron and Steel Institute.

The data collected by AISI follow standard LCI methodology as outlined in ISO 14040 and ISO 14041. Each profile includes a discussion of data quality. Because the data profiles were compiled from secondary sources, many of the data quality indicators reflected this secondary source of data. Table 7-3 summarizes the data quality assessment provided in each steel profile (adapted from AISI, 1999). Table 7-4 summarizes the domain and geographical coverage for steel production. Every attempt was made to collect high-quality primary data. Where primary data were not available, secondary or surrogate data were employed. For each process, information on the source, nature, and quality of the data was reported by the respondent. In addition to the data quality aspects of geographic coverage, temporal coverage, technology coverage, and data sources, data quality was reported using five data quality indicators (DQIs)—precision, consistency, completeness, representativeness, and reproducibility. Assessments for these DQIs are summarized below.

Table 7-2. Data for Production of 1 Ton of Primary (BOF) Steel[a]

Raw Materials*	Units	Total
Bentonite	lb	4.14E+01
Coal	lb	1.09E+03
Dolomite	lb	1.73E+02
Ilmenite	lb	4.00E-01
Iron	lb	2.58E+03
Limestone	lb	1.68E+02
Manganese	lb	3.24E+01
Natural Gas	lb	1.43E+02
Oil (in ground)	lb	1.13E+02
Olivine (in ground)	lb	1.30E+01
Sand (in ground)	lb	1.42E+00
Sodium Chloride	lb	3.06E+00
Uranium	lb	7.76E-03
Zinc	lb	3.38E-05
Scrap Steel	lb	4.16E+02
Water Used (total)	gal	5.73E+03

Energy Usage	Units	Total (Base Units)	Total (MMBtu)	Factor to Convert to MMBtu
Process Energy (Combustion and Precombustion)	MMBtu	2.12E+01	2.12E+01	1.00E+00
Transportation Energy (Combustion and Precombustion)	MMBtu	4.88E-01	4.88E-01	1.00E+00

Environmental Releases	Units	Total	Process	Fuel Related
Atmospheric Emissions				
Carbon Monoxide	lb	3.71E+01		
Carbon Dioxide-fossil	lb	3.64E+03		
Hydrocarbons (non CH_4)	lb	1.22E+01		
Hydrochloric acid	lb	1.36E-01		
Lead	lb	2.26E-04		
Methane	lb	4.62E+00		
Nitrogen Oxides	lb	5.52E+00		
Particulate	lb	2.63E+01		
Sulfur Oxides	lb	1.02E+01		

(continued)

Table 7-2. (concluded)

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Solid Wastes				
Unspecified	lb	8.70E+02		
Waterborne Emissions				
Ammonia	lb	1.23E-01		
Dissolved Solids	lb	1.73E+00		
Oil	lb	2.10E-02		
Phosphate	lb	1.26E-03		
Suspended Solids	lb	6.54E-01		

*Data for raw materials are not included for other materials and are not included in the decision support tool. AISI requested that these data to be presented.
** Further disaggregation of the data was not possible with the data provided by AISI.

Source: AISI (1999)

Table 7-3. Data Quality Summary for Steel Profiles

Data Quality Indicator	Basic Oxygen Furnace (BOF)	Electric Arc Furnace (EAF)
Geographic coverage	■ Steel production and its associated supply chain in Canada (provinces of Ontario and Quebec) and the U.S. (Maryland, Ohio, and Pennsylvania). ■ Iron ore mining data were collected from a site in Minnesota, which were augmented with primary data from an iron ore mining site in Sweden. ■ Primary data for limestone quarrying were based on a site in the United Kingdom. ■ The global coke production data are averages of 23 coke plants located in Europe, Japan, and Canada, representing production in 1994/95. For two instances where company-specific coke production data were not available, global coke production data collected by the International Iron and Steel Institute (IISI) were used.	■ The data cover: - One limestone quarry located in the United Kingdom - Three EAF steel production sites located in North America and Europe - Three bar production sites located in North America and Europe
Time Period Coverage	■ Primary data used for steel production are based on annual production in either 1994 or 1995. ■ Secondary data are based on sources from no later than 1990, though constituent data within the secondary sources may be older than 1990.	

(continued)

Table 7-3. (continued)

Data Quality Indicator	Basic Oxygen Furnace (BOF)	Electric Arc Furnace (EAF)
Technology Coverage	■ This LCI covers BOF steel-making technology that produces hot rolled coil. ■ BOF steel-making combines molten iron source from a blast furnace, recycled steel, limestone, and alloying additives. Oxygen is injected into the steel-making vessel to remove carbon from the molten iron. ■ BOF data cover continuous casting technology.	■ This LCI covers EAF steel-making technology that produces bar ■ EAF uses electricity to melt recycled steel for the casting of new materials. ■ Two technologies for the casting of steel are included in the LCI: continuous casting and ingot casting. Virtually all of the steel producers in North America use continuous casting technology, only one facility uses ingot casting.
Precision	■ For each unit process where primary data were collected, the mean, minimum, maximum, and standard deviation values were calculated for each data category (included in AISI report). ■ Secondary data used in the study generally consisted of a single value.	
Consistency	■ Consistent application of the LCI methodology. ■ Experts from steel companies around the world worked with the project consultant to produce process flow diagrams with common nomenclature. ■ The data collection procedure ensured verification and validity checking of data points. ■ The project consultant again checked the data entered into the LCI modeling software. ■ In addition to this, industry experts reviewed the model results to check for inconsistencies.	
Completeness	The steel LCI completeness for each data category was derived from the questionnaires submitted by each participating site to AISI. Where a site submitted a questionnaire that contained a missing value for a data category, the procedures defined in the U.S. Automotive Material Partnership report for the treatment of missing data were employed. On a unit process level, each of the sites that agreed to contribute to the sample domain reported data.	

(continued)

Table 7-3. (concluded)

Data Quality Indicator	Basic Oxygen Furnace (BOF)	Electric Arc Furnace (EAF)
Representativeness	■ The data in this profile are a representative sample of North American steel production ■ Comparing this data profile to global data collected by IISI for hot rolled steel product produced using BOF steel-making technology, for each steel product the difference between the North American and global data sets is less than 10% for each of the key indicative data categories.	■ The data in this profile are a representative sample of North American steel production. ■ North American average for recycled steel consumption is within 3.8% of the global average found in the international steel study
	■ For the global steel study, from which the North American average was derived, about 60% of the primary data values were measured, 25% were calculated, and about 15% were estimated.	
Reproducibility	■ Since the major sources of data for this profile were aggregated prior to presentation in the AISI report, the original data are not available. Results may be approximated based on the LCI profile and the methodology discussed.	
Sources of Data	■ AISI (1999)	
Uncertainty	■ The results of this study and its methodology were peer-reviewed as part of the U.S. Automotive Material Partnership project by an independent group of experts in the field. ■ Following ISO 14040, an internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review.	
Data Quality Rating	The primary hot rolled steel data are considered to be of excellent quality.	

Table 7-4. Domain and Geographical Coverage for Steel Production

Steel Technology	Unit Process	Geographical Region	Sites
BOF Steel Production	Iron ore pellet production	North America, Sweden	2
	Limestone Quarrying	United Kingdom	1
	Coke Production	North America (Global Avg.)	2 (23[a])
	Iron Production	North America	4
	BOF Steel Production	North America	4
	Hot Rolling	North America	4
Total			17(40[a])

[a] Number of sites in world-wide average for coke production.

The results of this study and its methodology were peer-reviewed as part of the U.S.AMP project by an independent group of experts in the field. Additionally, following ISO 14040, an internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review. In accordance with the ISO standards, the internal experts are familiar with the requirements of ISO 14040 and 14041 and have the necessary technical and scientific expertise. However, a report detailing the findings by the internal experts was not prepared.

Overall, the primary hot rolled steel data are considered to be of excellent quality.

7.2.11.1 Precision. This is a measure of variability from the mean of the data set. For each data category within each unit process, the mean and the standard deviation of the reported values are calculated. The precision measure provides the industry with an understanding of the variability of unit process performance and enables them to define opportunities for improvement from a benchmarking perspective.

In the steel study, for each of the unit processes where primary data were collected, the mean, minimum, maximum, and standard deviation values were calculated for each data category. Secondary data used in the study generally consisted of a single value.

7.2.11.2 Consistency. Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study.

Effort was undertaken to ensure the consistent application of the LCI methodology for the steel study. Experts from steel companies around the world worked with the project consultant to produce process flow diagrams with common nomenclature. A training session was held for all people collecting data at the unit process level. These people received comprehensive manuals that provided guidance on the unit processes, including the process flow diagrams with the common nomenclature, to further aid their data collection efforts. Each of these people could also call the project consultant to ask questions about data collection. The data collection used Excel spreadsheets with data verification based on initial data gathering from three sites. If a data value was entered into the spreadsheet that lay outside the initial data range, a warning to check data validity was issued. The person was then instructed to check the validity of the data point, keeping the value if it was valid or correcting the value if it was an error. Additionally, the spreadsheets calculated carbon and iron balances to give the user another check on the validity of the data entered. The data contained in the spreadsheets were electronically downloaded into the LCI modeling software. This procedure eliminated the chance of making a data transcription error. The project consultant again checked the data entered into the LCI modeling software. If an error was noted, the consultant contacted the data source for correction. In addition to this, industry experts reviewed the model results to check for inconsistencies.

7.2.11.3 Completeness. Completeness is the measure of primary data values used in the analysis divided by the number of possible data points for each data category within the sample domain. The steel LCI completeness for each data category was derived from the questionnaires submitted by each participating site. If a site submitted a questionnaire that contained a missing value for a data category, the procedures for the treatment of missing data were employed. On a unit process level, each of the sites that agreed to contribute to the sample domain reported data.

7.2.11.4 Representativeness. This indicator measures the degree to which the data values used in the analysis present a true and accurate measurement of the average processes that the study is examining. The degree of representativeness is normally judged by the comparison of values determined in the study with existing reported values in other analyses or published data sources dealing with the subject matter. Any major variances identified should be examined and explained.

The LCI used for steel materials was calculated using a small sample size. It would be natural to question whether the small sample size fairly represents the production of steel used in the generic automobile. The representativeness of primary steel data is presented in Table 7-5 as the percent of Canadian and U.S. production. Table 7-5 shows the number of sites where primary data were gathered and the percent of Canada and American production that these sites represent. One explanation of why the percent production is relatively high given the sample size is that the two largest steel producers in Canada and in the United States chose to take part in the LCI of steel materials. In addition, the largest iron ore mine in North America was included in the study. The participating steel companies represent about 26 percent of annual steel production in Canada and the United States.

Another way to address representativeness is to compare North American data to global data collected by IISI for key data categories. Table 7-6 presents the comparison of North American and global data for hot rolled steel product produced using BOF steel-making technology. It can be seen that, for each steel product, the difference between the North American and global data sets is less than 10 percent for each of the key indicative data categories. Based on this result and the knowledge that steel-making technology is similar among integrated steel producers in North America, it can be expected that expanding the North American sample size would have relatively little effect on the LCI results for hot rolled steel.

Table 7-5. Unit Process Sample Size and Percent of Production

Unit Process	Sample Size	Percent of Canada and U.S. Production
Iron ore mining	2	13.6[c]
Coke production	2	8.8[b,c]
Iron production	4	14.4[a]
BOF steel production	4	15.5[a]
Hot rolling	4	18.7[b]

[a] Based on 1995 AISI production data.
[b] Estimated from 1993 AISI production data.
[c] Figure does not include primary data from global steel study used to complement North American data.

Table 7-6. Percent Difference of North American Hot Rolled Steel Data Compared to Global Average

Data Category	Hot Rolled Steel
Iron ore (raw material)	-8.4
Coal (raw material)	-8.8
Carbon dioxide (air)	9.8
Total energy (energy)	3.2

To further assess the representativeness of the primary data, each site indicated whether each data value supplied was measured, calculated, or estimated. This information allows the industry to make a qualitative judgment regarding the level of confidence in the results. For the global steel study, from which the North American average was derived, about 60 percent of the primary data values were measured, 25 percent were calculated, and about 15 percent were estimated.

7.2.11.5 Reproducibility. This characteristic of data describes whether or not sufficient information, both methodological and data values, exists to permit someone to independently carry out the calculations and reproduce the results reported in the study.

AISI retains the original LCI and can reproduce the results. Others may approximate the results based on the LCI profile and the methodology discussed.

7.3 Secondary Steel Production (EAF Technology)

7.3.1 Introduction

This section contains an LCI profile for secondary steel bar product produced using EAF steel-making technology. It contains process flow diagrams and descriptions for production processes, LCI data tables for 1 ton of product, and a discussion of allocation and data quality.

The LCI data for this profile were collected by AISI (1999), and models EAF steel (hot rolled) product from cradle-to-gate. The boundaries for the EAF steel data in this profile include all unit processes from material acquisition through production of the EAF steel. Primary data were collected for limestone quarrying, EAF steel production, and bar production. Figure 7-2 shows a simplified process flow diagram for processing EAF steel. The two main inputs are secondary steel and limestone. These unit processes associated with EAF steel making are described in Sections 7.2.2 through 7.2.5.

7.3.2 Secondary Steel (Elvers et al., 1991; Honeycombe, 1981)

Scrap steel makes up a significant percentage of the feed to electric-arc furnaces. The scrap comes from steel fabrication operations and from discarded or obsolete goods made from iron and steel. Metal cuttings or imperfect materials are recycled by remelting, recasting, and redrawing within the steel mill.

7.3.3 Limestone Quarrying

Limestone is quarried primarily from open pits. In the central and eastern U.S., underground mining is becoming more common (U.S. Bureau of Mines, 1993). The most economical method of recovering the limestone has been through drilling, blasting, mechanical

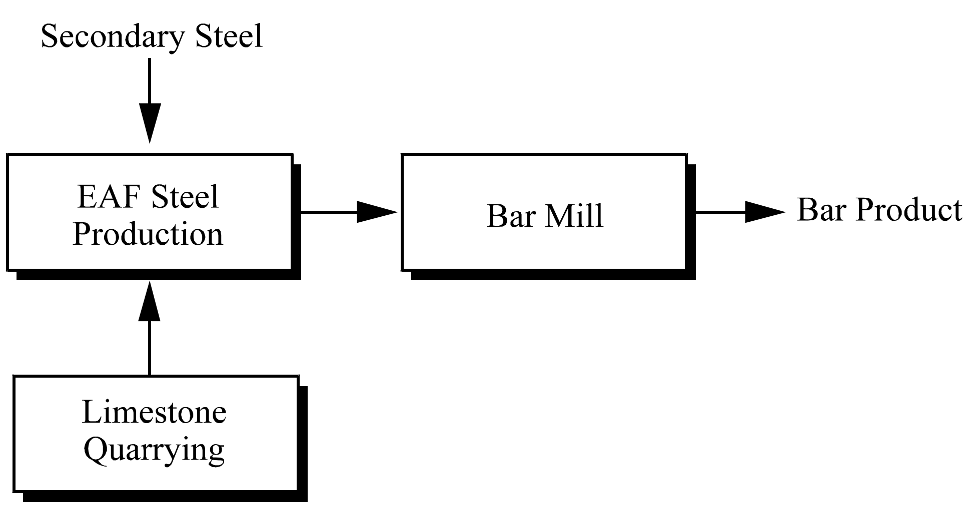

Figure 7-2. Simplified process flow diagram for EAF steel.

crushing, conveying, and screening (U.S. Bureau of Mines, 1993 and 1984). Airborne particulates are generated in the form of limestone dust throughout many of the operations. The limestone quarrying information used for the secondary bar steel LCI is based upon one site in the United Kingdom. No further information about the recovery method used at this site was available.

7.3.4 EAF Steel Production (Sims, 1962-63; Taylor, 1985; IISI, 1990; Fruehan, 1985)

About one third of the world's steel is produced by the electric-arc method (IISI website: www.worldsteel.org), which uses high-current electric arcs to melt steel scrap and convert it into liquid steel of a specified chemical composition and temperature. The external arc heating permits better thermal control than does the basic oxygen process, in which heating is accomplished by the exothermic oxidation of elements contained in the charge. This allows larger alloy additions to be made than are possible using the BOF process. However, EAF steel-making does not achieve the level of oxidation that BOF process does, and slag-metal mixing is not as intense; therefore, electric-arc steels normally have carbon contents higher than 0.05 percent. In addition, they usually have a higher nitrogen content (40 to 120 ppm), compared with 30 to 50 ppm in BOF steels. Nitrogen, which renders steel brittle, is absorbed by liquid steel from air in the high-temperature zone of the arc. The nitrogen content can be lowered by blowing other gases into the furnace, by heating with a short arc, and by applying a vigorous carbon monoxide boil or argon stir to the melt.

The major charge material of EAF steel-making is scrap steel. Its availability at low cost and proper quality is essential. The importance of scrap quality becomes apparent when making steels of high ductility, which must have a total maximum content of residuals (i.e., copper, chromium, nickel, molybdenum, and tin) of 0.2 percent. Most of these residuals are present in scrap and, instead of oxidizing during steel-making, they accumulate and increase in recycled scrap. In such cases, some shops augment their scrap charges with direct-reduced iron or cold blast-furnace iron, which do not contain residuals. Generally, the higher contents of carbon, nitrogen, and residuals make the electric-arc process less attractive for producing low-carbon, ductile steels.

Most scrap yards keep various grades of scrap separated. High-alloy shops, such as stainless-steel producers, accumulate, purchase, and charge scrap of similar composition to the steel they make in order to minimize expensive alloying additions.

Several EAFs are operated by direct current (dc) instead of alternating current (ac). Direct current furnaces normally have only one very large electrode extending through the centre of the roof, with the counter electrode embedded in the furnace bottom and contacting the melt. Power and electrode consumption is lower than in regular ac furnaces. The dc arc has a steadier and quieter burn, which results in less disturbance of the surrounding power system and less noise around the furnace. The electrical equipment is smaller but still expensive because of the required rectifiers. Critical in dc furnace operation are the short life of the bottom electrode, integrity of the hearth, and current limitations with a one-electrode system. Furnaces with capacities up to 130 tons are in operation.

7.3.5 Steel Bar (AIME, 1983)

Steel bars are long, usually of round, square, rectangular, or hexagonal cross section and of 0.5 to 2 inches (12- to 50-mm) diameter or equivalent. (Since bar mills are also capable of rolling small-shaped products such as angles, flats, channels, fence posts, and tees, these materials are sometimes called merchant bars). In principle, after removal of the furnace scale by water jets, a primary reduction takes place in several passes through roll stands in open, semicontinuous, or fully continuous arrangement. These can use an alternating square-diamond rolling principle on horizontal and vertical rolls or a series of oval-to-round passes.

The finishing stand of a bar mill gives the bar its final shape and often a specific surface pattern, such as the protrusions on concrete-reinforcing bars. The rolling speed increases as the cross section at each successive stand decreases, and the exit speed can be as high as 49 ft/s second (15 m/s). The hot bar is then cut by a flying shear into cooling-bed length (e.g., 164 ft), after which it is cooled, inspected, and cold-cut to shipping length.

7.3.6 Data Source and Calculation Procedures

Data were acquired from a combination of primary and secondary sources. Two North American sites and one European site provided primary data for bar steel. Further primary data were collected for some upstream processes, such as iron ore mining and lime production. Secondary data were obtained from LCI databases and literature.

Sources of primary and secondary data include

- EAF steelmaking: one in Canada, one in the United States, one in Europe
- Limestone quarrying: one in the United Kingdom.
- Secondary data from Ecobalance database and literature sources are shown in Table 7-1.

The EAF steel bar profile from AISI was converted from SI units (energy in MJ, mass in grams) per kilogram to U.S. units (mass in pounds [lb], volume in U.S. gallons [gal], gaseous volume in cubic feet [ft^3], and energy in British thermal units [Btu] per 1 ton [2,000 lb]).

7.3.7 Allocation Procedures

The steel LCI study includes consideration of several approaches to co-product allocation. Steel materials can be modeled by allocating inputs and outputs based on a mass, energy, or economics basis. Two other options are available, these being no allocation and avoiding allocation by using system expansion. The last option is not allocation, but is included here for convenience. AISI decided to pursue multiple approaches to co-product allocation because it is an issue of some debate and flexibility was a part of the study goals. The inputs and outputs of the wastewater treatment plant were allocated to a product based on the water flow from the unit process associated with the product. For secondary steel production, no co-product allocation issues were identified.

7.3.8 LCI Results

Table 7-7 summarizes the cradle-to-gate LCI data for secondary EAF steel bar. Energy consumed was followed back to elementary flows from the earth and presented as materials inflows (e.g., coal, natural gas, oil) in the AISI profile. In the summary results, energy reminders for total process energy and transport energy are presented. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and pre-combustion activities. Emissions to air and water include all emissions for processing, combustion (including electricity), transportation, and precombustion activities.

7.3.9 Data Quality

The Canadian and American steel data was derived from a world-wide LCI study commissioned by IISI. Table 7-8 summarizes the domain and geographic coverage for EAF steel production. There were a few exceptions to this geographic coverage. In the case of steel bar, a European steel production site was added to the North American database to increase the sample size and protect confidentiality of company data. This European site data were generated in the same LCI exercise as the North American site data, so the methodology applied is consistent. In addition, the European site data were coupled with energy and ancillary materials data common to this study to make it more consistent with the North American sites. Primary data for limestone quarrying were based on a site in the United Kingdom. These data were also collected as part of the international steel LCI study. For the two instances where company-specific coke production data were not available, global coke production data collected by IISI were used.

Every attempt was made to collect high-quality primary data. Where primary data were not available, secondary or surrogate data were employed. For each process, information on the source, nature, and quality of the data was reported by the respondent. In addition to the data quality aspects of geographic coverage, temporal coverage, technology coverage, and data sources, data quality was reported using five DQIs: precision, consistency, completeness, representativeness, and reproducibility. Assessments for these data quality indicators are summarized in below.

The results of this study and its methodology were peer-reviewed as part of the U.S. AMP project by an independent group of experts in the field. Additionally, following ISO 14040, internal expert review was carried out on this EPA effort. Experts independent of the original calculations performed this review. In accordance with the ISO standards, the internal experts are familiar with the requirements of ISO 14040 and 14041 and have the necessary technical and scientific expertise. However, a report detailing the findings by the internal experts was not prepared.

Table 7-7. Data for Production of 1 Ton of Secondary EAF Steel[a]

Raw Materials*	Units	Total
Bentonite	lb	2.00E-03
Coal	lb	3.54E+02
Dolomite	lb	3.32E+00
Iron	lb	1.98E+01
Limestone	lb	1.92E+02
Manganese	lb	3.32E+01
Natural Gas	lb	4.08E+01
Oil (in ground)	lb	3.58E+01
Sand (in ground)	lb	1.22E+01
Sodium Chloride	lb	2.06E-01
Uranium	lb	4.96E-03
Scrap Steel	lb	2.20E+03
Water Used (total)	gal	2.03E+03

Energy Usage	Units	Total (Base Units)	Total (Million Btu)	Factor to Convert to MMBtu
Process Energy (Combustion and Precombustion)	MMBtu	7.99E+00	7.99E+00	1.00E+00
Transportation Energy (Combustion and Precombustion)	MMBtu	1.44E-01	1.44E-01	1.00E+00

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Atmospheric Emissions				
Carbon Monoxide	lb	7.93E+00		
Carbon Dioxide-fossil	lb	1.19E+03		
Hydrocarbons (non CH_4)	lb	5.76E-01		
Hydrochloric acid	lb	1.79E-01		
Lead	lb	1.87E-03		
Methane	lb	2.58E+00		
Nitrogen Oxides	lb	3.53E+00		
Particulate	lb	1.44E+01		
Sulfur Oxides	lb	5.97E+00		

(continued)

Table 7-7. (concluded)

Environmental Emissions	Units	Total	Process and Transportation	Electrical Energy
Solid Wastes				
Unspecified	lb	2.66E+02		
Waterborne Emissions				
Ammonia	lb	2.08E-03		
Dissolved Solids	lb	3.38E-01		
Oil	lb	8.74E-03		
Phosphate	lb	7.56E-03		
Suspended Solids	lb	1.24E-01		

*Data for raw materials are not included for other materials and are not included in the decision support tool. AISI requested that these data be presented.
** Further disaggregation of the data was not possible with the data provided by AISI.

Source: AISI (1999)

Table 7-8. Domain and Geographical Coverage for Steel Production

Steel Technology	Unit Process	Geographical Region	Sites
EAF steel production	Limestone quarrying	United Kingdom	1
	EAF steel production	North America, Europe	3
	Bar production	North America, Europe	3
Total			**7**

The secondary EAF steel data are considered to be of excellent quality.

7.3.9.1 <u>Precision</u>. The precision measure provides the industry with an understanding of the variability of unit process performance and enables them to define opportunities for improvement from a benchmarking perspective. In the steel study, for each of the unit processes where primary data were collected, the mean, minimum, maximum, and standard deviation values were calculated for each data category. Secondary data used in the study generally consisted of a single value.

7.3.9.2 <u>Consistency</u>. Effort was undertaken to ensure the consistent application of the LCI methodology for the steel study. Experts from steel companies around the world worked with the project consultant to produce process flow diagrams with common nomenclature. A training session was held for all those people who were collecting data at the unit process level. These people received comprehensive manuals that provided guidance on the unit processes, including the process flow diagrams with the common nomenclature, to further aid their data collection efforts. Each of these people could also call the project consultant to ask questions about data collection. The data collection used Excel spreadsheets with data verification based on initial data gathering from three sites. If a data value was entered into the spreadsheet that lay outside the initial data range, a warning to check data validity was issued. The person then was instructed to check the validity of the data point, keeping the value if it was valid or correcting the value if it was an error. Additionally, the spreadsheets calculated carbon and iron balances to give the user another check on the validity of the data entered. The data contained in the spreadsheets were electronically downloaded into the LCI modeling software. This procedure eliminated the chance of making a data transcription error. The project consultant again checked the data entered into the LCI modeling software. If an error was noted, the consultant contacted the data source for correction. In addition to this, the industry experts reviewed the model results to check for inconsistencies.

7.3.9.3 Completeness. The steel LCI completeness for each data category was derived from the questionnaires submitted by each participating site. If a site submitted a questionnaire that contained a missing value for a data category, the procedures for the treatment of missing data were employed. On a unit process level, each of the sites that agreed to contribute to the sample domain reported data.

7.3.9.4 Representativeness. The LCI used for steel materials was calculated using a small sample size. It would be natural to question whether the small sample size fairly represents the production of steel used in the generic automobile. The representativeness of primary steel data is presented in Table 7-9 as the percent of Canadian and U.S. production. Table 7-9 shows the number of sites where primary data were gathered and the percent of Canadian and American production that these sites represent. One explanation why the percent production is relatively high given the sample size is that the two largest steel producers in Canada and in the United States chose to take part in the life cycle inventory of steel materials. The participating steel companies represent about 26 percent of annual steel production in Canada and the United States.

Another way to address representativeness is to compare North American data to global data collected by IISI for key data categories.

Table 7-9. Unit Process Sample Size and Percent of Production

Unit Process	Sample Size	Percent of Canada and U.S. Production
EAF steel production	3	3.2 [a,c]
Bar mill	3	5.8 [b]

[a] Based on 1995 AISI production data.
[b] Estimated from 1993 AISI production data.
[c] Figure does not include primary data from global steel study used to complement North American data.

In Table 7-10, it can be seen that the North American average for secondary steel consumption is within 3.8 percent of the global average found in the international steel study.

Table 7-10. Difference of North American Bars Compared to Global Average

Data Category	Bars
Secondary steel (raw material)	3.8%

Another way to look at the LCI for steel bars is to compare the casting technology employed. One electric arc furnace site in the inventory uses ingot casting while the other sites employ the more modern continuous casting technology. Again, looking at key indicators, the difference in secondary steel consumed is very small, with the ingot casting facility consuming 3.5 percent more secondary steel than the North American average. However, the indicators for total energy used and carbon dioxide emissions are more significant. The ingot casting facility consumes about 25 percent more energy than the average and has about 40 percent more carbon dioxide emissions. The higher energy and carbon dioxide emissions may be attributed to the older facilities and technology employed at the site using ingot casting. Consequently, the steel bar inventory may be said to overstate the North American average that would be expected if the sample size were increased.

To further assess the representativeness of the primary data, each site indicated whether each data value supplied was measured, calculated, or estimated. This information allows the industry to make a qualitative judgment regarding the level of confidence in the results. For the global steel study, from which the North American average was derived, about 60 percent of the primary data values were measured, 25 percent were calculated, and about 15 percent were estimated.

7.3.9.5 Reproducibility. AISI retains the original LCI and can reproduce the results. Others may approximate the results based on the LCI profile and the methodology discussed.

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Appendix A
Peer Reviewers for this Report

David Allen - University of Texas at Austin
Robert P. Anex - University of Oklahoma
Gregory A. Keoleian - University of Michigan
Mitchell Kessler - TIA Solid Waste Management Consultants, Inc.
Jay Lund - University of California at Davis
Ruksana Mirza - Formerly with Proctor and Redfern, Ltd.
Lynn Scarlett - Reason Public Policy Institute
Aarne Vesilind - Bucknell University

Appendix B
Project Stakeholders[1]

Peter Anderson
Recycle Worlds Consulting

Richard F. Anderson
Waste Management, Inc.

Bob Andrews
Consultant for American Plastics Council

Melissa Arndt
Manager of Waste Reduction Programs
City of Austin - Solid Waste Services

Greg Barthold
Asst Dir, Program Dev
ASME International

Stacey Palmer Barton
United States Conference of Mayors

Donald Berman
Representative for American Public Works Association (APWA)
Director of the Allegheny County Division of Waste Mgmt

Lauren Blum
Formerly with Environmental Defense Fund

Steve Brachman
University of Wisconsin Solid & Hazardous
Representative for National Association of Counties (NACO)

Jeffrey S. Burroughs
Town of Amherst, Eric County New York
Environmental Control Division

Duncan Bury
Environment Canada

Pamela Caird
Deputy Director
Bureau of Waste Reduction, Reuse & Recycling
NYC Department of Sanitation

Kerry Callahan
Association of State and Territorial Solid Waste Management Officials (ASTSWMO)

J. Cattaneo
Executive Vice President
Glass Packaging Institute (GPI)

Jeff Chavez
American Forest & Paper Assoc.

Scott Chubbs
Representative for American Iron and Steel Institute
Virterra Inc.

Marguerite Clark-Balbo
SITA

[1]This is a list of those who have provided input to this research since 1994. Some of these persons have moved on to other positions, retired, or passed away. Everyone's contribution is appreciated.

Kate Cooper
State of Wisconsin
Solid Waste Reduction & Recycling Section
Bureau of Solid & Hazardous Waste Management

David Cornell
CMA Representative
Eastman Chemical Company

Norm Crampton
Executive Director
Indiana Institute of Recycling

Gregory L. Crawford
Vice President of Recycling Operations
Steel Recycling Institute

Jennifer DeLong
Program Manager
U.S. Conference of Mayors

Richard Denison
Environmental Defense Fund

Eileen Doherty
Program Director
National Conference of State Legislatures

Frank Duncan, Jr.
Chairman, GPI Technical Committee
Glass Technologist

Marty Durbin
American Plastics Council

Robert A. Epler
Director - Environmental Services Dept
The City of San Diego

Marty Felker
Waste Management, Inc.

Ferretti, Will
Executive Director
National Recycling Coalition

James A. Frey
Resource Recycling Systems, Inc.

Naomi Friedman
Solid Waste & Pollution Prevention Project
National Assoc. of Counties

Rick Fuszek
Manager of Waste Reduction Programs
City of Austin

Lawrence Goodland
South Carolina Institute for Energy

John Green
The Aluminum Association

Jonathan Greenberg
Director of Environmental Policy
Representative for Browning-Ferris Industries

Michael Greenman
Interim Executive Director
Glass Manufacturing Industry Council

Karen Harrington, Principal Planner
Minnesota Office of Environmental Assistance

Randy Hartmann
Office of Environmental Management
Georgia Department of Community Affairs

Steven G. Hentges
American Plastics Council
Associate Director of Technical

William W. Hinkley
Chief, Bureau of Solid & Hazardous Waste
Florida Dept. of Environmental Regulations

Joseph Hruska
Executive Director
CSR: Corporations Supporting Recycling

Sig Huitt
GPI Representative
Carolina Public Relations/Marketing

Carl Hursh
Chief of Recycling
State of Pennsylvania / Div. Waste
Minimization & Planning
Bureau of Waste Management

David Isaacs
Electronic Industries Assn.

Ron Jones
Regional VP/Director of Corporate Design
Waste Management Inc.

Susan Keil
Manager-Business Services
Bureau of Environmental Services
City of Portland

Dorothy Kellog
Chemical Manufacturers Association

W. Ross King
GA Association of County Commissioners

Larry Land
Virginia Association of Counties

Pat Layton
Director, Materials & Energy Policy
American Forest & Paper Assoc.

Sandy Markwood
Deputy Director of County Services
National Assoc. of Counties

S. Marsh
United States Conference of Mayors

Tim Martin
Natural Resources Defense Council

Suzanne Y. Mattei
Office of the Public Advocate

Michael Matthews
Manager, Corporate Environmental Affairs
The Coca-Cola Company

Tracy Mattson
Institute of Scrap Recycling Industries, Inc.

Ron McCracken
Bes-Pack, Inc.

John F. McDonald
International Air Quality Advisory Board
International Joint Commission

Chaz Miller
Manager, Hauling and Recycling
National Solid Waste Mgmt. Assn.

Edgar M. Miller
Director of Policy and Program
National Recycling Coalition

Frank Miller, Jr.
Representative for APWA

John F. Minear
Lucas County Solid Waste Management
District

Reid A. Miner
Program Director
National Council of the Paper Industry for
Air & Stream Improvements, Inc.
(NCASI)

Randall B. Monk
Director of Operations
The Composting Council

A. Morgan
South Carolina Institute for Energy

Jeffrey Morris
Sound Resource Mgmt. Group

David Myers
Monterey Regional Waste Mgmt District

Richard E. Oakley III
President, BFI Gas Services

Jeremy K. O'Brien
Director of Applied Research
Solid Waste Assn. of North America

Stephanie Osborn
American Public Works Assn. (APWA)

Tom Osdoba
Research and Planning
Minnesota Office of Environmental
Assistance

Richard D. Otis, Jr.
American Plastics Council

J. W. Owens
Principal Scientist, Corporate P&RS
The Procter & Gamble Company

Stephen Pearson
Can Manufacturers Institute

Gary Pierce
Energy Answers Corporation, Inc.

Blair Pollack
County Commissioner
Orange County

Lonnie C. Poole, Chairman
Waste Industries, Inc.

Edward W. Repa, PhD
Environmental Industries Assn.

William Rhodes
Director, Solid Waste Servcies
City of Austin

Ellen Ryan
Integrated Waste Management
Office of Environmental Management
City of San Jose

Laurie Crick Sahatjian
Dyer, Ellis & Joseph
Representative for GPI

Patrick Schiavo
California Environmental Protection Agency
Integrated Waste Management Board

Judy Shehan
U.S. Conference of Mayors

Michael Shore
NC Depart. of Environment and
Natural Resources
Special Asst for Environmental Protection

Michael A. Sills
Representative for ASTSWMO
New Hampshire Department of
Environmental Services
Waste Management Division

Edmund J. Skernolis
Waste Management Inc.

John Skinner
Executive Director
Solid Waste Assn. of North America

Drew Sones
Bureau of Sanitation
City of Los Angeles

Richard Ian Stessel
Columbia University in the City of New York

David B. Sussman
Poubelle Associates
Govt & Public Relations

S. Thyagarajan
Energy Answers Corporation, Inc.

Steve Tilney
Solid Waste Manager
City of Philadelphia
Sanitation Division

Robert J. Towles
Owens-Illinois, Inc.
Manager, Env. Affairs

John Trotti
MSW Management

Richard M. Van Frank
Representative for Audobon

Joseph R. Vissalli, Program Mgr.
Municipal Wastes & Environmental Research
New York State Energy R&D Authority

Richard P. Watson
Chief of Engineering & Operations
Delaware Solid Waste Authority

Heidi Whitman
Solid Waste Planning Manager
County Waste Mgmt. Division

Charles E. Williams
V.P. - Environmental/Engineering
Waste Management Inc.

J. Kenneth Wittle
Elctro-Pyrolysis, Inc.
Representative for the American Society of Mechanical Engineers

Barbara Yuhas
International City/County Mgmt. Assn.

Maria Zannes
President/Executive Director
Integrated Waste Services Assn.