FINAL REPORT

CRADLE-TO-GATE LIFE CYCLE INVENTORY OF NINE PLASTIC RESINS AND FOUR POLYURETHANE PRECURSORS

Prepared for

THE PLASTICS DIVISION OF
THE AMERICAN CHEMISTRY COUNCIL

by

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PREFACE

This cradle-to-resin LCI study was conducted for the Plastics Division of the American Chemistry Council (ACC). Mike Levy was the project coordinator for the Plastics Division of the ACC. The report was made possible through the cooperation of ACC member companies and non-member companies who provided data on the production of nine plastic resins, four polyurethane precursors, and on a number of intermediate chemicals. This report is an update to the revised report dated December, 2007. Changes were made to the dioxins amount (TEQ values) for the production of PVC. Methodological changes were made for the handling of fuel gas created within the hydrocracker. New data was collected for formaldehyde and DNT. Chlorine/caustic data was revised with new percentages of technology used for weighting the data.

Eastern Research Group, Franklin Associates Division, carried out the work as an independent contractor for this project. Melissa Huff was Project Manager. Beverly Sauer provided technical and editorial review. Significant contributions were made by James Littlefield, Anne Marie Molen, Sarah Cashman, Rebe Feraldi, and Lori Snook. William E. Franklin served as original Principal in Charge. Robert G. Hunt provided technical guidance.

Franklin Associates and the Plastics Division of the American Chemistry Council are grateful to all of the companies and associations that participated in the LCI data collection process. These companies include Arch Chemicals, Inc.; TOTAL Petrochemicals USA, Inc.; BASF Corporation; Bayer Material Science, LLC; Ineos Olefins; Innovene USA; Huntsman International LLC; Chevron Phillips Chemical Company (CP Chem); Dow Chemical Company; Eastman Chemical; ExxonMobil Chemical Company; Formosa Plastics Corporation U.S.A.; Georgia Gulf Chemicals and Vinyls, LLC; Rubicon LLC; Lanxess Corporation; NOVA Chemicals Corporation; Occidental Chemical Corporation; Shintech, Inc.; and Wellman, Inc. We would also like to thank Neeva-Gayle Candelori of the ACC Center for the Polyurethanes Industry, Allen Blakey of The Vinyl Institute, and Fred Edgecombe of the Canadian Plastics Industry Association.

Thank you to all those who reviewed the draft appendices/report of the 2010 analysis. Finally, we thank David Russell, Fred Marechal, and Aafko Schanssema of PlasticsEurope and Ian Boustead of Boustead Consulting for reviewing the plastics/precursor energy data in 2006-7.

> Comparisons between plastic resins should not be made on the basis of cradle-to-resin/precursor results, as the ISO 14040 series of standards require that comparisons of product systems must be made on the basis of equivalent function, and functional equivalence cannot be established without including fabrication of the resin or precursor into a functional product.

July, 2010

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EXECUTIVE SUMMARY

All manufacturing or industrial processes have both inputs and outputs. A life cycle inventory (LCI) is the phase of a life cycle assessment (LCA) involving the compilation and quantification of inputs and outputs for a given product systems throughout its life cycle.

The cradle-to-gate life cycle inventory presented in this study quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of nine plastic resins and four polyurethane precursors produced in North America. The plastic resins studied are high-density polyethylene (HDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polypropylene (PP), polyethylene terephthalate (PET), general-purpose polystyrene (GPPS), high-impact polystyrene (HIPS), polyvinyl chloride (PVC), and acrylonitrile-butadiene-styrene (ABS). The four polyurethane precursors studied are flexible foam polyurethane (PU) polyether polyols, rigid foam PU polyether polyols, methylene diphenylene diisocyanate (MDI), and toluene diisocyanate (TDI).

The resulting LCI database was compiled by Franklin Associates and is based on data collected specifically for this project from 17 resin/precursor manufacturers, representing more than 80 plants in North America. Supplementary data on some upstream unit processes are from the Franklin Associates database. The fuels and energy database are from the U.S. LCI database.

The goal of this study was to provide both the members of the Plastics Division of the American Chemistry Council (ACC) and the general public with the most up to date LCI data for the resins and polyurethanes precursors analyzed in this database. The database will also be publicly available at the U.S. LCI Database website (http://www.nrel.gov/lci/). The results of this analysis are presented in both English and Metric units for the benefit of the eventual intended audience, which may include international users.

Providing the data to the U.S. LCI Database has several important benefits for Plastics Division of ACC members. The U.S. LCI Database project is a private/public partnership, with the Department of Energy (DOE), Environmental Protection Agency (EPA), and General Services Administration (GSA) providing some funding. Industry contribution from trade associations has been in-kind data (e.g., aluminum, plastics, wood) as well as industry customer contributions of data and resources (e.g., Vehicle Recycling Partnership). Once the major materials databases are developed – plastics, aluminum, steel, wood, paper, glass – the emphasis can be placed on the transformation (fabrication) processes such as injection molding, blow molding, and the like. Major customers (building & construction, automotive, electrical and electronics) indicate the need to access this LCI data and evaluate various transformation processes to make decisions on the most sustainable processes to consider in developing manufactured products. As LCIs are conducted by multiple stakeholders in the future (Non

Governmental Agencies/NGOs; governments, universities, LCI practitioners, industry) for a number of different reasons (e.g., benchmarking for product/process improvement, future impact assessments), the U.S. LCI Database Project provides a publicly available up to date database, while affording proprietary and confidentiality protection for individual industry data submissions.

This LCI report includes the following sections, which present a discussion of the study approach and methodology and specific polymer and polyurethanes precursor results:

- Chapter 1 – Study Approach and Methodology, including overview; LCI methodology; LCI practitioner methodology variation; data description; critical/peer review; methodology issues and decisions
- Chapters 2-14 – LCI inventory results for HDPE, LDPE, LLDPE, PP, PET, GPPS, HIPS, PVC, ABS, Rigid Foam PU Polyether Polyols, Flexible Foam PU Polyether Polyols, MDI, and TDI respectively
- Addendum – Differences between the U.S. LCI Plastics Database and the PlasticsEurope Eco-Profiles Database
- Bibliography
- Glossary of Terms

CHAPTER 1

STUDY APPROACH AND METHODOLOGY

OVERVIEW

The cradle-to-gate life cycle inventory (LCI) presented in this study quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of nine plastic resins and four polyurethane precursors. It is considered a cradle-to-gate LCI because this analysis ends at the resin/precursor production process. The system boundaries stop at resin or precursor production so that the resin/precursor data can be linked with fabrication, use, and end-of-life data to create full life cycle inventories for a variety of plastic products. The methodology used for this inventory is consistent with the methodology for Life Cycle Inventory (LCI) in the ISO 14040 Standard documents, specifically 14040, 14041, and 14043.

This analysis is not an impact assessment. It does not attempt to determine the fate of emissions, or the relative risk to humans or to the environment due to emissions from the systems. In addition, no judgments are made as to the merit of obtaining natural resources from various sources.

A life cycle inventory quantifies the energy consumption and environmental emissions (i.e., atmospheric emissions, waterborne emissions, and solid wastes) for a given product based upon the study boundaries established. Figure 1-1 illustrates the general approach used in a full LCI analysis. This cradle-to-gate LCI analysis stops after the “Materials Manufacture” box shown in the figure below.

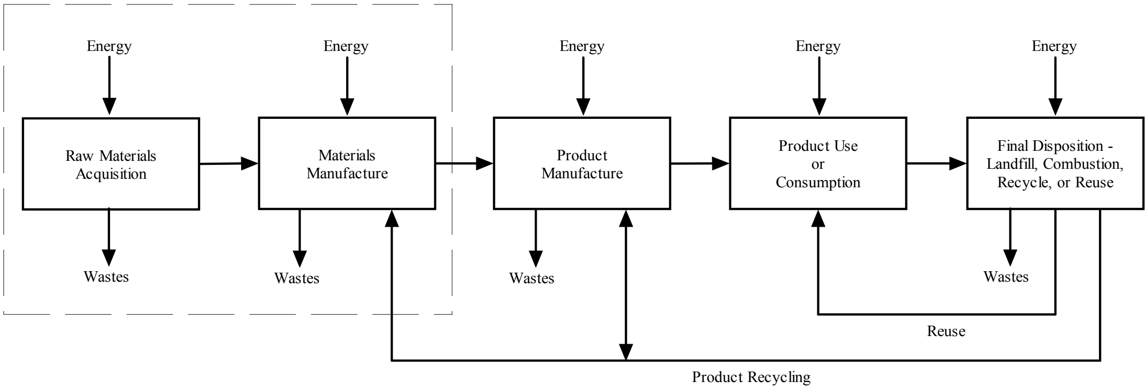

Figure 1-1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this LCI analysis. No recycled content or recycling is included in this analysis.

Study Goal and Intended Audience

This cradle-to-gate LCI of selected plastic resins and polyurethane precursors has been conducted to provide the Plastics Division of the ACC (and the greater plastics industry), with an updated average database on the production of commonly used plastic resins and polyurethane precursors. In due course, this plastics LCI database will be included in the U.S. Life Cycle Database, which is overseen by the National Renewable Energy Laboratory (NREL).

The intent of the study was to develop life cycle profiles for each of the plastic resins and polyurethane precursors using data from industry data, where available. Environmental profiles presented in this report for the plastic resins, polyurethane precursors, and a limited number of intermediate chemicals were developed using the data provided by participating companies for this study. For some intermediate chemicals and all raw materials, the energy and environmental data presented in this report were developed using the best and most current data available from Franklin Associates' U.S. life cycle database, updated to the extent possible to represent current technology using the data resources available.

U.S. Life Cycle Database Project

The primary intended audience for the report is member companies; however, the LCI data will be publicly available within the U.S. LCI Database at the U.S. LCI Database website (http://www.nrel.gov/lci/). The results for this analysis are presented in both English and Metric units for the benefit of the eventual intended audience, which may include international users.

Because the Plastics Division of the American Chemistry Council has indicated that a major goal of this study is to make this data available to the U.S. LCI database project, the objectives and requirements of this U.S. LCI database need to be made clear. The U.S, LCI database project research protocol ("the protocol", available at the project website www.nrel.gov/lci/) clearly states that "the ultimate objective of the U.S. LCI database project is to develop **publicly available** LCI data modules for commonly used materials, products, and processes." Key elements of the protocol are described in subsequent sections of the protocol. Two elements that are of particular relevance to this project are the unit process approach and transparency requirements.

Section 4 of the protocol addresses the importance of the unit process approach. Data must be collected and presented on a unit process basis "so that users of the data can understand and combine various components of a product system, and so that critical reviewers can conduct technical analyses. Higher levels of aggregation of data (i.e., defining a unit process to involve more activities (such as production of fuels or feedstock materials used in the process) will result in a loss of information, reduce the level of transparency, and inhibit critical review." Data must be prepared on a unit process basis.

Section 12 of the protocol describes transparency requirements. "Central transparency objectives of the U.S. LCI database project are to develop and publish LCI data in a form that provides enough information about the nature and sources of the data so that users and third parties can do the following for each data item:

- Know the source(s) and age of the data;
- Know how well the data represents an industry or process;
- Understand how the underlying calculations were made;
- Evaluate the appropriateness of the data for the user's intended application;
- Validate the results through testing and cross-checking of data and modeling; and, ultimately,
- Make an informed determination concerning the extent to which they can rely on the data and conclusions drawn from it."

Thus, in order for the resin databases developed here to be usable in the U.S. LCI database, the unit processes must meet the transparency requirements. Rolled-up data sets and data sets without documentation are not acceptable. All unit process data are shown in the Appendices of this report (separate document) in as much individual detail as confidentiality issues permit. Also, the unit process datasets for each resin or precursor have been linked to construct a cradle-to-resin/precursor process chain as well.

The existing public/private partnership U.S. LCI database is continuously being populated with data. Franklin Associates provided a fuels and energy database (e.g., coal mining, electricity generation, petroleum refining, and the like) in 2003. With this LCI analysis, the Plastics Division of ACC now has cradle-to-resin process chains published for access via the U.S. LCI database, as well as for its independent use.

Study Scope and Boundaries

This cradle-to-gate LCI encompasses production of the resins and precursors from raw material acquisition to resin production, rather than for a single manufacturing step or environmental emission. The study boundaries of this partial LCI of plastic resins and polyurethane precursors include the following elements:

- Raw materials acquisition
- Production of intermediate chemicals
- Production of the plastic resin or polyurethane precursor.

Detailed process flow diagrams, along with brief descriptions of processes for each resin or precursor can be found in the Appendices (separate document). The LCI quantifies energy and resource use, solid waste, and individual atmospheric and waterborne emissions for all stages listed above in the life cycle of each resin or precursor. Transportation of the resin or precursor to a manufacturer, fabrication of a product, and use of that product by consumers is not included in the study. Environmental burdens associated with end-of-life management of plastic products are not considered in this analysis.

The scope of the project does not include the manufacture of fillers, additives, or plasticizers that may be added to the resins/precursors analyzed. These types of materials/chemicals are commonly added to many of the resins/precursors; however, they depend highly on the type of product the resin is intended to produce.

LIFE CYCLE INVENTORY METHODOLOGY

Key elements of the LCI methodology include the study boundaries, resource inventory (raw materials and energy), emissions inventory (atmospheric, waterborne, and solid waste), and disposal practices. Additional discussion on the methodology used to calculate product life cycle resource and environmental emissions is presented in the following section of this chapter.

Franklin Associates developed a methodology for performing resource and environmental profile analyses (REPA), commonly called life cycle inventories. This methodology has been documented for the U.S. Environmental Protection Agency and is incorporated in the EPA report **Product Life-Cycle Assessment Inventory Guidelines and Principles.** The methodology is also consistent with the life cycle inventory methodology described in the ISO 14040 standards:

- ISO 14040 Environmental Management—Life Cycle Assessment—Principles and Framework. Reference No. ISO 14040:1997(E)
- ISO 14041 Environmental Management—Life Cycle Assessment—Goal and Scope Definition and Inventory Analysis. Reference No. 14041:1998(E)
- ISO 14043 Environmental Management—Life Cycle Assessment—Life Cycle Interpretation. Reference No. 14043:2000(E).

The data presented in this report were developed using this methodology, which has been in use for over 30 years.

Figure 1-2 illustrates the basic approach to data development for each major process in an LCI analysis. This approach provides the essential building blocks of data used to construct a complete resource and environmental emissions inventory profile for the entire life cycle of a product. Using this approach, each individual process included in the study is examined as a closed system, or “black box”, by fully accounting for all resource inputs and process outputs associated with that particular process. Resource inputs accounted for in the LCI include raw materials and energy use, while process outputs accounted for include products manufactured and environmental emissions to land, air, and water.

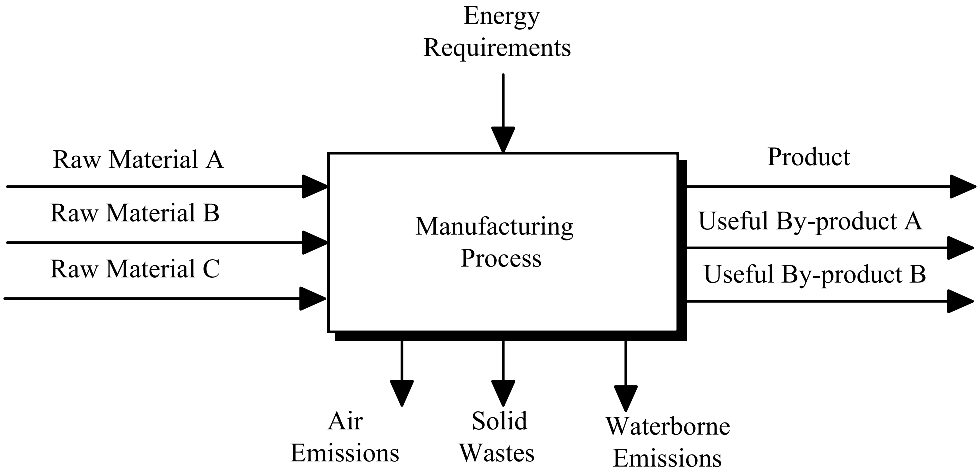

Figure 1-2. "Black box" concept for developing LCI data.

For each process included in the study, resource requirements and environmental emissions are determined and expressed in terms of a standard unit of output. A standard unit of output is used as the basis for determining the total life cycle resource requirements and environmental emissions of a product.

Material Requirements

Once the LCI study boundaries have been defined and the individual processes identified, a material balance is performed for each individual process. This analysis identifies and quantifies the input raw materials required per standard unit of output, such as 1,000 pounds or 1,000 kilograms, for each individual process included in the LCI. The purpose of the material balance is to determine the appropriate weight factors used in calculating the total energy requirements and environmental emissions associated with the resins or precursors. Energy requirements and environmental emissions are determined for each process and expressed in terms of the standard unit of output.

Once the detailed material balance has been established for a standard unit of output for each process included in the LCI, a comprehensive material balance for the entire life cycle of each product system is constructed. This analysis determines the quantity of materials required from each process to produce and dispose of the required quantity of each system component and is typically illustrated as a flow chart. Data must be gathered for each process shown in the flow diagram, and the weight relationships of inputs and outputs for the various processes must be developed.

Energy Requirements

The average energy requirements for each process identified in the LCI are first quantified in terms of fuel or electricity units, such as cubic feet of natural gas, liters of diesel fuel, or kilowatt-hours (kWh) of electricity. [The Appendices document presents fuel requirements for each process in both English and Standardized International (SI) units]. The fuel used to transport raw materials to each process is included as a part of the LCI energy requirements. Transportation energy requirements for each step in the life cycle are developed in the conventional units of ton-miles by each transport mode (e.g. truck, rail, barge, etc.). Government statistical data for the average efficiency of each transportation mode are used to convert from ton-miles to fuel consumption.

Once the fuel consumption for each industrial process and transportation step is quantified, the fuel units are converted from their original units to an equivalent Btu value based on standard conversion factors.

The conversion factors have been developed to account for the energy required to extract, transport, and process the fuels and to account for the energy content of the fuels. The energy to extract, transport, and process fuels into a usable form is labeled precombustion energy. For electricity, precombustion energy calculations include adjustments for the average efficiency of conversion of fuel to electricity and for transmission losses in power lines based on national averages.

The LCI methodology assigns a fuel-energy equivalent to raw materials that are derived from fossil fuels. Therefore, the total energy requirement for coal, natural gas, or petroleum based materials includes the fuel-energy of the raw material (called energy of material resource or inherent energy). In this study, this applies to the crude oil and natural gas used to produce the plastic resins and polyurethane precursors. No fuel-energy equivalent is assigned to combustible materials, such as wood, that are not major fuel sources in North America.

During the production of some hydrocarbons, an offgas or fuel gas is produced during the reaction. A portion of this offgas or fuel gas is used within the hydrocarbon production to produce steam or heat, while any remaining portion is exported from the hydrocarbon production as a coproduct, as discussed below. The offgas used within the production is shown as a weight of natural gas and petroleum input to produce the energy, as well as the energy amount produced from those weights.

When fuel coproducts, such as offgas, are exported from the hydrocarbon production, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the process, and the remaining inputs and outputs are allocated over the material products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{\text{attributed to remaining products}} \qquad \text{(Equation 1)}$$

where
IO = Input/Output Matrix to produce all products/coproducts
M_{EO} = Mass of Exported Offgas
M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set.

The Btu values for fuels and electricity consumed in each industrial process are summed and categorized into an energy profile according to the six basic energy sources listed below:

- Natural gas
- Petroleum
- Coal
- Nuclear
- Hydropower
- Other

The “other” category includes nonconventional sources, such as solar, biomass and geothermal energy. Also included in the LCI energy profile are the Btu values for all transportation steps and all fossil fuel-derived raw materials. Energy requirements for each resin/precursor examined in this LCI are presented in their individual chapters (2 through 12).

Environmental Emissions

Environmental emissions are categorized as atmospheric emissions, waterborne emissions, and solid wastes and represent discharges into the environment after the effluents pass through existing emission control devices. Similar to energy, environmental emissions associated with processing fuels into usable forms are also included in the inventory. When it is not possible to obtain actual industry emissions data, published emissions standards are used as the basis for determining environmental emissions.

The different categories of atmospheric and waterborne emissions are not totaled in this LCI because it is widely recognized that various substances emitted to the air and water differ greatly in their effect on the environment. Individual environmental emissions for each resin/precursor are presented in their individual chapters (2 through 12).

Atmospheric Emissions. These emissions include substances classified by regulatory agencies as pollutants, as well as selected nonregulated emissions such as carbon dioxide. For each process, atmospheric emissions associated with the combustion of fuel for process or transportation energy, as well as any emissions released from the process itself, are included in this LCI. Emissions are reported as both pounds of pollutant per 1,000 pounds of resin/precursor and kilograms of pollutant per 1,000 kilograms of resin/precursor. The amounts reported represent actual discharges into the atmosphere after the effluents pass through existing emission control devices. Some of the more commonly reported atmospheric emissions are: carbon dioxide, carbon monoxide, non-methane hydrocarbons, nitrogen oxides, particulates, and sulfur oxides.

Waterborne Emissions. As with atmospheric emissions, waterborne emissions include all substances classified as pollutants. Waterborne emissions are reported as both pounds of pollutant per 1,000 pounds of resin/precursor and kilograms of pollutant per 1,000 kilograms of resin/precursor. The values reported are the average quantity of pollutants still present in the wastewater stream after wastewater treatment and represent discharges into receiving waters. This includes both process-related and fuel-related waterborne emissions. Some of the most commonly reported waterborne emissions are: acid, ammonia, biochemical oxygen demand (BOD), chemical oxygen demand (COD), chromium, dissolved solids, iron, and suspended solids.

A large amount of primary data was used in this analysis. Many of the plants that provided data are part of a larger company site with one water treatment plant for all individual process plants on-site. In some cases, it was not possible for a plant to determine what waterborne emissions from the facility’s on-site treatment plant were associated with the specific processes of interest for this study. This situation was handled in one of two ways depending on the company. Either the plant did not provide their waterborne emissions data for use in this study, or the plant provided their waterborne emissions data for the specific process(es) of interest before the effluent was sent to the water treatment plant.

If a plant did not provide water emissions, that plant was excluded from the industry average calculation for those waterborne emissions. However, at least 1 plant did provide waterborne emissions data in all resin/precursor average datasets. In the cases of less than three plants providing this data, the order of magnitude of the emissions were included with the approval of the data provider(s).

In a few cases, plants provided the waterborne emissions data before the effluent was sent to the water treatment plant. Where this is the case, the data was included, and a footnote on the corresponding process table in the appendix remarks that those emissions may be overstated.

A few companies send their waterborne emissions to deepwell disposal. For this analysis, waterborne emissions sent to deepwell disposal were not included. Individual process descriptions found in the separate Appendices discuss the inclusion of deepwell disposal by companies.

Solid Wastes. This category includes solid wastes generated from all sources that are landfilled or disposed of in some other way, such as incineration with or without energy recovery. It does not include materials that are recovered for reuse or recycling.

Because this analysis is a cradle-to-gate LCI, and no products are fabricated, postconsumer wastes are not included. Only industrial wastes from processes and fuel-production are considered. Examples of industrial solid wastes are wastewater treatment sludge, solids collected in air pollution control devices, scrap or waste materials from manufacturing operations that are not recycled or sold, and fuel combustion residues such as the ash generated by burning coal.

LCI PRACTITIONER METHODOLOGY VARIATION

There is general consensus among life cycle practitioners on the fundamental methodology for performing LCIs.[1] However, for some specific aspects of life cycle inventory, there is some minor variation in methodology used by experienced practitioners. These areas include the method used to allocate energy requirements and environmental releases among more than one useful product produced by a process and the method used to account for the energy contained in material feedstocks. LCI practitioners vary to some extent in their approaches to these issues. The following sections describe the approach to each issue used in this study. A discussion of methodology differences between this U.S. plastics LCI database and the PlasticsEurope LCI database is found in an attached addendum to this report.

Coproduct Credit

One unique feature of life cycle inventories is that the quantification of inputs and outputs are related to a specific amount of product from a process. However, it is sometimes difficult or impossible to identify which inputs and outputs are associated with individual products of interest resulting from a single process (or process sequence) that produces multiple useful products. The practice of allocating inputs and outputs among

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[1] ISO 14040. Environmental Management—Life Cycle Assessment—Principles and Framework. Reference No. ISO 14040:1997(E).

multiple products from a process is often referred to as "coproduct credit"[2] or "partitioning"[3].

Coproduct credit is done out of necessity when raw materials and emissions cannot be directly attributed to one of several product outputs from a system. It has long been recognized that the practice of giving coproduct credit is less desirable than being able to identify which inputs lead to particular outputs.

Franklin Associates follows the guidelines for allocating coproduct credit shown in the ISO 14040 series. In the ISO 14040 series, the preferred hierarchy for handling allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. How product allocation is made will vary from one system to another but the choice of parameter is not arbitrary. The aim should be to find an allocation parameter that in some way reflects, as closely as possible, the physical behavior of the system itself.[4]

Some processes lend themselves to physical allocation because they have physical parameters that provide a good representation of the environmental burdens of each co-product. Examples of various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. Simple mass and enthalpy allocation have been chosen as the common forms of allocation in this analysis. However, these allocation methods were not chosen as a default choice, but made on a case by case basis after due consideration of the chemistry and basis for production.

In this analysis, coproduct credit is assigned to any useful process output that is produced and sold, whether it is produced and removed by choice or out of necessity.

All scrap coproduct in this analysis was allocated on a mass basis. All off-spec/scrap amounts for the plastics were 3 percent or less. Economic allocation was ruled out as it depends on the economic market, which can change dramatically over time depending on many factors unrelated to the chemical and physical relationships between process inputs and outputs. Useful scrap that is produced and sold should be allocated its share of the raw materials and energy required, as well as emissions released.

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[2] Hunt, Robert G., Sellers, Jere D., and Franklin, William E. **Resource and Environmental Profile Analysis: A Life Cycle Environmental Assessment for Products and Procedures.** Environmental Impact Assessment Review. 1992; 12:245-269.

[3] Boustead, Ian. **Eco-balance Methodology for Commodity Thermoplastics.** A report for The Centre for Plastics in the Environment (PWMI). Brussels, Belgium. December, 1992.

[4] Dr. David A. Russell, Sustainable Development and EH&S Business Integration Dow Europe GmbH; also currently Chairman of PlasticsEurope Life Cycle Task Force (formerly APME). November 17, 2004.

When the coproduct was heat or steam the energy amount (Btu or J) of the heat, steam, or fuel was shown as recovered energy category. If the coproduct was exported as a fuel, it carried with it the allocated share of the inputs and outputs for its production.

When looking at the steam cracking of hydrocarbons, either mass allocation or enthalpy allocation could have been used on the many coproducts of this process. Because of the variety of raw materials (from the steam cracker) used in the resins (ethylene, propylene, hexene, butene, octene, etc.) and such small heating value differences (<5%) between most of the steam cracking coproducts, mass allocation was used. Another case for mass allocation for steam cracking is any variety of the olefins could be used for raw materials in polyethylene resins. If a user of the U.S. LCI database is unaware of the specific raw materials (that is, they only know that olefins are used), the olefins unit process covers all of the specific possibilities.

In the US LCI database, unit process data are presented on a transparent, thoroughly documented basis. In cases where co-product allocation is necessary, both the raw (unallocated) data and the allocated data set are usually shown. However, because the primary datasets in this analysis are an average of numerous plants which do not always use the same technologies or produce the same coproducts, an allocation method has been chosen based on the hierarchy of the ISO 14040 series for each company dataset, and only the averages, which includes the allocated dataset(s), are shown in the unit process tables (see separate Appendices). Confidentiality issues prohibit the revealing of each plant's individual coproduct amounts. This is due to the fact that coproduct allocation is performed on each individual plant dataset, and then the allocated datasets are averaged.

Energy of Material Resource

For some raw materials, such as petroleum, natural gas, and coal, the amount consumed in all industrial applications as fuel far exceeds the amount consumed as raw materials (feedstock) for products. The primary use of these materials in the marketplace is for energy. The total amount of these materials can be viewed as an energy pool or reserve. This concept is illustrated in Figure 1-3.

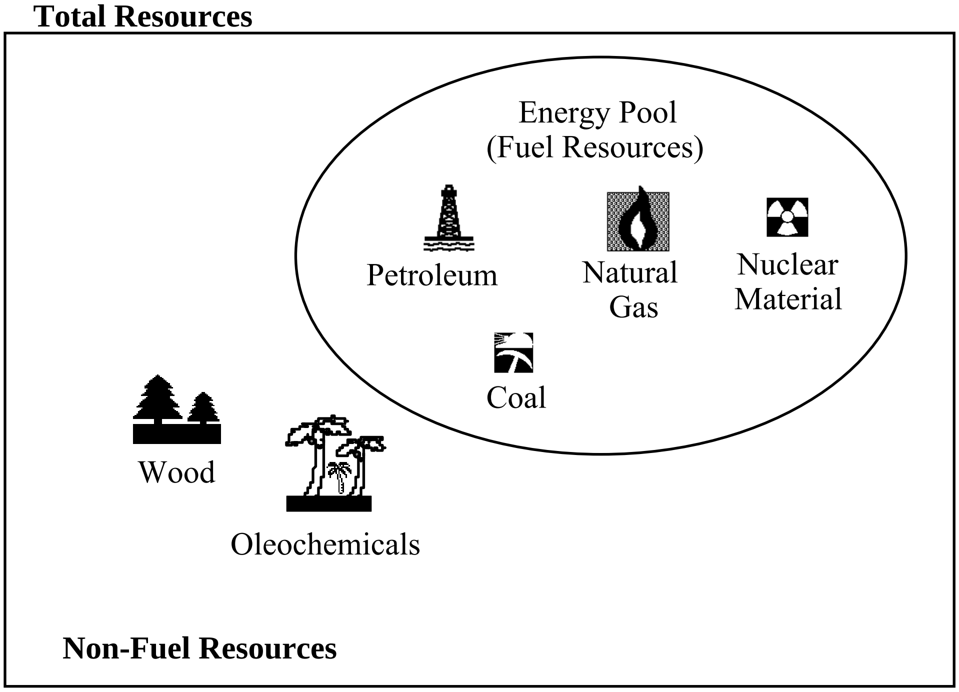

Figure 1-3. Illustration of the Energy of Material Resource Concept.

The use of a certain amount of these materials as feedstocks for products, rather than as fuels, removes that amount of material from the energy pool, thereby reducing the amount of energy available for consumption. This use of available energy as feedstock is called the "energy of material resource" and is included in the inventory. The energy of material resource represents the amount the energy pool is reduced by the consumption of fuel materials as raw materials in products and is quantified in energy units.

The energy of material resource is the energy content of the fuel materials *input* as raw materials or feedstocks. The energy of material resource assigned to a material is *not* the energy value of the final product, but is the energy value of the raw material at the point of extraction from its natural environment. For fossil fuels, this definition is straightforward. For instance, petroleum is extracted in the form of crude oil. Therefore, the energy of material resource for petroleum is the higher heating value of crude oil.

Once the feedstock is converted to a product, there is energy content that could be recovered, for instance through combustion in a waste-to-energy waste disposal facility. The energy that can be recovered in this manner is always somewhat less than the feedstock energy because the steps to convert from a gas or liquid to a solid material reduce the amount of energy left in the product itself. The maximum amounts of energy that could potentially be recovered from combustion of the nine plastics considered in this analysis are shown in Table 1-1 based on the higher heating value (HHV) of each resin. In North America, energy content is most often quoted as HHV; this value is determined when the product is burned and the product water formed is condensed. The use of HHV is considered preferable from the perspective of energy efficiency analysis, as it is a better measure of the energy inefficiency of processes.[5] Lower heating values (LHV), or net heating values, measure the heat of combustion when the water formed remains in the gaseous state. The difference between the HHV and the LHV depends on the hydrogen content of the product. As the carbon amount of the combusted material climbs higher, the difference in these two values levels off to approximately 7.5 percent.[6] A good estimate of the LHV for each of the plastics can be calculated by multiplying the HHV values in Table 1 by 0.925.

The energy amounts in Table 1-1 are for pure resin only. If additives or plasticizers are added to the resin, the heating values will vary.

Table 1-1

Higher Heating Values for the Plastic Resins Analyzed

Plastic Resin	**Higher Heating Value**	
	(Btu/lb)	**(MJ/kg)**
HDPE	19,985	46.5
LDPE	19,877	46.2
LLDPE	19,946	46.4
PP	19,948	46.4
PET	10,600	24.7
GPPS	18,000	41.9
HIPS	18,000	41.9
PVC	7,875	18.3
ABS	15,500	36.1

References: Fire, Frank L. **Combustibility of Plastics**. Van Nostrand. Reinhold. 1991.
Thermodynamic Data for Biomass Materials and Waste Components. The American Society of Mechanical Engineers. 1987.

Source: Franklin Associates, a Division of ERG

The materials are primarily used as fuels but can also be used as material inputs can change over time and with location. In the industrially developed countries included in this analysis, these materials are petroleum, natural gas, and coal. While some wood is burned for energy, the primary uses for wood are for products such as paper and lumber. Similarly, some oleochemical oils such as palm oils are burned for fuels, often referred to as “bio-diesel.” However, as in the case of wood, their primary consumption is as raw materials for products such as soaps, surfactants, cosmetics, etc.

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[5] Worrell, Ernst, Dian Phylipsen, Dan Einstein, and Nathan Martin. **Energy Use and Energy Intensity of the U.S. Chemical Industry.** Ernest Orlando Lawrence Berkeley National Laboratory. April, 2000. p. 12.

[6] Seddon, Dr. Duncan. **Gas Usage & Value**. PennWell Books. 2006. p. 76. Figure 4-1.

DATA

The accuracy of the study is only as good as the quality of input data. The development of methodology for the collection of data is essential to obtaining quality data. Careful adherence to that methodology determines not only data quality but also objectivity. Franklin Associates has developed a methodology for incorporating data quality and uncertainty into LCI calculations. Data quality and uncertainty are discussed in more detail at the end of this section.

If a user of this report is interested in the specific source of an individual emission shown in the results tables, information on emission sources can be found within the appendix tables. Table 1 of each resin/precursor appendix shows the full list of emissions released from the sequence of material production processes for each resin/precursor. If the emission of interest is listed in Table 1, a reader can then go through the individual appendix tables for each process shown in the flow diagram for that resin/precursor to identify the specific process source(s) of that emission. If the emission of interest is not listed in Table 1, then it is emitted from fuel-related sources. Tables listing emissions from the production and combustion of individual fuels are shown in Appendix A.

Data necessary for conducting this analysis are separated into two categories: process-related data and fuel-related data.

Process Data

Methodology for Collection/Verification. The process of gathering data is an iterative one. The data-gathering process for each system begins with a literature search to identify raw materials and processes necessary to produce the final product. The search is then extended to identify the raw materials and processes used to produce these raw materials. In this way, a flow diagram is systematically constructed to represent the production pathway of each system.

Each process identified during the construction of the flow diagram is then researched to identify potential industry sources for data. In this case, the Plastics Division of the ACC contacted member and non-member companies producing the resins/precursors to be included in this analysis. The companies that agreed to participate in this analysis by collecting process data were contacted, and worksheets and instructions developed specifically for this project were provided to assist in gathering the necessary process data for their product(s).

Upon receipt of the completed worksheets, the data were evaluated for completeness and reviewed for any material inputs that were additions or changes to the flow diagrams. In this way, the flow diagrams were revised to represent current industrial practices. Data suppliers were then contacted again to discuss the data, process technology, waste treatment, identify coproducts, and any assumptions necessary to understand the data and boundaries.

After each dataset was completed and verified, allocation is performed for any coproducts at the plant. Then, the datasets for each process were aggregated into a single set of data for that process. The method of aggregation for each process was determined on a case-by-case basis. Commonly, these datasets were weighted by plant production amount percentages. However, if more than one process technology was involved, market shares for these processes were used to create a weighted average (e.g. benzene production). In this way, a representative set of data can be estimated from a limited number of data sources. The provided process dataset and assumptions were then documented and returned with the aggregated data to each data supplier for their review.

Confidentiality. The data requested in the worksheets are often considered proprietary by potential suppliers of data. The method used to collect and review data provides each supplier the opportunity to review the aggregated average data calculated from all data supplied by industry. This allows each supplier to verify that their company’s data are not being published and that the averaged data are not aggregated in such a way that individual company data can be calculated or identified.

Objectivity. Each unit process is researched independently of all other processes. No calculations are performed to link processes together with the production of their raw materials until after data gathering and review are complete. The procedure of providing the aggregated data and documentation to suppliers and other industry experts provides several opportunities to review the individual data sets without affecting the objectivity of the research. This process serves as an external expert review of each process. Also, because these data are reviewed individually, assumptions are reviewed based on their relevance to the process rather than their effect on the overall outcome of the study.

Data Sources. As stated in the **Study Goal** section, the intended purpose of the study was to develop life cycle profiles for the resins/precursors using the most up-to-date primary data collected from the companies producing each resin/precursor.

Data collected specifically for this study include data on the production of the following chemicals, resins, and precursors:

- Olefins hydrocracking
- High-density polyethylene (HDPE) resin
- Low-density polyethylene (LDPE) resin
- Linear low-density polyethylene (LLDPE) resin
- Polypropylene (PP) resin
- Acetic acid
- Crude terephthalic acid (TPA)/dinitrotoluene (DNT)/purified terephthalic acid (PTA)/polyethylene terephthalate (PET) resin
- Benzene
- Ethylbenzene/styrene
- General-purpose polystyrene (GPPS) resin
- High-impact polystyrene (HIPS) resin

- Chlorine/caustic soda
- Ethylene dichloride (EDC)/vinyl chloride monomer (VCM)
- Polyvinyl chloride (PVC) resin
- Acrylonitrile
- Acrylonitrile-butadiene-styrene (ABS) resin
- Polyether polyol for rigid foam polyurethane
- Polyether polyol for flexible foam polyurethane
- Nitrobenzene/aniline
- Methylene diphenylene diisocyanate (MDI)
- Toluene diisocyanate (TDI)

In the case of PVC resin, two emissions (dioxins and vinyl chloride) were provided by The Vinyl Institute in place of the plant data average. In the case of vinyl chloride, the amount was based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. In the case of dioxins, the amount was based on 2003 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. The dioxin amounts were calculated as toxic equivalent values (TEQ). These values were used to represent more industry wide average values to account for facilities that did not participate in the LCI inventory.

Other than the data sets provided by industry for this study, or data developed for this study using secondary data sources, data sets for all other unit processes in this study were taken from Franklin Associates' U.S. industry average database. This database has been developed over a period of years through research for many LCI projects encompassing a wide variety of products and materials.

Another advantage of the database is that it is continually updated. For each ongoing LCI project, verification and updating is carried out for the portions of the database that are accessed by that project.

Fuel Data

When fuels are used for process or transportation energy, there are energy and emissions associated with the production and delivery of the fuels as well as the energy and emissions released when the fuels are burned. Before each fuel is usable, it must be mined, as in the case of coal or uranium, or extracted from the earth in some manner. Further processing is often necessary before the fuel is usable. For example, coal is crushed or pulverized and sometimes cleaned. Crude oil is refined to produce fuel oils, and "wet" natural gas is processed to produce natural gas liquids for fuel or feedstock.

To distinguish between environmental emissions from the combustion of fuels and emissions associated with the production of fuels, different terms are used to describe the different emissions. The combustion products of fuels are defined as "combustion data." Energy consumption and emissions which result from the mining, refining, and transportation of fuels are defined as "precombustion data." Precombustion data and combustion data together are referred to as "fuel-related data."

Fuel-related data are developed for fuels that are burned directly in industrial furnaces, boilers, and transport vehicles. Fuel-related data are also developed for the production of electricity. These data are assembled into a database from which the energy requirements and environmental emissions for the production and combustion of process fuels are calculated.

Energy data are developed in the form of units of each primary fuel required per unit of each fuel type. For electricity production, federal government statistical records provided data for the amount of fuel required to produce electricity from each fuel source, and the total amount of electricity generated from petroleum, natural gas, coal, nuclear, hydropower, and other (solar, geothermal, etc.). Literature sources and federal government statistical records provided data for the emissions resulting from the combustion of fuels in utility boilers, industrial boilers, stationary equipment such as pumps and compressors, and transportation equipment. Because electricity is required to produce primary fuels, which are in turn used to generate electricity, a circular loop is created. Iteration techniques are utilized to resolve this loop.

In 2003, Franklin Associates updated our fuels and energy database for inclusion in the U.S. LCI database. This fuels and energy database is used in this analysis.

Data Quality Goals for This Study

ISO standards 14040, 14041 and 14043 each detail various aspects of data quality and data quality analysis. ISO 14041 Section 5.3.6 states: "Descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study." The section goes on to list three critical data quality requirements: time-related coverage, geographical coverage, and technology coverage. Additional data quality descriptors that should be considered include whether primary or secondary data were used and whether the data were measured, calculated, or estimated.

As described earlier in this chapter, the data quality goal for this study was to use primary data collected from the resin/precursor producers to develop data that were representative of the high-volume resins/precursors currently available in terms of time, geographic, and technology coverage.

In some cases, it was possible to achieve the intended data quality goals of the study in terms of current primary data and geographic and technology coverage. The data sets submitted for polyether polyols and ABS represent at least 50 percent of total North American production of these materials. The data sets provided for the remaining resins cover less than 50 percent of total North American production amount of these materials. While data were provided by a small sample of plants in these cases, the resin producers who provided data verified that the characteristics of their plants are representative of a majority of North American production. The average resin and precursor datasets were reviewed and accepted respectively by each data provider. These data are current primary data and are considered to be of the highest quality.

Data for most other processes and materials in this study were taken from Franklin Associates' LCI database or estimated based on secondary data sources. The quality of these data vary in terms of age, representativeness, measured values or estimates, etc.; however, all materials and process data sets used in this study were thoroughly reviewed for accuracy and currency and updated to the best of our capabilities for this analysis. All fuel data were reviewed and extensively updated in 2003.

Each chapter of this report includes a brief data quality summary of the key primary data sources used for each resin or precursor. The report bibliography lists the published data sources that were used to develop the LCI models for each resin or precursor. Additional detail on the data sources used in the modeling of each unit process is provided in the separate Appendices document.

Data Accuracy

An important issue to consider when using LCI study results is the reliability of the data. In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates. However, the reliability of the study can be assessed in other ways.

A key question is whether the LCI profiles are accurate and study conclusions are correct. Because this study develops cradle-to-resin profiles for plastic resins and precursors, rather than comparing functionally equivalent products made from these materials, no comparative conclusions are drawn in this analysis. However, it is important that the environmental profiles accurately reflect the relative magnitude of energy requirements and other environmental burdens for the various materials analyzed.

The accuracy of an environmental profile depends on the accuracy of the numbers that are combined to arrive at that conclusion. Because of the many processes required to produce plastic resins and precursors, many numbers in the LCI are added together for a total numeric result. Each number by itself may contribute little to the total, so the accuracy of each number by itself has a small effect on the overall accuracy of the total. There is no widely accepted analytical method for assessing the accuracy of each number to any degree of confidence. In many cases, plant personnel reported actual plant data. The data reported may represent operations for the previous year or may be representative of engineering and/or accounting methods. All data received are evaluated to determine whether or not they are representative of the typical industry practices for that operation or process being evaluated. Taking into consideration budget considerations and limited industry participation, the data used in this report are believed to be the best that can be currently obtained.

There are several other important points with regard to data accuracy. Each number generally contributes a small part to the total value, so a large error in one data point does not necessarily create a problem. For process steps that make a larger than average contribution to the total, special care is taken with the data quality. It is assumed that with careful scrutiny of the data, any errors will be random. That is, some numbers will be a little high due to errors, and some will be slightly low, but in the summing process these random high and low errors will offset each other to some extent.

There is another dimension to the reliability of the data. Certain numbers do not stand alone, but rather affect several numbers in the system. An example is the amount of a raw material required for a process. This number will affect every step in the production sequence prior to the process. Errors such as this that propagate throughout the system are more significant in steps that are closest to the end of the production sequence. For example, changing the weight of an input to the final polymerization process changes the amounts of the inputs to that process, and so on back to the quantities of crude oil and natural gas.

In summary, for the particular data sources used and for the specific methodology described in this report, the results of this report are believed to be as accurate and reasonable as possible.

ISO Data Quality Requirements and Use of Study

The authors provide the following guidelines and restrictions regarding appropriate use of the study results:

Comparisons between plastic resins should not be made on the basis of cradle-to-resin/precursor results, as the ISO 14040 series of standards require that comparisons of product systems must be made on the basis of equivalent function, and functional equivalence cannot be established without including fabrication of the resin or precursor into a functional product.

CRITICAL/PEER REVIEW

Individual datasets for unit processes in each resin system have been reviewed and approved by industry experts. Unit process data, resin models, and cradle-to-resin results have been reviewed internally by Franklin Associates LCA staff. The energy results have also been reviewed by PlasticsEurope staff, as well as Ian Boustead of Boustead Consulting in 2006-2007.

The Plastics Division of the ACC plans to post the results of this analysis to the U.S. LCI database website. At this time, peer review guidelines have been established, but no formal review process has been implemented. Datasets posted to US LCI database website have a disclaimer noting that they have not undergone a formal external peer review.

METHODOLOGY ISSUES

The following sections discuss how several key methodological issues are handled in this study.

Raw Material Use for Internal Energy

As data was collected from data providers in this study, it was noted that the raw material inputs for the hydrocracker were much higher than would be expected to produce the mass of output material. After many discussions with the data providers, it was discovered that some of the raw materials were actually combusted within the hydrocracker, which in turn produced an amount of energy, decreasing the amount of purchased energy required for the reaction. Data providers listed this energy as fuel gas or offgas and supplied the heating value of this gas. Using this information, Franklin Associates calculated the amount of raw material combusted within the hydrocracker to produce offgas energy.

This internal energy is included in the analysis by including the production of the raw materials combusted to produce the energy as well as the energy amount attributed to the combustion of those raw materials. Unlike the raw materials that become part of the product output mass, no energy of material resource is assigned to the raw materials inputs that are combusted within the process. Instead they are assigned an “Internal offgas use” energy.

Recovered Energy Exported from System Boundaries

Table 2 in each chapter shows a line for recovered energy. This recovered energy is energy (heat or steam) that data providers reported as being exported from the boundaries of the system, so it would replace purchased fuels for another process outside the system. Because it is not known what form of purchased energy the recovered energy would replace, no credit has been given besides recording the recovered energy amount. In Table 1 in each chapter, credit is given to the resin/precursor by subtracting the recovered energy from the process and total energy for a net reduction in energy.

When fuel coproducts, such as offgas, are exported from the hydrocarbon production, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the process, and the remaining inputs and outputs are allocated over the material products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{\text{attributed to remaining products}} \qquad \text{(Equation 1)}$$

where

IO = Input/Output Matrix to produce all products/coproducts

M_{EO} = Mass of Exported Offgas

M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set.

Precombustion Energy and Emissions

The energy content of fuels has been adjusted to include the energy requirements for extracting, processing, and transporting fuels, in addition to the primary energy of a fuel resulting from its combustion. In this study, this additional energy is called precombustion energy. Precombustion energy refers to all the energy that must be expended to prepare and deliver the primary fuel. Adjustments for losses during transmission, spills, leaks, exploration, and drilling/mining operations are incorporated into the calculation of precombustion energy.

Precombustion environmental emissions (air, waterborne, and solid waste) are also associated with the acquisition, processing, and transportation of the primary fuel. These precombustion emissions are added to the emissions resulting from the burning of the fuels.

Electricity Grid Fuel Profile

In general, detailed data do not exist on the fuels used to generate the electricity consumed by each industry. Electricity production and distribution systems in the United States are interlinked and are not easily separated. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid. Therefore, the U.S. average fuel consumption by electrical utilities is assumed.

Electricity generated on-site at a manufacturing facility is represented in the process data by the fuels used to produce it. A portion of on-site generated electricity is sold to the electricity grid. This portion is accounted for in the calculations for the fuel mix in the grid.

Data for this analysis was collected from plants in the U.S., Canada, and Mexico. Although a number of datasets are from Canada and Mexico, the overall production percentages of each resin/precursor per individual country would be needed to represent the electricity grid of the specific resin/precursor accurately. Access to statistics on the relative U.S. and Canadian production percentages for each resin was not available; thus, for consistency the U.S. electricity grid, which was updated in the U.S. LCI database in 2003, was used.

Electricity/Heat Cogeneration

Cogeneration is the use of steam for generation of both electricity and heat. The most common configuration is to generate high temperature steam in a cogeneration boiler and use that steam to generate electricity. The steam exiting the electricity turbines is then used as a process heat source for other operations. Significant energy savings occur because in a conventional operation, the steam exiting the electricity generation process is condensed, and the heat is dissipated to the environment.

For LCI purposes, the fuel consumed and the emissions generated by the cogeneration boiler need to be allocated to the two energy-consuming processes: electricity generation and subsequent process steam. Because these are both energy-consuming processes, the logical basis for allocation is Btu of energy.

In order to allocate fuel consumption and environmental emissions to both electricity and steam generation, the share of the two forms of energy (electrical and thermal) produced must be correlated to the quantity of fuel consumed by the boiler. Data on the quantity of fuel consumed and the associated environmental emissions from the combustion of the fuel, the amount of electricity generated, and the thermal output of the steam exiting electricity generation must be known in order to allocate fuel consumption and environmental emissions accordingly. These three types of data are discussed below.

1. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2003 industry statistics, natural gas accounted for 59 percent of industrial cogeneration, while coal and waste gases accounted for 28 percent and 13 percent, respectively. For this analysis, the data for the combustion of natural gas in industrial boilers was used to determine the environmental emissions from natural gas combustion in cogeneration boilers. For cases in which coal is used in cogeneration boilers, the data for the combustion of bituminous coal in industrial boilers is recommended. For cases in which waste gas is used in cogeneration boilers, the data for the combustion of LPG (liquefied petroleum gas) in industrial boilers is recommended.

2. **Kilowatt-Hours of Electricity Generated:** In this analysis, the data providers reported the kilowatt-hours of electricity from cogeneration. The Btu of fuel required for this electricity generation was calculated by multiplying the kilowatt-hours of electricity by 6,826 Btu/kWh (which utilizes a thermal to electrical conversion efficiency of 50 percent). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the electricity allocation factor. Note that the kilowatt-hours of electricity generation and consumption of fuel must be on the same production basis, whether a common unit of time or a specified quantity of fuel consumption.

3. **Thermal Output of Steam Exiting Electricity Generation:** In this analysis, the data providers stated the pounds and pressure of steam from cogeneration. The thermal output (in Btu) of this steam was calculated from enthalpy tables (in most cases steam ranged from 1,000 to 1,200 Btu/lb). An efficiency of 80 percent was used for the industrial boiler to calculate the amount of fuel used. This Btu value was then divided by the

Btu value of fuel consumed in the cogeneration boiler to determine the steam allocation factor. Note that the thermal output of steam and consumption of fuel must be on the same production basis, whether a common unit of time or a specified quantity of fuel consumption.

METHODOLOGICAL DECISIONS

Some general decisions are always necessary to limit a study such as this to a reasonable scope. It is important to understand these decisions. The key assumptions and limitations for this study are discussed in the following sections.

Geographic Scope

Data collected for this analysis came from plants located in North America, including the U.S., Canada, and Mexico.

Data for foreign processes are generally not available. This is usually only a consideration for the production of oil that is obtained from overseas. In cases such as this, the energy requirements and emissions are assumed to be the same as if the materials originated in the United States. Since foreign standards and regulations vary from those of the United States, it is acknowledged that this assumption may introduce some error. Fuel usage for transportation of materials from overseas locations is included in the study.

System Components Not Included

The following components of each system are not included in this LCI study:

Water Consumption. In primary datasets collected for this analysis, water consumption data was collected for each resin/precursor and for some of the intermediate chemicals. These collected water consumption data can be found in the unit process tables in the Appendices (separate document), but were not included in the cradle-to-resin average datasets due to the lack of corresponding data for the raw materials and intermediate chemicals.

In this analysis, water consumption is defined as the following: (1) water consumed in the process(es) (e.g. water that becomes part of the product or evaporation loss), and (2) water removed from one water source and released to a different receiving body of water. Cooling water that is circulated in a closed-loop system is not included.

Water Use, Land Use, and Farming. Because of the lack of availability of good data on water use for raw material and intermediate unit processes, Franklin Associates' LCI database does not include water use, nor does Franklin Associates' database include data on land use and erosion.

The quantities and compositions of pesticides, herbicides, and other chemical agents used in farming vary widely, and data on the production of specialized agricultural chemicals are largely unavailable. Thus, production and use of these materials is not included in the analysis, although the LCI does include the production of basic fertilizer inputs used in farming.

Capital Equipment. The energy and wastes associated with the manufacture of capital equipment are not included. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. The energy and emissions associated with such capital equipment generally, for 1,000 pounds (or kilograms) of materials, become negligible when averaged over the millions of pounds (or kilograms) of product manufactured over the useful lifetime of the capital equipment.

Space Conditioning. The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations in most cases. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. Energy consumed for space conditioning is usually less than one percent of the total energy consumption for the manufacturing process. This assumption has been checked in the past by Franklin Associates staff using confidential data from manufacturing plants. The data collection forms developed for this project specifically requested that the data provider exclude energy use for space conditioning, or indicate if the reported energy requirements included space conditioning.

Support Personnel Requirements. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

Miscellaneous Materials and Additives. Selected materials such as catalysts, pigments, or other additives which total less than one percent by weight of the net process inputs are not included in the assessment. Omitting miscellaneous materials and additives helps keep the scope of the study focused and manageable within budget and time constraints. However, it is possible that some toxic emissions may be released from the production of these materials and additives. As noted earlier in Chapter 1, additives such as plasticizers, stabilizers, etc. added to resins or precursors to adapt them for specific product applications were not included, since the purpose of the analysis was to provide data that can be linked to fabrication data sets to model a wide variety of plastic products.

CHAPTER 2

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR HDPE RESIN

This chapter presents LCI results for the production of high-density polyethylene (HDPE) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of HDPE resin. Figure 2-1 presents the flow diagram for the production of HDPE resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix B of the Appendices (separate document).

Primary data was collected for olefins and HDPE resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

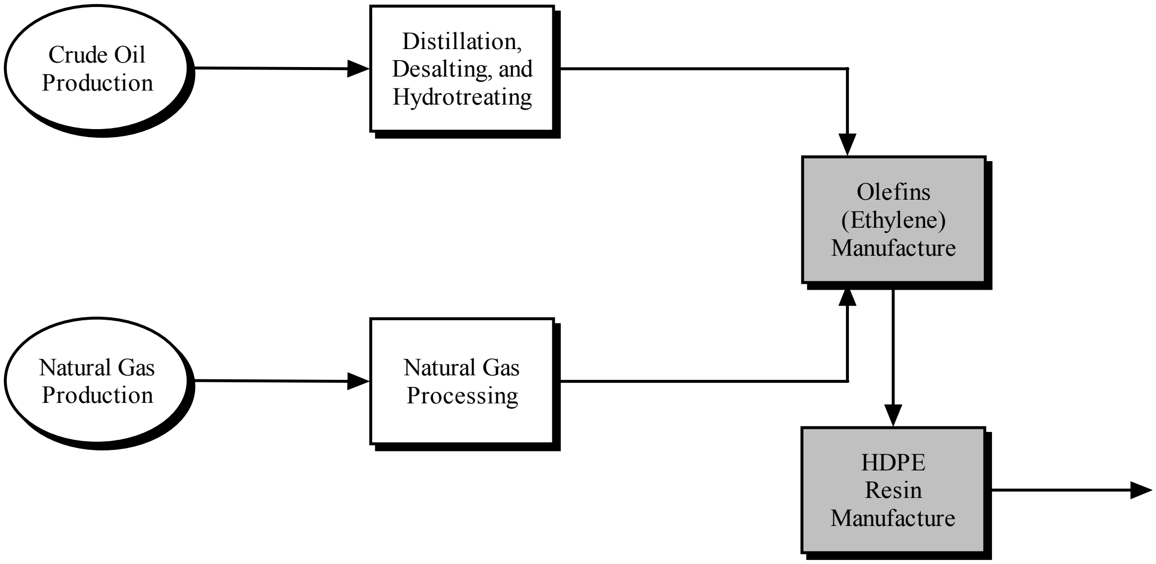

Figure 2-1. Flow diagram for the manufacture of virgin high-density polyethylene (HDPE) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

A weighted average using production amounts was calculated from the HDPE production data from five plants collected from three leading producers in North America. As of 2003, there were 10 HDPE producers and 23 HDPE plants in the U.S. The captured production amount is approximately 20 percent of the available capacity for HDPE production in the U.S. and Canada. Scrap resin (e.g. off-spec) is produced as a coproduct during this process. A mass basis was used to allocate the credit for each coproduct.

DESCRIPTION OF TABLES

The average gross energy required to produce HDPE resin is 35.8 million Btu per 1,000 pounds of resin or 83.2 GJ per 1,000 kilograms of resin. Tables 2-1 and 2-2 show the breakdown of energy requirements for the production of HDPE resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table B-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of HDPE resin. Natural gas and petroleum used as raw material inputs for the production of HDPE, reported as energy of material resource in Table 2-1, are included in the totals for natural gas and petroleum energy in Table 2-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 2-2 are used to generate purchased electricity along with the fossil fuels.

Table 2-1

Energy by Category for the Production of HDPE Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	11.9	27.6
Transportation	0.52	1.22
Energy of Material Resource	23.4	54.4
Total Energy	**35.8**	**83.2**
Energy Category (Percent)		
Process	33%	33%
Transportation	1%	1%
Energy of Material Resource	65%	65%
Total	100%	100%

---

(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 2-2

Energy Profile for the Production of HDPE Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	29.4	68.3
Petroleum	5.03	11.7
Coal	1.04	2.42
Hydropower	0.047	0.11
Nuclear	0.25	0.58
Wood	0	0
Other	0.048	0.11
Recovered Energy (1)	-0.012	-0.028
Total Energy	**35.8**	**83.2**
Energy Source (Percent)		
Natural Gas	82%	82%
Petroleum	14%	14%
Coal	3%	3%
Hydropower	0%	0%
Nuclear	1%	1%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

---

(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 2-3 shows the weight of solid waste generated during the production of HDPE resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 2-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 2-3

Solid Wastes by Weight for the Production of HDPE Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	29.5	29.5
Incinerated	3.84	3.84
Waste-to-Energy	0.027	0.027
Fuel	41.2	41.2
Total	**74.6**	**74.6**
Weight Percent by Category		
Process		
Landfilled	40%	40%
Incinerated	5%	5%
Waste-to-Energy	0%	0%
Fuel	55%	55%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 2-5 provides a greenhouse gas (GHG) summary for the production of HDPE resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 2-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 2-4 are multiplied by their global warming potential and shown in Table 2-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 2-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 2-4

Atmospheric Emissions for the Production of HDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.10	0.18	0.28
Particulates (PM2.5)	0.012	0	0.012
Particulates (PM10)	0.14	0.085	0.23
Nitrogen Oxides	0.13	2.33	2.46
Hydrocarbons (unspecified)	1.13	0.056	1.19
VOC (unspecified)	0.73	0.27	1.00
TNMOC (unspecified)	0	0.0056	0.0056
Sulfur Dioxide	0	8.11	8.11
Sulfur Oxides	23.6	0.33	23.9
Carbon Monoxide	4.22	1.28	5.50
Fossil CO2	76.9	1,377	1,454
Non-Fossil CO2	0	4.90	4.90
Aldehydes (Formaldehyde)	0	9.3E-04	9.3E-04
Aldehydes (Acetaldehyde)	0	5.3E-05	5.3E-05
Aldehydes (Propionaldehyde)	0	9.3E-09	9.3E-09
Aldehydes (unspecified)	0.013	0.0012	0.014
Organics (unspecified)	0.011	3.1E-04	0.011
Ammonia	0.0064	5.8E-04	0.0070
Ammonia Chloride	0	3.9E-05	3.9E-05
Methane	12.9	4.26	17.2
Kerosene	0	7.0E-05	7.0E-05
Chorine	9.9E-05	2.0E-05	1.2E-04
HCl	9.9E-07	0.063	0.063
HF	0	0.0076	0.0076
Metals (unspecified)	0	0.0011	0.0011
Mercaptan	0	4.9E-06	4.9E-06
Antimony	0	1.1E-06	1.1E-06
Arsenic	0	2.5E-05	2.5E-05
Beryllium	0	1.3E-06	1.3E-06
Cadmium	0	9.7E-06	9.7E-06
Chromium (VI)	0	4.0E-06	4.0E-06
Chromium	0	2.3E-05	2.3E-05
Cobalt	0	1.8E-05	1.8E-05
Copper	0	2.8E-07	2.8E-07
Lead	0	2.9E-05	2.9E-05
Magnesium	0	5.6E-04	5.6E-04
Manganese	0	7.3E-05	7.3E-05
Mercury	0	6.1E-06	6.1E-06
Nickel	0	2.0E-04	2.0E-04
Selenium	0	6.8E-05	6.8E-05
Zinc	0	1.8E-07	1.8E-07
Acetophenone	0	3.7E-10	3.7E-10
Acrolein	0	1.2E-04	1.2E-04
Nitrous Oxide	0	0.020	0.020
Benzene	0.090	0.026	0.12
Benzyl Chloride	0	1.7E-08	1.7E-08
Bis(2-ethylhexyl) Phthalate (DEHP)	0	1.8E-09	1.8E-09
1,3 Butadiene	0	9.7E-07	9.7E-07
2-Chloroacetophenone	0	1.7E-10	1.7E-10
Chlorobenzene	0	5.4E-10	5.4E-10
2,4-Dinitrotoluene	0	6.8E-12	6.8E-12
Ethyl Chloride	0	1.0E-09	1.0E-09
Ethylbenzene	0.011	0.0031	0.014

Table 2-4

Atmospheric Emissions for the Production of HDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethylene Dibromide	0	2.9E-11	2.9E-11
Ethylene Dichloride	0	9.7E-10	9.7E-10
Hexane	0	1.6E-09	1.6E-09
Isophorone (C9H14O)	0	1.4E-08	1.4E-08
Methyl Bromide	0	3.9E-09	3.9E-09
Methyl Chloride	0	1.3E-08	1.3E-08
Methyl Ethyl Ketone	0	9.5E-09	9.5E-09
Methyl Hydrazine	0	4.1E-09	4.1E-09
Methyl Methacrylate	0	4.9E-10	4.9E-10
Methyl Tert Butyl Ether (MTBE)	0	8.5E-10	8.5E-10
Naphthalene	0	8.7E-06	8.7E-06
Propylene	0	6.4E-05	6.4E-05
Styrene	0	6.1E-10	6.1E-10
Toluene	0.14	0.041	0.18
Trichloroethane	3.0E-08	3.1E-09	3.3E-08
Vinyl Acetate	0	1.9E-10	1.9E-10
Xylenes	0.082	0.024	0.11
Bromoform	0	9.5E-10	9.5E-10
Chloroform	0	1.4E-09	1.4E-09
Carbon Disulfide	0	3.2E-09	3.2E-09
Dimethyl Sulfate	0	1.2E-09	1.2E-09
Cumene	0	1.3E-10	1.3E-10
Cyanide	0	6.1E-08	6.1E-08
Perchloroethylene	0	2.3E-06	2.3E-06
Methylene Chloride	0	3.4E-05	3.4E-05
Carbon Tetrachloride	3.7E-09	1.1E-06	1.1E-06
Phenols	0	1.1E-05	1.1E-05
Fluorides	0	4.3E-06	4.3E-06
Polyaromatic Hydrocarbons (total)	0	5.4E-06	5.4E-06
Biphenyl	0	8.6E-08	8.6E-08
Acenaphthene	0	2.6E-08	2.6E-08
Acenaphthylene	0	1.3E-08	1.3E-08
Anthracene	0	1.1E-08	1.1E-08
Benzo(a)anthracene	0	4.0E-09	4.0E-09
Benzo(a)pyrene	0	1.9E-09	1.9E-09
Benzo(b,j,k)fluroanthene	0	5.6E-09	5.6E-09
Benzo(g,h,i) perylene	0	1.4E-09	1.4E-09
Chrysene	0	5.1E-09	5.1E-09
Fluoranthene	0	3.6E-08	3.6E-08
Fluorene	0	4.6E-08	4.6E-08
Indeno(1,2,3-cd)pyrene	0	3.1E-09	3.1E-09
Naphthanlene	0	6.6E-07	6.6E-07
Phenanthrene	0	1.4E-07	1.4E-07
Pyrene	0	1.7E-08	1.7E-08
5-Methyl Chrysene	0	1.1E-09	1.1E-09
Dioxins (unspecified)	0	4.2E-08	4.2E-08
Furans (unspecified)	0	2.3E-10	2.3E-10
CFC12	0	3.1E-09	3.1E-09
Radionuclides (unspecified) (1)	0	0.0039	0.0039
HCFC-22	9.9E-07	0	9.9E-07
Hydrogen	0.0039	0	0.0039
Acid (unknown)	0.73	0	0.73

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 320,611 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 2-5

Greenhouse Gas Summary for the Production of HDPE Resin
(lb carbon dioxide equivalents per 1,000 lb HDPE or kg carbon dioxide equivalents per 1,000 kg HDPE)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,377	76.9	1,454
Methane	107	323	430
Nitrous oxide	6.06	0	6.06
Methyl bromide	1.9E-08	0	1.9E-08
Methyl chloride	2.1E-07	0	2.1E-07
Trichloroethane	4.4E-07	4.1E-06	4.6E-06
Chloroform	4.3E-08	0	4.3E-08
Methylene chloride	3.4E-04	0	3.4E-04
Carbon tetrachloride	0.0016	5.1E-06	0.0016
CFC-012	3.4E-05	0	3.4E-05
HCFC-22	0	0.0018	0.0018
Total	1,490	400	1,890

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 2-6

Waterborne Emissions for the Production of HDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0014	0.0014
Acid (benzoic)	0.0051	0.0013	0.0064
Acid (hexanoic)	0.0011	2.7E-04	0.0013
Dissolved Solids	226	56.4	283
Suspended Solids	9.34	1.02	10.4
BOD	1.22	0.25	1.47
COD	5.23	0.34	5.57
Phenol/Phenolic Compounds	0.0031	5.7E-04	0.0037
Sulfur	0	0.0034	0.0034
Sulfates	0.37	0.14	0.51
Sulfides	6.5E-04	5.0E-06	6.5E-04
Oil	0.23	0.025	0.26
Hydrocarbons	0	2.5E-04	2.5E-04
Ammonia	0.18	0.019	0.20
Ammonium	0	3.1E-05	3.1E-05
Aluminum	0.26	0.030	0.29
Antimony	1.6E-04	1.9E-05	1.8E-04
Arsenic	0.0012	2.9E-04	0.0015
Barium	3.64	0.45	4.09
Beryllium	6.3E-05	1.3E-05	7.7E-05
Cadmium	1.8E-04	4.2E-05	2.2E-04
Chromium (unspecified)	0.0073	8.4E-04	0.0082
Chromium (hexavalent)	2.4E-05	0	2.4E-05
Cobalt	1.1E-04	2.8E-05	1.4E-04
Copper	0.0011	2.0E-04	0.0013
Iron	0.57	0.087	0.66
Lead	0.0022	4.3E-04	0.0027
Lithium	2.92	1.26	4.17
Magnesium	3.17	0.80	3.97
Manganese	0.0051	0.0020	0.0071
Mercury	2.8E-06	3.3E-07	3.2E-06
Molybdenum	1.2E-04	2.9E-05	1.5E-04
Nickel	0.0011	2.3E-04	0.0013
Selenium	3.1E-05	1.5E-05	4.6E-05
Silver	0.011	0.0027	0.013
Sodium	51.5	12.9	64.4
Strontium	0.28	0.069	0.34
Thallium	3.4E-05	3.9E-06	3.8E-05
Tin	8.2E-04	1.5E-04	9.7E-04
Titanium	0.0025	2.8E-04	0.0028
Vanadium	1.4E-04	3.4E-05	1.7E-04
Yttrium	3.4E-05	8.5E-06	4.3E-05
Zinc	0.0063	7.9E-04	0.0071
Chlorides (unspecified)	182	45.7	228
Chlorides (methyl chloride)	2.0E-07	5.1E-08	2.5E-07
Calcium	16.2	4.07	20.3
Fluorides	0	5.1E-04	5.1E-04
Nitrates	0.010	7.8E-05	0.010
Nitrogen (ammonia)	0	2.7E-05	2.7E-05

Table 2-6

Waterborne Emissions for the Production of HDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Bromide		1.08	0.27	1.35
Boron		0.016	0.0040	0.020
Total Organic Carbon		7.4E-04	0.0059	0.0067
Cyanide		3.6E-07	9.1E-08	4.6E-07
Hardness		50.0	12.5	62.5
Total Alkalinity		0.40	0.10	0.50
Surfactants		0	0.0012	0.0012
Acetone		5.1E-05	1.3E-05	6.3E-05
Alkylated Benzenes		1.4E-04	1.6E-05	1.6E-04
Alkylated Fluorenes		8.2E-06	9.4E-07	9.1E-06
Alkylated Naphthalenes		2.3E-06	2.7E-07	2.6E-06
Alkylated Phenanthrenes		9.6E-07	1.1E-07	1.1E-06
Benzene		0.0085	0.0021	0.011
Cresols		3.0E-04	7.4E-05	3.8E-04
Cymene		5.0E-07	1.3E-07	6.3E-07
Dibenzofuran		9.6E-07	2.4E-07	1.2E-06
Dibenzothiophene		7.8E-07	1.9E-07	9.7E-07
2,4 dimethylphenol		1.4E-04	3.5E-05	1.8E-04
Ethylbenzene		0.0012	1.2E-04	0.0013
2-Hexanone		3.3E-05	8.3E-06	4.1E-05
Methyl Ethyl Ketone (MEK)		4.1E-07	1.0E-07	5.1E-07
1-methylfluorene		5.7E-07	1.4E-07	7.2E-07
2-methyl naphthalene		8.0E-05	2.0E-05	1.0E-04
4-methyl 2-pentanone		2.1E-05	5.3E-06	2.7E-05
Naphthalene		9.2E-05	2.3E-05	1.1E-04
Pentamethyl benzene		3.8E-07	9.5E-08	4.7E-07
Phenanthrene		1.0E-06	1.8E-07	1.2E-06
Toluene		0.0081	0.0020	0.010
Total Biphenyls		9.2E-06	1.1E-06	1.0E-05
Total Dibenzo-thiophenes		2.8E-08	3.2E-09	3.2E-08
Xylenes		0.0043	0.0011	0.0054
Radionuclides (unspecified)	(1)	0	5.5E-08	5.5E-08
Phosphorus		0	0	0
Lead 210		5.2E-13	0	5.2E-13
n-Decane		1.5E-04	0	1.5E-04
n-Docosane		5.4E-06	0	5.4E-06
n-Dodecane		2.8E-04	0	2.8E-04
n-Eicosane		7.7E-05	0	7.7E-05
n-Hexacosane		3.4E-06	0	3.4E-06
n-Hexadecane		3.0E-04	0	3.0E-04
n-Octadecane		7.5E-05	0	7.5E-05
n-Tetradecane		1.2E-04	0	1.2E-04
Styrene		6.7E-04	0	6.7E-04
Furans		0	0	0
Process solvents		0	0	0
Fluorine		4.2E-06	0	4.2E-06
Radium 226		1.8E-10	0	1.8E-10
Radium 228		9.3E-13	0	9.3E-13

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 4.48 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 3

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR LDPE RESIN

This chapter presents LCI results for the production of low-density polyethylene (LDPE) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of LDPE resin. Figure 3-1 presents the flow diagram for the production of LDPE resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix C of the Appendices (separate document).

Primary data was collected for olefins and LDPE resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

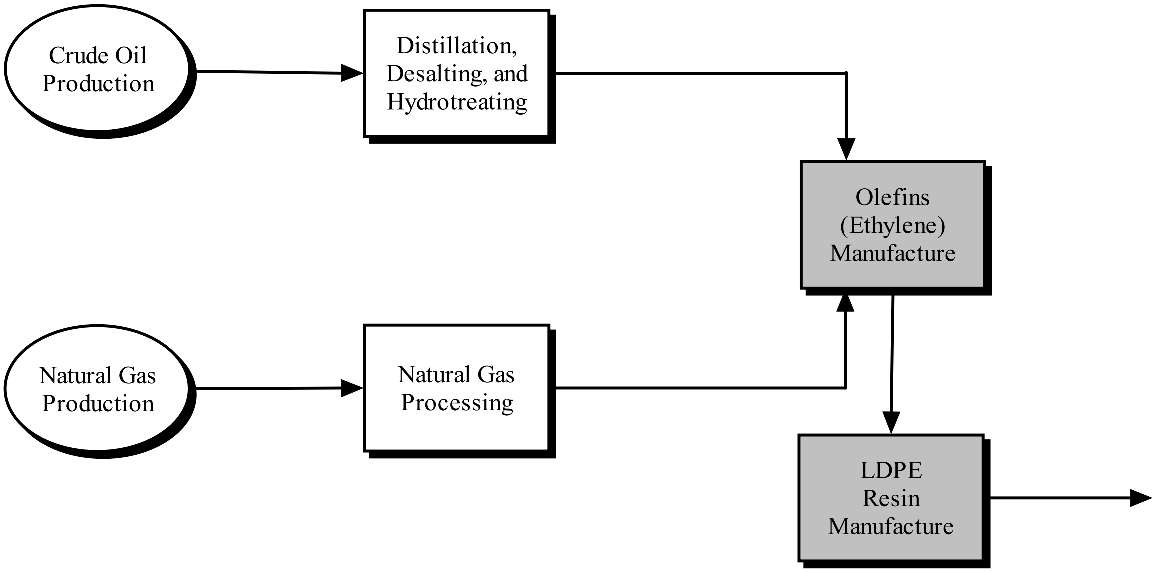

Figure 3-1. Flow diagram for the manufacture of virgin low-density polyethylene (LDPE) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

A weighted average using production amounts was calculated from the LDPE production data from seven plants collected from three leading producers in North America. As of 2003, there were 8 LDPE producers and 15 LDPE plants in the U.S. The captured production amount is approximately 30 percent of the 2003 production amount for LDPE production in the U.S. and Canada. Scrap resin (e.g. off-spec) and steam are produced as coproducts during this process. A mass basis was used to allocate the credit for scrap, while the energy amount for the steam was reported separately as recovered energy.

DESCRIPTION OF TABLES

The average gross energy required to produce LDPE resin is 38.1 million Btu per 1,000 pounds of resin or 88.6 GJ per 1,000 kilograms of resin. Tables 3-1 and 3-2 show the breakdown of energy requirements for the production of LDPE resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table C-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of LDPE resin. Natural gas and petroleum used as raw material inputs for the production of LDPE, reported as energy of material resource in Table 3-1, are included in the totals for natural gas and petroleum energy in Table 3-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 3-2 are used to generate purchased electricity along with the fossil fuels.

Table 3-1

Energy by Category for the Production of LDPE Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	13.7	32.0
Transportation	0.53	1.24
Energy of Material Resource	23.8	55.4
Total Energy	**38.1**	**88.6**
Energy Category (Percent)		
Process	36%	36%
Transportation	1%	1%
Energy of Material Resource	63%	63%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 3-2

Energy Profile for the Production of LDPE Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	31.8	73.9
Petroleum	5.04	11.7
Coal	1.09	2.54
Hydropower	0.049	0.11
Nuclear	0.26	0.61
Wood	0	0
Other	0.051	0.12
Recovered Energy (1)	-0.18	-0.43
Total Energy	**38.1**	**88.6**
Energy Source (Percent)		
Natural Gas	83%	83%
Petroleum	13%	13%
Coal	3%	3%
Hydropower	0%	0%
Nuclear	1%	1%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

---

(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 3-3 shows the weight of solid waste generated during the production of LDPE resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 3-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 3-3

Solid Wastes by Weight for the Production of LDPE Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	31.6	31.6
Incinerated	3.89	3.89
Waste-to-Energy	0.024	0.024
Fuel	45.0	45.0
Total	**80.6**	**80.6**
Weight Percent by Category		
Process		
Landfilled	39%	39%
Incinerated	5%	5%
Waste-to-Energy	0%	0%
Fuel	56%	56%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 3-5 provides a greenhouse gas (GHG) summary for the production of LDPE resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 3-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 3-4 are multiplied by their global warming potential and shown in Table 3-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 3-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 3-4

Atmospheric Emissions for the Production of LDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.10	0.19	0.30
Particulates (PM2.5)	0.0055	0	0.0055
Particulates (PM10)	0.13	0.10	0.23
Nitrogen Oxides	0.072	2.53	2.60
Hydrocarbons (unspecified)	1.40	0.048	1.44
VOC (unspecified)	0.75	0.35	1.10
TNMOC (unspecified)	0	0.0058	0.0058
Sulfur Dioxide	0	10.3	10.3
Sulfur Oxides	23.8	0.30	24.1
Carbon Monoxide	2.86	1.40	4.26
Fossil CO2	88.3	1,617	1,705
Non-Fossil CO2	0	5.14	5.14
Aldehydes (Formaldehyde)	0	0.0011	0.0011
Aldehydes (Acetaldehyde)	0	5.7E-05	5.7E-05
Aldehydes (Propionaldehyde)	0	9.7E-09	9.7E-09
Aldehydes (unspecified)	0.0090	0.0010	0.010
Organics (unspecified)	0.051	3.2E-04	0.051
Ammonia	0.0045	5.0E-04	0.0050
Ammonia Chloride	0	4.1E-05	4.1E-05
Methane	14.3	5.50	19.8
Kerosene	0	7.3E-05	7.3E-05
Chorine	1.0E-04	2.1E-05	1.2E-04
HCl	1.0E-06	0.065	0.065
HF	0	0.0079	0.0079
Metals (unspecified)	0	0.0011	0.0011
Mercaptan	0	5.2E-06	5.2E-06
Antimony	0	1.2E-06	1.2E-06
Arsenic	0	2.6E-05	2.6E-05
Beryllium	0	1.4E-06	1.4E-06
Cadmium	0	1.2E-05	1.2E-05
Chromium (VI)	0	4.2E-06	4.2E-06
Chromium	0	2.6E-05	2.6E-05
Cobalt	0	1.5E-05	1.5E-05
Copper	0	2.9E-07	2.9E-07
Lead	0	3.0E-05	3.0E-05
Magnesium	0	5.8E-04	5.8E-04
Manganese	0	7.6E-05	7.6E-05
Mercury	0	6.8E-06	6.8E-06
Nickel	0	1.6E-04	1.6E-04
Selenium	0	7.1E-05	7.1E-05
Zinc	0	2.0E-07	2.0E-07
Acetophenone	0	3.8E-10	3.8E-10
Acrolein	0	1.3E-04	1.3E-04
Nitrous Oxide	0.0010	0.025	0.026
Benzene	0.092	0.035	0.13
Benzyl Chloride	0	1.8E-08	1.8E-08
Bis(2-ethylhexyl) Phthalate (DEHP)	0	1.9E-09	1.9E-09
1,3 Butadiene	0	1.0E-06	1.0E-06
2-Chloroacetophenone	0	1.8E-10	1.8E-10
Chlorobenzene	0	5.6E-10	5.6E-10
2,4-Dinitrotoluene	0	7.2E-12	7.2E-12
Ethyl Chloride	0	1.1E-09	1.1E-09

Table 3-4

Atmospheric Emissions for the Production of LDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethylbenzene	0.011	0.0042	0.016
Ethylene Dibromide	0	3.1E-11	3.1E-11
Ethylene Dichloride	0	1.0E-09	1.0E-09
Hexane	0	1.7E-09	1.7E-09
Isophorone (C9H14O)	0	1.5E-08	1.5E-08
Methyl Bromide	0	4.1E-09	4.1E-09
Methyl Chloride	0	1.4E-08	1.4E-08
Methyl Ethyl Ketone	0	1.0E-08	1.0E-08
Methyl Hydrazine	0	4.3E-09	4.3E-09
Methyl Methacrylate	0	5.1E-10	5.1E-10
Methyl Tert Butyl Ether (MTBE)	0	8.9E-10	8.9E-10
Naphthalene	0	9.4E-06	9.4E-06
Propylene	0	6.9E-05	6.9E-05
Styrene	0	6.4E-10	6.4E-10
Toluene	0.14	0.054	0.20
Trichloroethane	2.1E-08	2.8E-09	2.4E-08
Vinyl Acetate	0	1.9E-10	1.9E-10
Xylenes	0.083	0.031	0.11
Bromoform	0	1.0E-09	1.0E-09
Chloroform	0	1.5E-09	1.5E-09
Carbon Disulfide	0	3.3E-09	3.3E-09
Dimethyl Sulfate	0	1.2E-09	1.2E-09
Cumene	0	1.4E-10	1.4E-10
Cyanide	0	6.4E-08	6.4E-08
Perchloroethylene	0	2.4E-06	2.4E-06
Methylene Chloride	0	3.2E-05	3.2E-05
Carbon Tetrachloride	2.6E-09	1.2E-06	1.2E-06
Phenols	0	8.9E-06	8.9E-06
Fluorides	0	4.5E-06	4.5E-06
Polyaromatic Hydrocarbons (total)	0	5.7E-06	5.7E-06
Biphenyl	0	9.0E-08	9.0E-08
Acenaphthene	0	2.7E-08	2.7E-08
Acenaphthylene	0	1.3E-08	1.3E-08
Anthracene	0	1.1E-08	1.1E-08
Benzo(a)anthracene	0	4.2E-09	4.2E-09
Benzo(a)pyrene	0	2.0E-09	2.0E-09
Benzo(b,j,k)fluroanthene	0	5.8E-09	5.8E-09
Benzo(g,h,i) perylene	0	1.4E-09	1.4E-09
Chrysene	0	5.3E-09	5.3E-09
Fluoranthene	0	3.8E-08	3.8E-08
Fluorene	0	4.8E-08	4.8E-08
Indeno(1,2,3-cd)pyrene	0	3.2E-09	3.2E-09
Naphthanlene	0	6.9E-07	6.9E-07
Phenanthrene	0	1.4E-07	1.4E-07
Pyrene	0	1.7E-08	1.7E-08
5-Methyl Chrysene	0	1.2E-09	1.2E-09
Dioxins (unspecified)	0	4.4E-08	4.4E-08
Furans (unspecified)	0	2.4E-10	2.4E-10
CFC12	0	2.7E-09	2.7E-09
Radionuclides (unspecified) (1)	0	0.0041	0.0041
HCFC-22	0.0010	0	0.0010
Hydrogen	0.0040	0	0.0040
Acid (unknown)	0.75	0	0.75

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 336,262 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 3-5

Greenhouse Gas Summary for the Production of LDPE Resin
(lb carbon dioxide equivalents per 1,000 lb LDPE or kg carbon dioxide equivalents per 1,000 kg LDPE)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,617	88.3	1,705
Methane	137	358	495
Nitrous oxide	7.42	0.30	7.72
Methyl bromide	2.0E-08	0	2.0E-08
Methyl chloride	2.2E-07	0	2.2E-07
Trichloroethane	3.9E-07	2.9E-06	3.3E-06
Chloroform	4.5E-08	0	4.5E-08
Methylene chloride	3.2E-04	0	3.2E-04
Carbon tetrachloride	0.0017	3.6E-06	0.0017
CFC-012	2.9E-05	0	2.9E-05
HCFC-22	0	1.81	1.81
Total	1,762	448	2,210

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 3-6

Waterborne Emissions for the Production of LDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0019	0.0019
Acid (benzoic)	0.0051	0.0017	0.0067
Acid (hexanoic)	0.0011	3.4E-04	0.0014
Dissolved Solids	224	72.8	296
Suspended Solids	4.86	1.22	6.08
BOD	0.89	0.32	1.21
COD	1.60	0.45	2.05
Phenol/Phenolic Compounds	0.0033	7.4E-04	0.0040
Sulfur	0	0.0043	0.0043
Sulfates	0.37	0.17	0.54
Sulfides	4.1E-05	4.3E-06	4.5E-05
Oil	0.10	0.032	0.13
Hydrocarbons	0	3.3E-04	3.3E-04
Ammonia	0.067	0.025	0.092
Ammonium	0	3.3E-05	3.3E-05
Aluminum	0.15	0.036	0.18
Antimony	9.2E-05	2.2E-05	1.1E-04
Arsenic	0.0012	3.7E-04	0.0015
Barium	2.17	0.54	2.71
Beryllium	5.5E-05	1.7E-05	7.1E-05
Cadmium	1.7E-04	5.4E-05	2.2E-04
Chromium (unspecified)	0.0041	0.0010	0.0051
Chromium (hexavalent)	7.9E-06	0	7.9E-06
Cobalt	1.1E-04	3.6E-05	1.5E-04
Copper	8.2E-04	2.5E-04	0.0011
Iron	0.38	0.11	0.49
Lead	0.0018	5.4E-04	0.0023
Lithium	4.54	1.66	6.21
Magnesium	3.15	1.03	4.18
Manganese	0.0051	0.0024	0.0074
Mercury	1.6E-06	4.0E-07	2.0E-06
Molybdenum	1.2E-04	3.8E-05	1.5E-04
Nickel	9.6E-04	2.9E-04	0.0013
Selenium	1.8E-05	1.6E-05	3.4E-05
Silver	0.011	0.0034	0.014
Sodium	51.1	16.6	67.7
Strontium	0.27	0.089	0.36
Thallium	1.9E-05	4.7E-06	2.4E-05
Tin	6.4E-04	1.9E-04	8.3E-04
Titanium	0.0014	3.4E-04	0.0017
Vanadium	1.4E-04	4.4E-05	1.8E-04
Yttrium	3.4E-05	1.1E-05	4.5E-05
Zinc	0.0037	9.5E-04	0.0047
Chlorides (unspecified)	181	59.0	240
Chlorides (methyl chloride)	2.0E-07	6.6E-08	2.7E-07
Calcium	16.1	5.25	21.4
Fluorides	0	5.3E-04	5.3E-04
Nitrates	0	8.1E-05	8.1E-05
Nitrogen (ammonia)	0	2.8E-05	2.8E-05

Table 3-6

Waterborne Emissions for the Production of LDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Bromide	1.07	0.35	1.42
Boron	0.016	0.0051	0.021
Total Organic Carbon	0.0010	0.0078	0.0088
Cyanide	3.6E-07	1.2E-07	4.8E-07
Hardness	49.7	16.2	65.8
Total Alkalinity	0.40	0.13	0.53
Surfactants	0	0.0016	0.0016
Acetone	5.0E-05	1.6E-05	6.7E-05
Alkylated Benzenes	8.0E-05	1.9E-05	1.0E-04
Alkylated Fluorenes	4.6E-06	1.1E-06	5.8E-06
Alkylated Naphthalenes	1.3E-06	3.2E-07	1.6E-06
Alkylated Phenanthrenes	5.5E-07	1.3E-07	6.8E-07
Benzene	0.0084	0.0027	0.011
Cresols	3.0E-04	9.5E-05	4.0E-04
Cymene	5.0E-07	1.6E-07	6.6E-07
Dibenzofuran	9.5E-07	3.1E-07	1.3E-06
Dibenzothiophene	7.7E-07	2.5E-07	1.0E-06
2,4 dimethylphenol	1.4E-04	4.6E-05	1.9E-04
Ethylbenzene	4.8E-04	1.5E-04	6.4E-04
2-Hexanone	3.3E-05	1.1E-05	4.3E-05
Methyl Ethyl Ketone (MEK)	4.0E-07	1.3E-07	5.4E-07
1-methylfluorene	5.7E-07	1.9E-07	7.6E-07
2-methyl naphthalene	7.9E-05	2.6E-05	1.1E-04
4-methyl 2-pentanone	2.1E-05	6.9E-06	2.8E-05
Naphthalene	9.1E-05	3.0E-05	1.2E-04
Pentamethyl benzene	3.8E-07	1.2E-07	5.0E-07
Phenanthrene	7.7E-07	2.2E-07	9.9E-07
Toluene	0.0081	0.0026	0.011
Total Biphenyls	5.2E-06	1.2E-06	6.4E-06
Total Dibenzo-thiophenes	1.6E-08	3.9E-09	2.0E-08
Xylenes	0.0043	0.0014	0.0057
Radionuclides (unspecified) (1)	0	5.8E-08	5.8E-08
Phosphorus	1.0E-04	0	1.0E-04
Lead 210	5.2E-13	0	5.2E-13
n-Decane	1.5E-04	0	1.5E-04
n-Docosane	5.4E-06	0	5.4E-06
n-Dodecane	2.8E-04	0	2.8E-04
n-Eicosane	7.6E-05	0	7.6E-05
n-Hexacosane	3.3E-06	0	3.3E-06
n-Hexadecane	3.0E-04	0	3.0E-04
n-Octadecane	7.5E-05	0	7.5E-05
n-Tetradecane	1.2E-04	0	1.2E-04
Styrene	1.0E-06	0	1.0E-06
Fluorine	2.6E-06	0	2.6E-06
Radium 226	1.8E-10	0	1.8E-10
Radium 228	9.3E-13	0	9.3E-13
Isopropyl alcohol	1.0E-04	0	1.0E-04
CFC-011	1.0E-04	0	1.0E-04

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 4.70 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 4

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR LLDPE RESIN

This chapter presents LCI results for the production of linear low-density polyethylene (LLDPE) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of LLDPE resin. Figure 4-1 presents the flow diagram for the production of LLDPE resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix D of the Appendices (separate document).

Primary data was collected for olefins and LLDPE resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

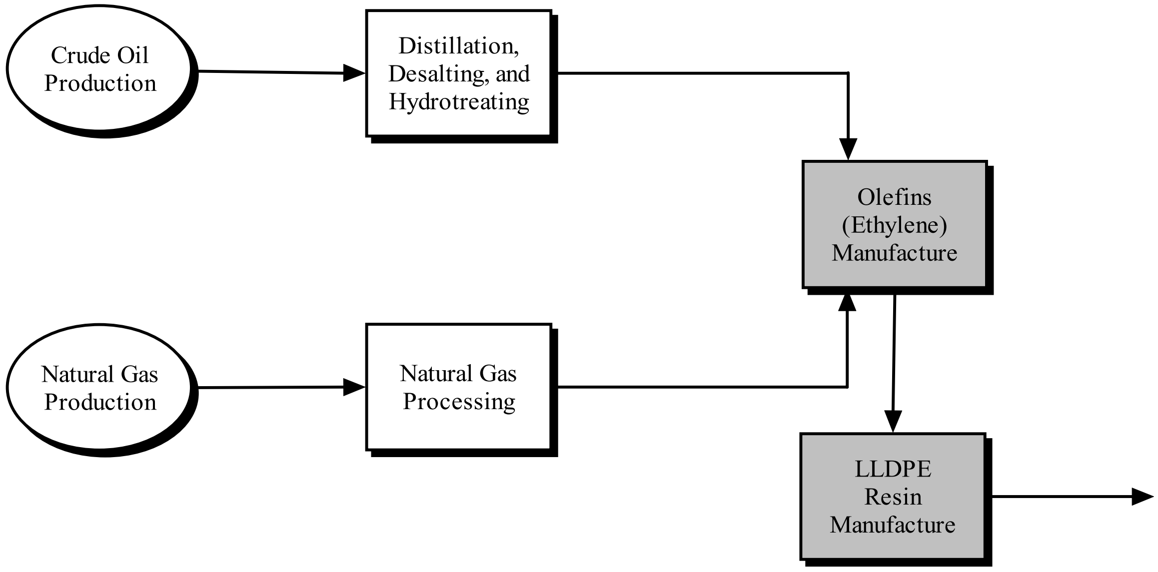

Figure 4-1. Flow diagram for the manufacture of virgin linear low-density (LLDPE) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

A weighted average using production amounts was calculated from the LLDPE production data from five plants collected from three leading producers in North America. As of 2003, there were 11 LLDPE producers and 24 LLDPE plants in the U.S. The captured production amount is approximately 45 percent of the 2003 production amount for LLDPE production in the U.S. and Canada. Scrap resin (e.g. off-spec) is produced as a coproduct during this process. A mass basis was used to allocate the credit for each coproduct.

DESCRIPTION OF TABLES

The average gross energy required to produce LLDPE resin is 35.7 million Btu per 1,000 pounds of resin or 83 GJ per 1,000 kilograms of resin. Tables 4-1 and 4-2 show the breakdown of energy requirements for the production of LLDPE resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table D-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of LLDPE resin. Natural gas and petroleum used as raw material inputs for the production of LLDPE, reported as energy of material resource in Table 4-1, are included in the totals for natural gas and petroleum energy in Table 4-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 4-2 are used to generate purchased electricity along with the fossil fuels.

Table 4-1

Energy by Category for the Production of LLDPE Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	11.5	26.8
Transportation	0.53	1.23
Energy of Material Resource	23.6	54.9
Total Energy	**35.7**	**83.0**
Energy Category (Percent)		
Process	32%	32%
Transportation	1%	1%
Energy of Material Resource	66%	66%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 4-2

Energy Profile for the Production of LLDPE Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	29.5	68.5
Petroleum	5.01	11.7
Coal	0.90	2.10
Hydropower	0.040	0.094
Nuclear	0.22	0.50
Wood	0	0
Other	0.042	0.097
Recovered Energy (1)	-0.012	-0.028
Total Energy	**35.7**	**83.0**
Energy Source (Percent)		
Natural Gas	83%	83%
Petroleum	14%	14%
Coal	3%	3%
Hydropower	0%	0%
Nuclear	1%	1%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

---

(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 4-3 shows the weight of solid waste generated during the production of LLDPE resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 4-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 4-3

Solid Wastes by Weight for the Production of LLDPE Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	31.6	31.6
Incinerated	3.75	3.75
Waste-to-Energy	0.11	0.11
Fuel	36.6	36.6
Total	**72.1**	**72.1**
Weight Percent by Category		
Process		
Landfilled	44%	44%
Incinerated	5%	5%
Waste-to-Energy	0%	0%
Fuel	51%	51%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 4-5 provides a greenhouse gas (GHG) summary for the production of LLDPE resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 4-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 4-4 are multiplied by their global warming potential and shown in Table 4-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 4-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 4-4

Atmospheric Emissions for the Production of LLDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.069	0.16	0.23
Particulates (PM2.5)	0.010	0	0.010
Particulates (PM10)	0.11	0.081	0.19
Nitrogen Oxides	0.10	2.21	2.31
Hydrocarbons (unspecified)	0.88	0.049	0.93
VOC (unspecified)	0.74	0.26	1.00
TNMOC (unspecified)	0	0.0048	0.0048
Sulfur Dioxide	0	7.78	7.78
Sulfur Oxides	23.6	0.30	23.9
Carbon Monoxide	2.92	1.22	4.14
Fossil CO2	128	1,327	1,455
Non-Fossil CO2	0	4.24	4.24
Aldehydes (Formaldehyde)	0	8.9E-04	8.9E-04
Aldehydes (Acetaldehyde)	0	5.1E-05	5.1E-05
Aldehydes (Propionaldehyde)	0	8.0E-09	8.0E-09
Aldehydes (unspecified)	0.0089	0.0010	0.010
Organics (unspecified)	0.011	2.7E-04	0.011
Ammonia	0.0045	5.1E-04	0.0050
Ammonia Chloride	0	3.4E-05	3.4E-05
Methane	14.2	4.13	18.3
Kerosene	0	6.1E-05	6.1E-05
Chorine	1.0E-04	1.7E-05	1.2E-04
HCl	1.0E-06	0.054	0.054
HF	0	0.0066	0.0066
Metals (unspecified)	0	9.3E-04	9.3E-04
Mercaptan	0	4.3E-06	4.3E-06
Antimony	0	9.6E-07	9.6E-07
Arsenic	0	2.2E-05	2.2E-05
Beryllium	0	1.2E-06	1.2E-06
Cadmium	0	9.0E-06	9.0E-06
Chromium (VI)	0	3.5E-06	3.5E-06
Chromium	0	2.1E-05	2.1E-05
Cobalt	0	1.5E-05	1.5E-05
Copper	0	2.7E-07	2.7E-07
Lead	0	2.5E-05	2.5E-05
Magnesium	0	4.8E-04	4.8E-04
Manganese	0	6.4E-05	6.4E-05
Mercury	0	5.5E-06	5.5E-06
Nickel	0	1.7E-04	1.7E-04
Selenium	0	5.9E-05	5.9E-05
Zinc	0	1.8E-07	1.8E-07
Acetophenone	0	3.2E-10	3.2E-10
Acrolein	0	1.0E-04	1.0E-04
Nitrous Oxide	0.017	0.019	0.036
Benzene	0.091	0.026	0.12
Benzyl Chloride	0	1.5E-08	1.5E-08
Bis(2-ethylhexyl) Phthalate (DEHP)	0	1.5E-09	1.5E-09
1,3 Butadiene	0	9.8E-07	9.8E-07
2-Chloroacetophenone	0	1.5E-10	1.5E-10
Chlorobenzene	0	4.7E-10	4.7E-10
2,4-Dinitrotoluene	0	5.9E-12	5.9E-12
Ethyl Chloride	0	8.9E-10	8.9E-10
Ethylbenzene	0.011	0.0031	0.014

Table 4-4

Atmospheric Emissions for the Production of LLDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethylene Dibromide	0	2.5E-11	2.5E-11
Ethylene Dichloride	0	8.5E-10	8.5E-10
Hexane	0	1.4E-09	1.4E-09
Isophorone (C9H14O)	0	1.2E-08	1.2E-08
Methyl Bromide	0	3.4E-09	3.4E-09
Methyl Chloride	0	1.1E-08	1.1E-08
Methyl Ethyl Ketone	0	8.2E-09	8.2E-09
Methyl Hydrazine	0	3.6E-09	3.6E-09
Methyl Methacrylate	0	4.2E-10	4.2E-10
Methyl Tert Butyl Ether (MTBE)	0	7.4E-10	7.4E-10
Naphthalene	0	7.8E-06	7.8E-06
Propylene	0	6.5E-05	6.5E-05
Styrene	0	5.3E-10	5.3E-10
Toluene	0.14	0.040	0.18
Trichloroethane	2.1E-08	2.7E-09	2.3E-08
Vinyl Acetate	0	1.6E-10	1.6E-10
Xylenes	0.083	0.023	0.11
Bromoform	0	8.2E-10	8.2E-10
Chloroform	0	1.2E-09	1.2E-09
Carbon Disulfide	0	2.7E-09	2.7E-09
Dimethyl Sulfate	0	1.0E-09	1.0E-09
Cumene	0	1.1E-10	1.1E-10
Cyanide	0	5.3E-08	5.3E-08
Perchloroethylene	0	2.0E-06	2.0E-06
Methylene Chloride	0	2.9E-05	2.9E-05
Carbon Tetrachloride	2.5E-09	9.8E-07	9.8E-07
Phenols	0	9.0E-06	9.0E-06
Fluorides	0	3.7E-06	3.7E-06
Polyaromatic Hydrocarbons (total)	0	5.3E-06	5.3E-06
Biphenyl	0	7.5E-08	7.5E-08
Acenaphthene	0	2.2E-08	2.2E-08
Acenaphthylene	0	1.1E-08	1.1E-08
Anthracene	0	9.2E-09	9.2E-09
Benzo(a)anthracene	0	3.5E-09	3.5E-09
Benzo(a)pyrene	0	1.7E-09	1.7E-09
Benzo(b,j,k)fluroanthene	0	4.8E-09	4.8E-09
Benzo(g,h,i) perylene	0	1.2E-09	1.2E-09
Chrysene	0	4.4E-09	4.4E-09
Fluoranthene	0	3.1E-08	3.1E-08
Fluorene	0	4.0E-08	4.0E-08
Indeno(1,2,3-cd)pyrene	0	2.7E-09	2.7E-09
Naphthanlene	0	5.7E-07	5.7E-07
Phenanthrene	0	1.2E-07	1.2E-07
Pyrene	0	1.4E-08	1.4E-08
5-Methyl Chrysene	0	9.6E-10	9.6E-10
Dioxins (unspecified)	0	3.6E-08	3.6E-08
Furans (unspecified)	0.0010	2.0E-10	0.0010
CFC12	0	2.7E-09	2.7E-09
Radionuclides (unspecified) (1)	0	0.0034	0.0034
HCFC-22	1.1E-05	0	1.1E-05
Hydrogen	0.0039	0	0.0039
Acid (unknown)	0.74	0	0.74
Aluminum Compounds	1.0E-04	0	1.0E-04

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 278,293 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 4-5

Greenhouse Gas Summary for the Production of LLDPE Resin
lb carbon dioxide equivalents per 1,000 lb LLDPE or kg carbon dioxide equivalents per 1,000 kg LLDPE

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,327	128	1,455
Methane	103	355	458
Nitrous oxide	5.74	5.07	10.8
Methyl bromide	1.7E-08	0	1.7E-08
Methyl chloride	1.8E-07	0	1.8E-07
Trichloroethane	3.8E-07	2.9E-06	3.3E-06
Chloroform	3.7E-08	0	3.7E-08
Methylene chloride	2.9E-04	0	2.9E-04
Carbon tetrachloride	0.0014	3.6E-06	0.0014
CFC-012	3.0E-05	0	3.0E-05
HCFC-22	0	0.020	0.020
Total	1,436	488	1,924

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 4-6

Waterborne Emissions for the Production of LLDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0014	0.0014
Acid (benzoic)	0.0050	0.0012	0.0063
Acid (hexanoic)	0.0010	2.6E-04	0.0013
Dissolved Solids	222	54.9	277
Suspended Solids	4.84	0.97	5.81
BOD	0.87	0.24	1.12
COD	1.50	0.34	1.83
Phenol/Phenolic Compounds	0.0033	5.6E-04	0.0038
Sulfur	0	0.0033	0.0033
Sulfates	0.37	0.13	0.50
Sulfides	4.0E-05	4.4E-06	4.5E-05
Oil	0.10	0.024	0.13
Hydrocarbons	0	2.5E-04	2.5E-04
Ammonia	0.067	0.019	0.085
Ammonium	0	2.7E-05	2.7E-05
Aluminum	0.15	0.029	0.18
Antimony	9.1E-05	1.8E-05	1.1E-04
Arsenic	0.0011	2.8E-04	0.0014
Barium	2.15	0.43	2.58
Beryllium	5.4E-05	1.3E-05	6.7E-05
Cadmium	1.7E-04	4.1E-05	2.1E-04
Chromium (unspecified)	0.0041	8.0E-04	0.0049
Chromium (hexavalent)	7.8E-06	0	7.8E-06
Cobalt	1.1E-04	2.7E-05	1.4E-04
Copper	8.2E-04	1.9E-04	0.0010
Iron	0.38	0.083	0.46
Lead	0.0018	4.2E-04	0.0022
Lithium	4.50	1.23	5.73
Magnesium	3.12	0.77	3.90
Manganese	0.0050	0.0018	0.0069
Mercury	1.6E-06	3.2E-07	1.9E-06
Molybdenum	1.1E-04	2.8E-05	1.4E-04
Nickel	9.5E-04	2.2E-04	0.0012
Selenium	1.8E-05	1.3E-05	3.1E-05
Silver	0.010	0.0026	0.013
Sodium	50.7	12.6	63.2
Strontium	0.27	0.067	0.34
Thallium	1.9E-05	3.7E-06	2.3E-05
Tin	6.4E-04	1.5E-04	7.8E-04
Titanium	0.0014	2.7E-04	0.0017
Vanadium	1.4E-04	3.3E-05	1.7E-04
Yttrium	3.4E-05	8.3E-06	4.2E-05
Zinc	0.0037	7.5E-04	0.0044
Chlorides (unspecified)	180	44.5	224
Chlorides (methyl chloride)	2.0E-07	5.0E-08	2.5E-07
Calcium	16.0	3.96	19.9
Fluorides	0	4.4E-04	4.4E-04
Nitrates	0	6.7E-05	6.7E-05
Nitrogen (ammonia)	0	2.4E-05	2.4E-05

Table 4-6

Waterborne Emissions for the Production of LLDPE Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Bromide	1.07	0.26	1.33
Boron	0.016	0.0039	0.019
Total Organic Carbon	0.0010	0.0058	0.0068
Cyanide	3.6E-07	8.9E-08	4.5E-07
Hardness	49.2	12.2	61.4
Total Alkalinity	0.40	0.10	0.50
Surfactants	0	0.0012	0.0012
Acetone	5.0E-05	1.2E-05	6.2E-05
Alkylated Benzenes	8.0E-05	1.5E-05	9.5E-05
Alkylated Fluorenes	4.6E-06	8.9E-07	5.5E-06
Alkylated Naphthalenes	1.3E-06	2.5E-07	1.6E-06
Alkylated Phenanthrenes	5.4E-07	1.0E-07	6.5E-07
Benzene	0.0084	0.0021	0.010
Cresols	3.0E-04	7.2E-05	3.7E-04
Cymene	5.0E-07	1.2E-07	6.2E-07
Dibenzofuran	9.5E-07	2.3E-07	1.2E-06
Dibenzothiophene	7.7E-07	1.9E-07	9.6E-07
2,4 dimethylphenol	1.4E-04	3.5E-05	1.7E-04
Ethylbenzene	4.8E-04	1.2E-04	6.0E-04
2-Hexanone	3.2E-05	8.0E-06	4.1E-05
Methyl Ethyl Ketone (MEK)	4.0E-07	9.9E-08	5.0E-07
1-methylfluorene	5.7E-07	1.4E-07	7.1E-07
2-methyl naphthalene	7.9E-05	2.0E-05	9.8E-05
4-methyl 2-pentanone	2.1E-05	5.2E-06	2.6E-05
Naphthalene	9.0E-05	2.2E-05	1.1E-04
Pentamethyl benzene	3.7E-07	9.2E-08	4.7E-07
Phenanthrene	7.6E-07	1.7E-07	9.3E-07
Toluene	0.0080	0.0020	0.010
Total Biphenyls	5.1E-06	1.0E-06	6.1E-06
Total Dibenzo-thiophenes	1.6E-08	3.1E-09	1.9E-08
Xylenes	0.0042	0.0010	0.0053
Radionuclides (unspecified) (1)	0	4.8E-08	4.8E-08
Phosphorus	1.0E-04	0	1.0E-04
Lead 210	5.2E-13	0	5.2E-13
n-Decane	1.4E-04	0	1.4E-04
n-Docosane	5.3E-06	0	5.3E-06
n-Dodecane	2.8E-04	0	2.8E-04
n-Eicosane	7.6E-05	0	7.6E-05
n-Hexacosane	3.3E-06	0	3.3E-06
n-Hexadecane	3.0E-04	0	3.0E-04
n-Octadecane	7.4E-05	0	7.4E-05
n-Tetradecane	1.2E-04	0	1.2E-04
Styrene	1.0E-06	0	1.0E-06
Process solvents	1.0E-04	0	1.0E-04
Fluorine	2.6E-06	0	2.6E-06
Radium 226	1.8E-10	0	1.8E-10
Radium 228	9.2E-13	0	9.2E-13
Cyclohexane	1.0E-04	0	1.0E-04
Butene	1.0E-04	0	1.0E-04

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 3.89 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 5

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR PP RESIN

This chapter presents LCI results for the production of polypropylene (PP) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of PP resin. Figure 5-1 presents the flow diagram for the production of PP resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix E of the Appendices (separate document).

Primary data was collected for olefins and PP resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 8 producers and at least 16 plants producing polymer-grade propylene in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

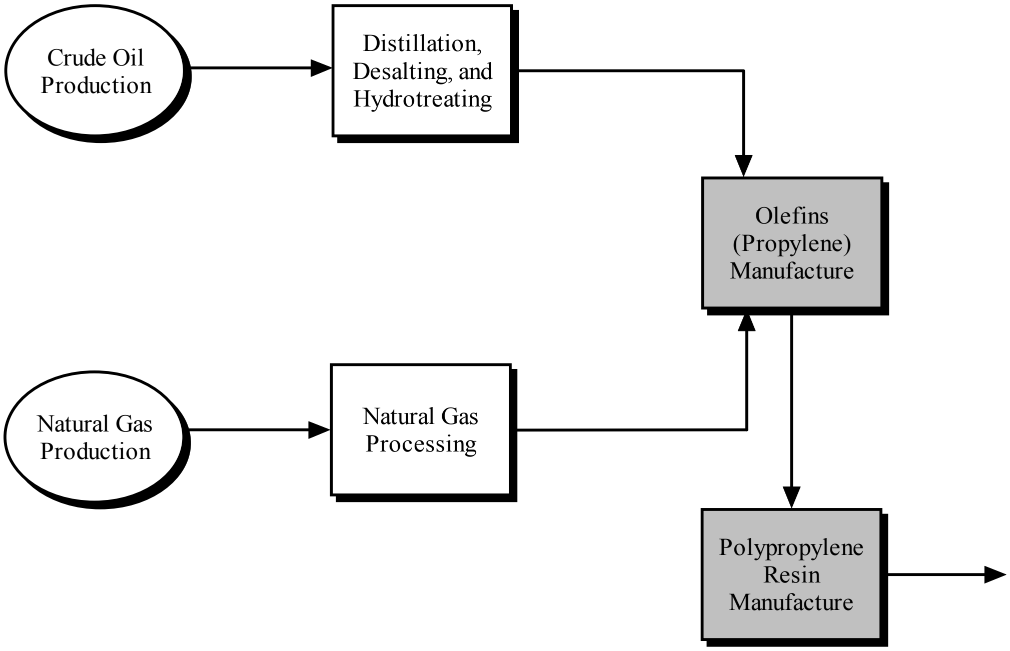

Figure 5-1. Flow diagram for the manufacture of virgin polypropylene (PP) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

A weighted average using production amounts was calculated from the PP production data from four plants collected from three leading producers in North America. As of 2003, there were 11 PP producers and 20 PP plants in the U.S. The captured production amount is more than 20 percent of the 2003 production amount for PP production in the U.S. and Canada. Scrap resin (e.g. off-spec) and some alkane/alkene streams are produced as a coproduct during this process. A mass basis was used to allocate the credit for each coproduct.

DESCRIPTION OF TABLES

The average gross energy required to produce PP resin is 34.9 million Btu per 1,000 pounds of resin or 81.3 GJ per 1,000 kilograms of resin. Tables 5-1 and 5-2 show the breakdown of energy requirements for the production of PP resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table E-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of PP resin. Natural gas and petroleum uses as raw material inputs for the production of PP, reported as energy of material resource in Table 5-1, are included in the totals for natural gas and petroleum energy in Table 5-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 5-2 are used to generate purchased electricity along with the fossil fuels.

Table 5-1

Energy by Category for the Production of PP Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	11.8	27.3
Transportation	0.58	1.35
Energy of Material Resource	22.6	52.6
Total Energy	**34.9**	**81.3**
Energy Category (Percent)		
Process	34%	34%
Transportation	2%	2%
Energy of Material Resource	65%	65%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 5-2

Energy Profile for the Production of PP Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	23.5	54.8
Petroleum	9.87	23.0
Coal	1.14	2.66
Hydropower	0.051	0.12
Nuclear	0.27	0.63
Wood	0	0
Other	0.053	0.12
Recovered Energy (1)	-0.0023	-0.0053
Total Energy	**34.9**	**81.3**
Energy Source (Percent)		
Natural Gas	67%	67%
Petroleum	28%	28%
Coal	3%	3%
Hydropower	0%	0%
Nuclear	1%	1%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 5-3 shows the weight of solid waste generated during the production of PP resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 5-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 5-3

Solid Wastes by Weight for the Production of PP Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	33.6	33.6
Incinerated	7.63	7.63
Waste-to-Energy	0.0044	0.0044
Fuel	43.4	43.4
Total	**84.7**	**84.7**
Weight Percent by Category		
Process		
Landfilled	40%	40%
Incinerated	9%	9%
Waste-to-Energy	0%	0%
Fuel	51%	51%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 5-5 provides a greenhouse gas (GHG) summary for the production of PP resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 5-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 5-4 are multiplied by their global warming potential and shown in Table 5-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 5-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 5-4

Atmospheric Emissions for the Production of PP Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.13	0.20	0.34
Particulates (PM2.5)	1.0E-05	0	1.0E-05
Particulates (PM10)	0.10	0.092	0.19
Nitrogen Oxides	0.15	2.74	2.90
Hydrocarbons (unspecified)	1.12	0.077	1.20
VOC (unspecified)	0.59	0.24	0.83
TNMOC (unspecified)	0	0.0061	0.0061
Sulfur Dioxide	0	6.94	6.94
Sulfur Oxides	19.4	0.45	19.9
Carbon Monoxide	5.79	1.33	7.13
Fossil CO2	81.3	1,381	1,463
Non-Fossil CO2	0	5.36	5.36
Aldehydes (Formaldehyde)	0	8.2E-04	8.2E-04
Aldehydes (Acetaldehyde)	0	5.0E-05	5.0E-05
Aldehydes (Propionaldehyde)	0	1.0E-08	1.0E-08
Aldehydes (unspecified)	0.018	0.0016	0.020
Organics (unspecified)	0.011	3.4E-04	0.011
Ammonia	0.0090	8.0E-04	0.0098
Ammonia Chloride	0	4.3E-05	4.3E-05
Methane	12.3	3.59	15.9
Kerosene	0	7.7E-05	7.7E-05
Chorine	1.0E-04	2.2E-05	1.2E-04
HCl	1.0E-06	0.069	0.069
HF	0	0.0083	0.0083
Metals (unspecified)	0	0.0012	0.0012
Mercaptan	0	5.4E-06	5.4E-06
Antimony	0	1.2E-06	1.2E-06
Arsenic	0	2.8E-05	2.8E-05
Beryllium	0	1.5E-06	1.5E-06
Cadmium	0	9.0E-06	9.0E-06
Chromium (VI)	0	4.4E-06	4.4E-06
Chromium	0	2.4E-05	2.4E-05
Cobalt	0	2.2E-05	2.2E-05
Copper	0	2.8E-07	2.8E-07
Lead	1.0E-12	3.2E-05	3.2E-05
Magnesium	0	6.1E-04	6.1E-04
Manganese	0	8.1E-05	8.1E-05
Mercury	0	6.3E-06	6.3E-06
Nickel	0	2.5E-04	2.5E-04
Selenium	0	7.5E-05	7.5E-05
Zinc	1.0E-06	1.9E-07	1.2E-06
Acetophenone	0	4.0E-10	4.0E-10
Acrolein	0	1.3E-04	1.3E-04
Nitrous Oxide	0.0045	0.019	0.023
Benzene	0.073	0.021	0.094
Benzyl Chloride	0	1.9E-08	1.9E-08
Bis(2-ethylhexyl) Phthalate (DEHP)	0	2.0E-09	2.0E-09
1,3 Butadiene	0	8.5E-07	8.5E-07
2-Chloroacetophenone	0	1.9E-10	1.9E-10
Chlorobenzene	0	5.9E-10	5.9E-10
2,4-Dinitrotoluene	0	7.5E-12	7.5E-12
Ethyl Chloride	0	1.1E-09	1.1E-09
Ethylbenzene	0.0091	0.0025	0.012

Table 5-4

Atmospheric Emissions for the Production of PP Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethylene Dibromide	0	3.2E-11	3.2E-11
Ethylene Dichloride	0	1.1E-09	1.1E-09
Hexane	0	1.8E-09	1.8E-09
Isophorone ($C_9H_{14}O$)	0	1.6E-08	1.6E-08
Methyl Bromide	0	4.3E-09	4.3E-09
Methyl Chloride	0	1.4E-08	1.4E-08
Methyl Ethyl Ketone	0	1.0E-08	1.0E-08
Methyl Hydrazine	0	4.5E-09	4.5E-09
Methyl Methacrylate	0	5.3E-10	5.3E-10
Methyl Tert Butyl Ether (MTBE)	0	9.4E-10	9.4E-10
Naphthalene	0	8.8E-06	8.8E-06
Propylene	0	5.6E-05	5.6E-05
Styrene	0	6.7E-10	6.7E-10
Toluene	0.11	0.033	0.15
Trichloroethane	4.1E-08	4.2E-09	4.6E-08
Vinyl Acetate	0	2.0E-10	2.0E-10
Xylenes	0.066	0.019	0.085
Bromoform	0	1.0E-09	1.0E-09
Chloroform	0	1.6E-09	1.6E-09
Carbon Disulfide	0	3.5E-09	3.5E-09
Dimethyl Sulfate	0	1.3E-09	1.3E-09
Cumene	0	1.4E-10	1.4E-10
Cyanide	0	6.7E-08	6.7E-08
Perchloroethylene	0	2.6E-06	2.6E-06
Methylene Chloride	0	3.9E-05	3.9E-05
Carbon Tetrachloride	5.1E-09	1.2E-06	1.2E-06
Phenols	0	1.3E-05	1.3E-05
Fluorides	0	4.7E-06	4.7E-06
Polyaromatic Hydrocarbons (total)	0	4.9E-06	4.9E-06
Biphenyl	0	9.4E-08	9.4E-08
Acenaphthene	0	2.8E-08	2.8E-08
Acenaphthylene	0	1.4E-08	1.4E-08
Anthracene	0	1.2E-08	1.2E-08
Benzo(a)anthracene	0	4.4E-09	4.4E-09
Benzo(a)pyrene	0	2.1E-09	2.1E-09
Benzo(b,j,k)fluroanthene	0	6.1E-09	6.1E-09
Benzo(g,h,i) perylene	0	1.5E-09	1.5E-09
Chrysene	0	5.5E-09	5.5E-09
Fluoranthene	0	3.9E-08	3.9E-08
Fluorene	0	5.0E-08	5.0E-08
Indeno(1,2,3-cd)pyrene	0	3.4E-09	3.4E-09
Naphthanlene	0	7.2E-07	7.2E-07
Phenanthrene	0	1.5E-07	1.5E-07
Pyrene	0	1.8E-08	1.8E-08
5-Methyl Chrysene	0	1.2E-09	1.2E-09
Dioxins (unspecified)	0	4.6E-08	4.6E-08
Furans (unspecified)	0	2.5E-10	2.5E-10
CFC12	0	4.3E-09	4.3E-09
Radionuclides (unspecified) (1)	0	0.0043	0.0043
HCFC-22	1.0E-06	0	1.0E-06
Hydrogen	0.0052	0	0.0052
Acid (unknown)	0.59	0	0.59

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 351,997 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 5-5

Greenhouse Gas Summary for the Production of PP Resin
(lb carbon dioxide equivalents per 1,000 lb PP or kg carbon dioxide equivalents per 1,000 kg PP)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,381	81.3	1,463
Methane	89.8	309	399
Nitrous oxide	5.59	1.34	6.93
Methyl bromide	2.1E-08	0	2.1E-08
Methyl chloride	2.3E-07	0	2.3E-07
Trichloroethane	5.8E-07	5.8E-06	6.4E-06
Chloroform	4.7E-08	0	4.7E-08
Methylene chloride	3.9E-04	0	3.9E-04
Carbon tetrachloride	0.0017	7.2E-06	0.0017
CFC-012	4.7E-05	0	4.7E-05
HCFC-22	0	0.0018	0.0018
Total	1,477	391	1,868

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 5-6

Waterborne Emissions for the Production of PP Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0011	0.0011
Acid (benzoic)	0.0050	0.0011	0.0061
Acid (hexanoic)	0.0010	2.3E-04	0.0013
Dissolved Solids	219	47.7	267
Suspended Solids	6.47	0.97	7.44
BOD	0.87	0.22	1.09
COD	1.53	0.28	1.81
Phenol/Phenolic Compounds	0.0033	4.9E-04	0.0038
Sulfur	0	0.0028	0.0028
Sulfates	0.36	0.13	0.49
Sulfides	8.1E-05	7.0E-06	8.8E-05
Oil	0.10	0.021	0.12
Hydrocarbons	0	2.2E-04	2.2E-04
Ammonia	0.071	0.017	0.088
Ammonium	0	3.4E-05	3.4E-05
Aluminum	0.20	0.030	0.23
Antimony	1.3E-04	1.8E-05	1.4E-04
Arsenic	0.0012	2.5E-04	0.0014
Barium	2.88	0.43	3.31
Beryllium	5.8E-05	1.1E-05	6.9E-05
Cadmium	1.7E-04	3.6E-05	2.1E-04
Chromium (unspecified)	0.0057	8.1E-04	0.0065
Chromium (hexavalent)	1.6E-05	0	1.6E-05
Cobalt	1.1E-04	2.4E-05	1.3E-04
Copper	9.2E-04	1.8E-04	0.0011
Iron	0.47	0.080	0.55
Lead	0.0020	3.8E-04	0.0024
Lithium	3.60	1.01	4.60
Magnesium	3.09	0.67	3.76
Manganese	0.0050	0.0018	0.0068
Mercury	2.2E-06	3.3E-07	2.5E-06
Molybdenum	1.1E-04	2.5E-05	1.4E-04
Nickel	0.0010	2.0E-04	0.0012
Selenium	2.4E-05	1.6E-05	4.0E-05
Silver	0.010	0.0022	0.013
Sodium	50.1	10.9	61.0
Strontium	0.27	0.058	0.33
Thallium	2.6E-05	3.8E-06	3.0E-05
Tin	7.2E-04	1.3E-04	8.5E-04
Titanium	0.0019	2.8E-04	0.0022
Vanadium	1.3E-04	2.9E-05	1.6E-04
Yttrium	3.3E-05	7.2E-06	4.0E-05
Zinc	0.0049	7.5E-04	0.0057
Chlorides (unspecified)	178	38.7	216
Chlorides (methyl chloride)	2.0E-07	4.3E-08	2.4E-07
Calcium	15.8	3.44	19.2
Fluorides	0	5.5E-04	5.5E-04

Table 5-6

Waterborne Emissions for the Production of PP Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Nitrates	0	8.5E-05	8.5E-05
Nitrogen (ammonia)	0	3.0E-05	3.0E-05
Bromide	1.05	0.23	1.28
Boron	0.015	0.0034	0.019
Total Organic Carbon	0.0010	0.0047	0.0057
Cyanide	3.5E-07	7.7E-08	4.3E-07
Hardness	48.7	10.6	59.3
Total Alkalinity	0.39	0.086	0.48
Surfactants	0	0.0010	0.0010
Acetone	4.9E-05	1.1E-05	6.0E-05
Alkylated Benzenes	1.1E-04	1.6E-05	1.3E-04
Alkylated Fluorenes	6.4E-06	9.1E-07	7.3E-06
Alkylated Naphthalenes	1.8E-06	2.6E-07	2.1E-06
Alkylated Phenanthrenes	7.5E-07	1.1E-07	8.5E-07
Benzene	0.0083	0.0018	0.010
Cresols	2.9E-04	6.2E-05	3.6E-04
Cymene	4.9E-07	1.1E-07	6.0E-07
Dibenzofuran	9.3E-07	2.0E-07	1.1E-06
Dibenzothiophene	7.6E-07	1.7E-07	9.2E-07
2,4 dimethylphenol	1.4E-04	3.0E-05	1.7E-04
Ethylbenzene	4.7E-04	1.0E-04	5.8E-04
2-Hexanone	3.2E-05	7.0E-06	3.9E-05
Methyl Ethyl Ketone (MEK)	4.0E-07	8.6E-08	4.8E-07
1-methylfluorene	5.6E-07	1.2E-07	6.8E-07
2-methyl naphthalene	7.8E-05	1.7E-05	9.5E-05
4-methyl 2-pentanone	2.1E-05	4.5E-06	2.5E-05
Naphthalene	8.9E-05	1.9E-05	1.1E-04
Pentamethyl benzene	3.7E-07	8.0E-08	4.5E-07
Phenanthrene	8.8E-07	1.6E-07	1.0E-06
Toluene	0.0079	0.0017	0.0096
Total Biphenyls	7.1E-06	1.0E-06	8.1E-06
Total Dibenzo-thiophenes	2.2E-08	3.1E-09	2.5E-08
Xylenes	0.0042	9.0E-04	0.0051
Radionuclides (unspecified) (1)	0	6.0E-08	6.0E-08
Lead 210	5.1E-13	0	5.1E-13
n-Decane	1.4E-04	0	1.4E-04
n-Docosane	5.3E-06	0	5.3E-06
n-Dodecane	2.7E-04	0	2.7E-04
n-Eicosane	7.5E-05	0	7.5E-05
n-Hexacosane	3.3E-06	0	3.3E-06
n-Hexadecane	3.0E-04	0	3.0E-04
n-Octadecane	7.3E-05	0	7.3E-05
n-Tetradecane	1.2E-04	0	1.2E-04
Styrene	1.0E-06	0	1.0E-06
Fluorine	3.4E-06	0	3.4E-06
Radium 226	1.8E-10	0	1.8E-10
Radium 228	9.1E-13	0	9.1E-13

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 4.92 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 6

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR PET RESIN

This chapter presents LCI results for the production of polyethylene terephthalate (PET) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of PET resin. Figure 6-1 presents the flow diagram for the production of PET resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix F of the Appendices (separate document).

Primary data was collected for olefins, acetic acid, TPA/PTA and PET resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

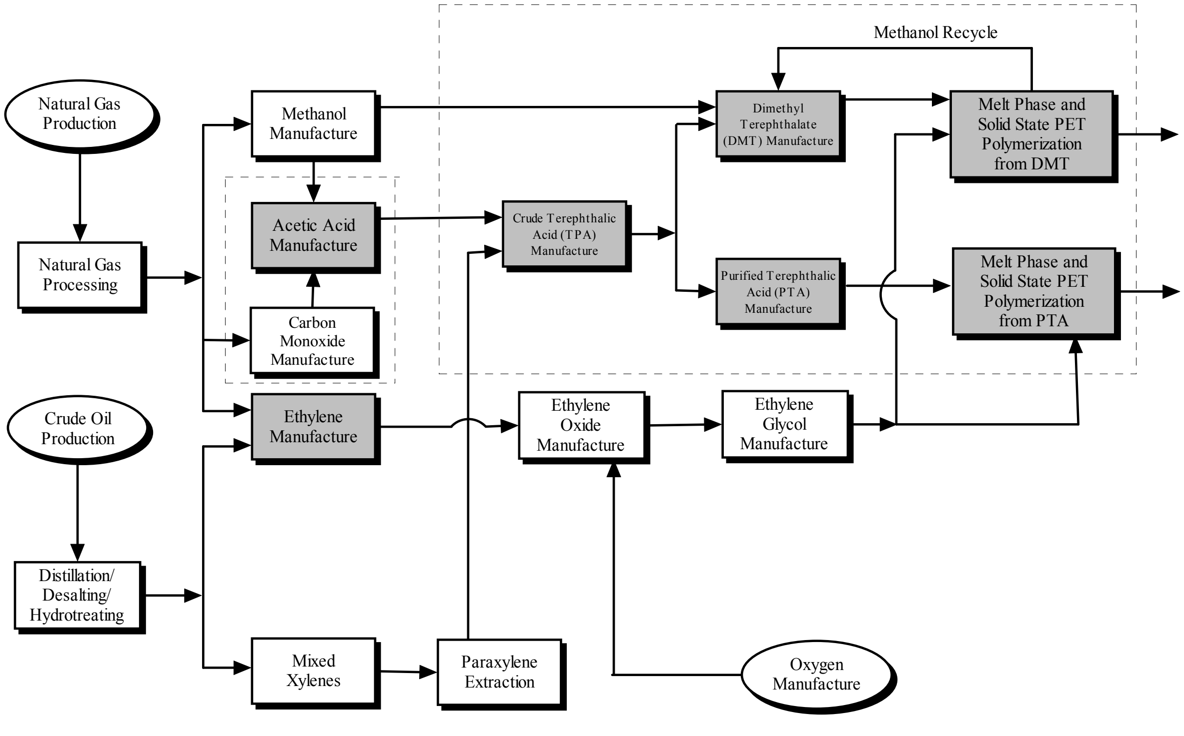

Figure 6-1. Flow diagram for the manufacture of virgin polyethylene terephthalate(PET) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted rectangle are included in an aggregated dataset.

Only one company provided 2003 data for acetic acid. This dataset was arithmetically averaged with a confidential dataset from 1994. Mixed acid and off-gas are coproducts of acetic acid. A mass basis was used to allocate the credit for the acid, while the energy amount for the off-gas was reported separately as recovered energy.

The data in this table includes an aggregation of TPA, PTA, DMT, and PET production. New data was collected for DMT, PTA (including TPA), and PET production. A weighted average using production amounts was calculated from the PTA production data from two plants collected from two leading producers in North America. A weighted average using production amounts was also calculated from the PET production data from two plants collected from two leading producers in North America. Data from primary sources in the early 1990's was used for PET from DMT production. The two PET technologies were weighted accordingly at 15 percent PET from DMT and 85 percent PET from PTA.

As of 2003, there were 16 PET producers and 29 PET plants in the U.S. The captured production amount is approximately 15 percent of the 2003 production amount for PET production from PTA in the U.S. and Canada. Scrap resin (e.g. off-spec) and steam are produced as coproducts during the production of PET from PTA. A mass basis was used to allocate the credit for scrap, while the energy amount for the steam was reported separately as recovered energy.

DESCRIPTION OF TABLES

The average gross energy required to produce PET resin is 31.9 million Btu per 1,000 pounds of resin or 74.2 GJ per 1,000 kilograms of resin. Tables 6-1 and 6-2 show the breakdown of energy requirements for the production of PET resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table F-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of PET resin. Natural gas and petroleum used as raw material inputs for the production of PET, reported as energy of material resource in Table 6-1, are included in the totals for natural gas and petroleum energy in Table 6-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 6-2 are used to generate purchased electricity along with the fossil fuels.

Table 6-1

Energy by Category for the Production of PET Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	14.9	34.7
Transportation	0.66	1.53
Energy of Material Resource	16.4	38.0
Total Energy	**31.9**	**74.2**
Energy Category (Percent)		
Process	47%	47%
Transportation	2%	2%
Energy of Material Resource	51%	51%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 6-2

Energy Profile for the Production of PET Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	14.1	32.9
Petroleum	14.0	32.6
Coal	2.97	6.91
Hydropower	0.12	0.27
Nuclear	0.62	1.44
Wood	0	0
Other	0.12	0.28
Recovered Energy (1)	-0.064	-0.15
Total Energy	**31.9**	**74.2**
Energy Source (Percent)		
Natural Gas	44%	44%
Petroleum	44%	44%
Coal	9%	9%
Hydropower	0%	0%
Nuclear	2%	2%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

---

(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 6-3 shows the weight of solid waste generated during the production of PET resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 6-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 6-3

Solid Wastes by Weight for the Production of PET Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	32.9	32.9
Incinerated	1.03	1.03
Waste-to-Energy	0.59	0.59
Fuel	107	107
Total	**142**	**142**
Weight Percent by Category		
Process		
Landfilled	23%	23%
Incinerated	1%	1%
Waste-to-Energy	0%	0%
Fuel	76%	76%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 6-4

Atmospheric Emissions for the Production of PET Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.29	0.51	0.80
Particulates (PM10)	0.020	0.27	0.29
Nitrogen Oxides	0.24	5.91	6.15
Hydrocarbons (unspecified)	6.71	0.28	6.99
VOC (unspecified)	0.18	0.44	0.62
TNMOC (unspecified)	0	0.019	0.019
Sulfur Dioxide	0	13.3	13.3
Sulfur Oxides	7.06	1.13	8.20
Carbon Monoxide	13.3	3.19	16.5
Fossil CO2	296	2,159	2,455
Non-Fossil CO2	0	12.2	12.2
Aldehydes (Formaldehyde)	0	0.0016	0.0016
Aldehydes (Acetaldehyde)	0	8.5E-05	8.5E-05
Aldehydes (Propionaldehyde)	0	6.9E-06	6.9E-06
Aldehydes (unspecified)	0.19	0.0058	0.19
Organics (unspecified)	1.11	7.7E-04	1.11
Ammonia	0.033	0.0029	0.036
Ammonia Chloride	0	9.7E-05	9.7E-05
Methane	6.36	6.76	13.1
Kerosene	0	1.7E-04	1.7E-04
Chorine	2.0E-05	5.0E-05	7.0E-05
HCl	2.0E-07	0.17	0.17
HF	0	0.021	0.021
Metals (unspecified)	0	0.0027	0.0027
Mercaptan	0	0.0039	0.0039
Antimony	0	3.1E-06	3.1E-06
Arsenic	0	7.6E-05	7.6E-05
Beryllium	0	4.2E-06	4.2E-06
Cadmium	0	2.2E-05	2.2E-05
Chromium (VI)	0	1.1E-05	1.1E-05
Chromium	0	5.9E-05	5.9E-05
Cobalt	0	8.2E-05	8.2E-05
Copper	0	1.7E-06	1.7E-06
Lead	0	1.4E-04	1.4E-04
Magnesium	0	0.0016	0.0016
Manganese	0	2.1E-04	2.1E-04
Mercury	0	3.8E-05	3.8E-05
Nickel	0	0.0010	0.0010
Selenium	0	2.0E-04	2.0E-04
Zinc	0	1.1E-06	1.1E-06
Acetophenone	0	2.7E-07	2.7E-07
Acrolein	0	2.9E-04	2.9E-04
Nitrous Oxide	0	0.050	0.050
Benzene	0.023	0.038	0.061
Benzyl Chloride	0	1.3E-05	1.3E-05
Bis(2-ethylhexyl) Phthalate (DEHP)	0	1.3E-06	1.3E-06
1,3 Butadiene	0	8.2E-07	8.2E-07
2-Chloroacetophenone	0	1.3E-07	1.3E-07
Chlorobenzene	0	4.0E-07	4.0E-07
2,4-Dinitrotoluene	0	5.1E-09	5.1E-09
Ethyl Chloride	0	7.6E-07	7.6E-07
Ethylbenzene	0.0028	0.0043	0.0071
Ethylene Dibromide	0	2.2E-08	2.2E-08
Ethylene Dichloride	0	7.2E-07	7.2E-07
Hexane	0	1.2E-06	1.2E-06

Table 6-4

Atmospheric Emissions for the Production of PET Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Isophorone (C9H14O)	0	1.0E-05	1.0E-05
Methyl Bromide	0	2.9E-06	2.9E-06
Methyl Chloride	0	9.6E-06	9.6E-06
Methyl Ethyl Ketone	0	7.0E-06	7.0E-06
Methyl Hydrazine	0	3.1E-06	3.1E-06
Methyl Methacrylate	0	3.6E-07	3.6E-07
Methyl Tert Butyl Ether (MTBE)	0	6.3E-07	6.3E-07
Naphthalene	0	2.4E-05	2.4E-05
Propylene	0	5.4E-05	5.4E-05
Styrene	0	4.5E-07	4.5E-07
Toluene	0.035	0.055	0.091
Trichloroethane	5.5E-08	3.7E-07	4.3E-07
Vinyl Acetate	0	1.4E-07	1.4E-07
Xylenes	0.062	0.032	0.094
Bromoform	0	7.0E-07	7.0E-07
Chloroform	0	1.1E-06	1.1E-06
Carbon Disulfide	0	2.3E-06	2.3E-06
Dimethyl Sulfate	0	8.7E-07	8.7E-07
Cumene	0	9.6E-08	9.6E-08
Cyanide	0	4.5E-05	4.5E-05
Perchloroethylene	0	7.1E-06	7.1E-06
Methylene Chloride	0	1.2E-04	1.2E-04
Carbon Tetrachloride	6.8E-09	2.8E-06	2.8E-06
Phenols	0	5.3E-05	5.3E-05
Fluorides	0	8.1E-04	8.1E-04
Polyaromatic Hydrocarbons (total)	0	6.6E-06	6.6E-06
Biphenyl	0	2.4E-07	2.4E-07
Acenaphthene	0	7.3E-08	7.3E-08
Acenaphthylene	0	3.6E-08	3.6E-08
Anthracene	0	3.0E-08	3.0E-08
Benzo(a)anthracene	0	1.1E-08	1.1E-08
Benzo(a)pyrene	0	5.5E-09	5.5E-09
Benzo(b,j,k)fluroanthene	0	1.6E-08	1.6E-08
Benzo(g,h,i) perylene	0	3.9E-09	3.9E-09
Chrysene	0	1.4E-08	1.4E-08
Fluoranthene	0	1.0E-07	1.0E-07
Fluorene	0	1.3E-07	1.3E-07
Indeno(1,2,3-cd)pyrene	0	8.8E-09	8.8E-09
Naphthanlene	0	1.9E-06	1.9E-06
Phenanthrene	0	3.9E-07	3.9E-07
Pyrene	0	4.7E-08	4.7E-08
5-Methyl Chrysene	0	3.2E-09	3.2E-09
Dioxins (unspecified)	0	1.1E-07	1.1E-07
Furans (unspecified)	0	5.7E-10	5.7E-10
CFC12	0	1.6E-08	1.6E-08
Radionuclides (unspecified) (1)	0	0.0098	0.0098
HCFC-22	2.0E-07	0	2.0E-07
Hydrogen	7.9E-04	0	7.9E-04
Acid (unknown)	0.18	0	0.18
TOC	0.081	0	0.081
Ethylene Oxide	0.024	0	0.024
Acetic Acid	0.051	0	0.051
Bromine	0.079	0	0.079
Methyl Acetate	0.040	0	0.040
Methanol	0.0015	0	0.0015

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 797,040 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 6-5 provides a greenhouse gas (GHG) summary for the production of PET resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 6-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 6-4 are multiplied by their global warming potential and shown in Table 6-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 6-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 6-5

Greenhouse Gas Summary for the Production of PET Resin
(lb carbon dioxide equivalents per 1,000 lb PET or kg carbon dioxide equivalents per 1,000 kg PET)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	2,159	296	2,455
Methane	169	159	328
Nitrous oxide	15.0	0	15.0
Methyl bromide	1.4E-05	0	1.4E-05
Methyl chloride	1.5E-04	0	1.5E-04
Trichloroethane	5.2E-05	7.7E-06	6.0E-05
Chloroform	3.2E-05	0	3.2E-05
Methylene chloride	0.0012	0	0.0012
Carbon tetrachloride	0.0040	9.5E-06	0.0040
CFC-012	1.7E-04	0	1.7E-04
HCFC-22	0	3.6E-04	3.6E-04
Total	2,343	455	2,798

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 6-6

Waterborne Emissions for the Production of PET Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0.036	0.0020	0.038
Acid (benzoic)	0.0032	0.0021	0.0053
Acid (hexanoic)	6.5E-04	4.4E-04	0.0011
Metal (unspecified)	4.5E-06	0	4.5E-06
Dissolved Solids	139	92.7	231
Suspended Solids	6.43	2.37	8.80
BOD	1.43	0.41	1.84
COD	2.50	0.49	2.99
Phenol/Phenolic Compounds	0.0017	9.6E-04	0.0027
Sulfur	0	0.0055	0.0055
Sulfates	0.23	0.28	0.51
Sulfides	1.1E-04	2.5E-05	1.3E-04
Oil	0.068	0.042	0.11
Hydrocarbons	0	4.2E-04	4.2E-04
Ammonia	0.16	0.033	0.20
Ammonium	0.0013	7.7E-05	0.0014
Aluminum	0.20	0.073	0.28
Antimony	1.3E-04	4.5E-05	1.7E-04
Arsenic	8.0E-04	4.9E-04	0.0013
Barium	2.84	1.05	3.89
Beryllium	4.3E-05	2.3E-05	6.6E-05
Cadmium	1.2E-04	7.2E-05	1.9E-04
Chromium (unspecified)	0.012	0.0020	0.014
Chromium (hexavalent)	2.1E-05	0	2.1E-05
Cobalt	6.9E-05	4.6E-05	1.2E-04
Copper	7.4E-04	3.9E-04	0.0011
Iron	0.43	0.18	0.61
Lead	0.0016	7.9E-04	0.0023
Lithium	1.12	1.72	2.84
Magnesium	1.96	1.31	3.26
Manganese	0.0031	0.0040	0.0071
Mercury	2.2E-06	8.1E-07	3.1E-06
Molybdenum	7.2E-05	4.8E-05	1.2E-04
Nickel	7.5E-04	4.1E-04	0.0012
Selenium	2.5E-05	3.6E-05	6.1E-05
Silver	0.0065	0.0044	0.011
Sodium	31.7	21.2	52.9
Strontium	0.17	0.11	0.28
Thallium	2.7E-05	9.5E-06	3.6E-05
Tin	5.8E-04	2.8E-04	8.6E-04
Titanium	0.0020	6.9E-04	0.0027
Vanadium	8.5E-05	5.6E-05	1.4E-04
Yttrium	2.1E-05	1.4E-05	3.5E-05
Zinc	0.013	0.0018	0.015
Chlorides (unspecified)	113	75.1	188
Chlorides (methyl chloride)	1.3E-07	8.4E-08	2.1E-07
Calcium	10.0	6.69	16.7
Fluorides	5.1E-05	0.0013	0.0013
Nitrates	0	1.9E-04	1.9E-04
Nitrogen (ammonia)	0	6.7E-05	6.7E-05

Table 6-6

Waterborne Emissions for the Production of PET Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Bromide	0.67	0.45	1.11
Boron	0.0098	0.0065	0.016
Total Organic Carbon	0.044	0.0081	0.052
Cyanide	2.2E-07	1.5E-07	3.7E-07
Hardness	30.8	20.6	51.4
Total Alkalinity	0.25	0.17	0.414
Surfactants	0	0.0020	0.0020
Acetone	3.1E-05	2.1E-05	5.2E-05
Alkylated Benzenes	1.1E-04	3.9E-05	1.5E-04
Alkylated Fluorenes	6.5E-06	2.3E-06	8.8E-06
Alkylated Naphthalenes	1.8E-06	6.5E-07	2.5E-06
Alkylated Phenanthrenes	7.6E-07	2.7E-07	1.0E-06
Benzene	0.0052	0.0035	0.0087
Cresols	1.9E-04	1.2E-04	3.1E-04
Cymene	3.1E-07	2.1E-07	5.2E-07
Dibenzofuran	5.9E-07	4.0E-07	9.9E-07
Dibenzothiophene	4.8E-07	3.2E-07	8.0E-07
2,4 dimethylphenol	8.7E-05	5.8E-05	1.5E-04
Ethylbenzene	3.0E-04	2.0E-04	4.9E-04
2-Hexanone	2.0E-05	1.4E-05	3.4E-05
Methyl Ethyl Ketone (MEK)	2.5E-07	1.7E-07	4.2E-07
1-methylfluorene	3.5E-07	2.4E-07	5.9E-07
2-methyl naphthalene	4.9E-05	3.3E-05	8.2E-05
4-methyl 2-pentanone	1.3E-05	8.7E-06	2.2E-05
Naphthalene	5.7E-05	3.8E-05	9.5E-05
Pentamethyl benzene	2.3E-07	1.6E-07	3.9E-07
Phenanthrene	7.2E-07	3.4E-07	1.1E-06
Toluene	0.0050	0.0033	0.0083
Total Biphenyls	7.3E-06	2.5E-06	9.8E-06
Total Dibenzo-thiophenes	2.2E-08	7.9E-09	3.0E-08
Xylenes	0.0027	0.0018	0.0044
Radionuclides (unspecified) (1)	0	1.4E-07	1.4E-07
Phosphates	5.1E-04	0	5.1E-04
Lead 210	3.2E-13	0	3.2E-13
n-Decane	9.1E-05	0	9.1E-05
n-Docosane	3.3E-06	0	3.3E-06
n-Dodecane	1.7E-04	0	1.7E-04
n-Eicosane	4.7E-05	0	4.7E-05
n-Hexacosane	2.1E-06	0	2.1E-06
n-Hexadecane	1.9E-04	0	1.9E-04
n-Octadecane	4.6E-05	0	4.6E-05
n-Tetradecane	7.5E-05	0	7.5E-05
Styrene	2.0E-07	0	2.0E-07
Fluorine	3.3E-06	0	3.3E-06
Aldehydes	0.025	0	0.025
Radium 226	1.1E-10	0	1.1E-10
Radium 228	5.8E-13	0	5.8E-13
Aldehydes	0.025	0	0.025

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 11.14 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 7

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR GPPS RESIN

This chapter presents LCI results for the production of general purpose polystyrene (GPPS) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of GPPS resin. Figure 7-1 presents the flow diagram for the production of GPPS resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix G of the Appendices (separate document).

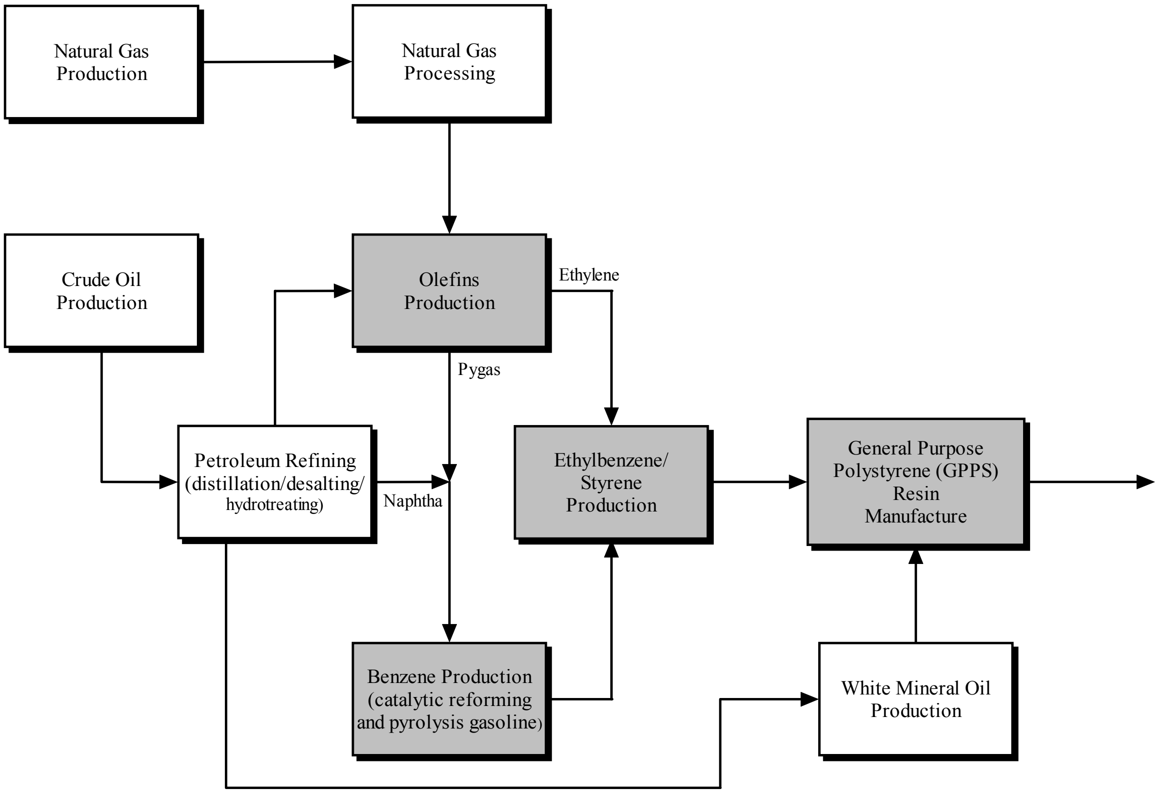

Figure 7-1. Flow diagram for the production of general purpose polystyrene resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Primary data was collected for olefins, benzene, ethylbenzene/styrene, and GPPS resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

It is estimated that one-third of the benzene production is from pyrolysis gasoline and two-thirds are produced from catalytic reforming. These percentages were used to weight the collected datasets for benzene. Catalytic reforming is represented by 2 primary datasets from 1992. The benzene data collected for this analysis represent 1 producer and 1 plant in the U.S. using the pyrolysis gasoline production method. As of 2002 there were 22 benzene producers and 38 benzene plants in the U.S. for the three standard technologies. The captured production amount is approximately 10 percent of the available capacity for benzene production in the U.S. Numerous aromatic coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the reactor, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit the remaining aromatic products.

Two of the three ethylbenzene/styrene datasets were collected for this project and represents 2002-2003 data, while the other dataset comes from 1993. As of 2001 there were 8 styrene producers and 8 styrene plants in the U.S. The styrene data collected for this module represent 2 producers and 2 plants in the U.S. The captured production amount is approximately 25 percent of the available capacity for styrene production in the U.S. Various coproduct streams are produced during this process. A mass basis was used to allocate the credit these coproducts in the datasets collected during this analysis.

A weighted average using production amounts was calculated from the GPPS production data from six plants collected from four leading producers in North America. As of 2002 there were 12 PS producers and 24 PS plants in the U.S. The captured production amount is approximately 20 percent of the available capacity for all polystyrene production in the U.S. and Canada. Scrap resin (e.g. off-spec) and some alkane/alkene streams are produced as a coproduct during this process. A mass basis was used to allocate the credit for each coproduct.

DESCRIPTION OF TABLES

The average gross energy required to produce GPPS resin is 42.5 million Btu per 1,000 pounds of resin or 98.7 GJ per 1,000 kilograms of resin. Tables 7-1 and 7-2 show the breakdown of energy requirements for the production of GPPS resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table G-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of GPPS resin. Natural gas and petroleum used as raw material inputs for the production of GPPS, reported as energy of material resource in Table 7-1, are included in the totals for natural gas and petroleum energy in Table 7-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 7-2 are used to generate purchased electricity along with the fossil fuels.

Table 7-1

Energy by Category for the Production of GPPS Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	18.0	41.8
Transportation	1.09	2.53
Energy of Material Resource	23.4	54.4
Total Energy	**42.5**	**98.7**
Energy Category (Percent)		
Process	42%	42%
Transportation	3%	3%
Energy of Material Resource	55%	55%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 7-2

Energy Profile for the Production of GPPS Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	23.4	54.5
Petroleum	16.9	39.4
Coal	1.57	3.64
Hydropower	0.070	0.16
Nuclear	0.37	0.87
Wood	0	0
Other	0.073	0.17
Recovered Energy (1)	-0.0042	-0.0097
Total Energy	**42.5**	**98.7**
Energy Source (Percent)		
Natural Gas	55%	55%
Petroleum	40%	40%
Coal	4%	4%
Hydropower	0%	0%
Nuclear	1%	1%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 7-3 shows the weight of solid waste generated during the production of GPPS resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 7-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 7-3

Solid Wastes by Weight for the Production of GPPS Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	38.6	38.6
Incinerated	03.4	3.43
Waste-to-Energy	01.5	1.55
Fuel	66.9	66.9
Total	**110**	**110**
Weight Percent by Category		
Process		
Landfilled	35%	35%
Incinerated	3%	3%
Waste-to-Energy	1%	1%
Fuel	61%	61%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 7-5 provides a greenhouse gas (GHG) summary for the production of GPPS resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 7-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 7-4 are multiplied by their global warming potential and shown in Table 7-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 7-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 7-4

Atmospheric Emissions for the Production of GPPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.23	0.28	0.51
Particulates (PM2.5)	0.0078	0	0.0078
Particulates (PM10)	0.056	0.20	0.26
Nitrogen Oxides	0.43	5.48	5.92
Hydrocarbons (unspecified)	1.67	0.21	1.88
VOC (unspecified)	0.38	0.58	0.96
Sulfur Dioxide	0	14.9	14.9
Sulfur Oxides	13.6	0.96	14.6
Carbon Monoxide	9.99	2.95	12.9
Fossil CO2	335	2,385	2,720
Aldehydes (unspecified)	0.031	0.0043	0.035
Organics (unspecified)	0.011	4.6E-04	0.011
Ammonia	0.015	0.0021	0.017
Ammonia Chloride	0	5.8E-05	5.8E-05
Methane	9.42	8.20	17.6
Kerosene	0	1.1E-04	1.1E-04
Chorine	1.3E-04	3.0E-05	1.6E-04
HCl	5.5E-07	0.097	0.097
HF	0	0.011	0.011
Metals (unspecified)	0	0.0016	0.0016
Mercaptan	0	7.4E-06	7.4E-06
Antimony	0	1.7E-06	1.7E-06
Arsenic	0	4.3E-05	4.3E-05
Beryllium	0	2.3E-06	2.3E-06
Cadmium	0	1.9E-05	1.9E-05
Chromium (VI)	0	6.0E-06	6.0E-06
Chromium	0	4.2E-05	4.2E-05
Cobalt	0	4.8E-05	4.8E-05
Magnesium	0	8.4E-04	8.4E-04
Manganese	0	1.2E-04	1.2E-04
Zinc	0	4.2E-07	4.2E-07
Acetophenone	0	5.5E-10	5.5E-10
Acrolein	0	1.8E-04	1.8E-04
Nitrous Oxide	0	0.039	0.039
Benzene	0.046	0.051	0.096
Benzyl Chloride	0	2.6E-08	2.6E-08
Bis(2-ethylhexyl) Phthalate (DEHP)	0	2.7E-09	2.7E-09
1,3 Butadiene	0	1.0E-06	1.0E-06
2-Chloroacetophenone	0	2.6E-10	2.6E-10
Chlorobenzene	0	8.1E-10	8.1E-10
2,4-Dinitrotoluene	0	1.0E-11	1.0E-11
Ethyl Chloride	0	1.5E-09	1.5E-09
Ethylbenzene	0.0057	0.0060	0.012
Ethylene Dibromide	0	4.4E-11	4.4E-11
Ethylene Dichloride	0	1.5E-09	1.5E-09
Hexane	0	2.5E-09	2.5E-09
Isophorone (C9H14O)	0	2.1E-08	2.1E-08

Table 7-4

Atmospheric Emissions for the Production of GPPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Methyl Bromide	0	5.9E-09	5.9E-09
Methyl Chloride	0	1.9E-08	1.9E-08
Methyl Ethyl Ketone	2.6E-04	1.4E-08	2.6E-04
Methyl Hydrazine	0	6.2E-09	6.2E-09
Methyl Methacrylate	0	7.3E-10	7.3E-10
Methyl Tert Butyl Ether (MTBE)	0	1.3E-09	1.3E-09
Naphthalene	0	1.8E-05	1.8E-05
Propylene	0	6.9E-05	6.9E-05
Styrene	0	9.2E-10	9.2E-10
Toluene	0.071	0.078	0.15
Trichloroethane	7.1E-08	1.1E-08	8.1E-08
Vinyl Acetate	0	2.8E-10	2.8E-10
Xylenes	0.041	0.045	0.087
Bromoform	0	1.4E-09	1.4E-09
Chloroform	0	2.2E-09	2.2E-09
Carbon Disulfide	0	4.8E-09	4.8E-09
Dimethyl Sulfate	0	1.8E-09	1.8E-09
Cumene	0	1.9E-10	1.9E-10
Cyanide	0	9.2E-08	9.2E-08
Perchloroethylene	0	3.8E-06	3.8E-06
Methylene Chloride	0	6.9E-05	6.9E-05
Carbon Tetrachloride	8.7E-09	1.7E-06	1.7E-06
Phenols	0	3.0E-05	3.0E-05
Fluorides	0	6.5E-06	6.5E-06
Polyaromatic Hydrocarbons (total)	0	6.2E-06	6.2E-06
Biphenyl	0	1.3E-07	1.3E-07
Acenaphthene	0	3.9E-08	3.9E-08
Acenaphthylene	0	1.9E-08	1.9E-08
Anthracene	0	1.6E-08	1.6E-08
Benzo(a)anthracene	0	6.1E-09	6.1E-09
Benzo(a)pyrene	0	2.9E-09	2.9E-09
Benzo(b,j,k)fluroanthene	0	8.4E-09	8.4E-09
Benzo(g,h,i) perylene	0	2.1E-09	2.1E-09
Chrysene	0	7.6E-09	7.6E-09
Fluoranthene	0	5.4E-08	5.4E-08
Fluorene	0	6.9E-08	6.9E-08
Indeno(1,2,3-cd)pyrene	0	4.6E-09	4.6E-09
Naphthanlene	0	9.9E-07	9.9E-07
Phenanthrene	0	2.1E-07	2.1E-07
Pyrene	0	2.5E-08	2.5E-08
5-Methyl Chrysene	0	1.7E-09	1.7E-09
Dioxins (unspecified)	0	6.3E-08	6.3E-08
Furans (unspecified)	0	3.5E-10	3.5E-10
CFC12	0	1.2E-08	1.2E-08
Radionuclides (unspecified) (1)	0	0.0059	0.0059
Phosphorus	0	3.3E-05	3.3E-05
HCFC-22	0.0010	0.0010	0.0020
HCFC-123	0	1.0E-05	1.0E-05
HFC-134a	0	5.6E-04	5.6E-04
Hydrogen	0.0026	0	0.0026
Acid (unknown)	0.38	0	0.38

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 482,214 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 7-5

Greenhouse Gas Summary for the Production of GPPS Resin
(lb carbon dioxide equivalents per 1,000 lb GPPS or kg carbon dioxide equivalents per 1,000 kg GPPS)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	2,385	335	2,720
Methane	205	236	440
Nitrous oxide	11.5	0	11.5
Methyl bromide	2.9E-08	0	2.9E-08
Methyl chloride	3.1E-07	0	3.1E-07
Trichloroethane	1.5E-06	9.9E-06	1.1E-05
Chloroform	6.5E-08	0	6.5E-08
Methylene chloride	6.9E-04	0	6.9E-04
Carbon tetrachloride	0.0024	1.2E-05	0.0024
CFC-012	1.3E-04	0	1.3E-04
HCFC-22	1.81	1.81	3.62
HCFC-123	7.7E-04	0	7.7E-04
HFC-134a	0.80	0	0.80
Total	2,603	572	3,175

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 7-6

Waterborne Emissions for the Production of GPPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0027	0.0027
Acid (benzoic)	0.0048	0.0026	0.0075
Acid (hexanoic)	0.0010	5.5E-04	0.0016
Dissolved Solids	214	116	330
Suspended Solids	8.72	2.43	11.2
BOD	1.22	0.47	1.69
COD	2.39	0.67	3.06
Phenol/Phenolic Compounds	0.0029	0.0012	0.0040
Sulfur	0	0.0069	0.0069
Sulfates	0.35	0.27	0.62
Sulfides	9.2E-04	1.9E-05	9.4E-04
Oil	0.12	0.051	0.17
Hydrocarbons	1.0E-05	5.2E-04	5.3E-04
Ammonia	0.077	0.040	0.12
Ammonium	0	4.7E-05	4.7E-05
Aluminum	0.28	0.074	0.35
Antimony	1.7E-04	4.5E-05	2.2E-04
Arsenic	0.0012	6.0E-04	0.0018
Barium	3.89	1.08	4.96
Beryllium	6.3E-05	2.8E-05	9.1E-05
Cadmium	1.8E-04	8.8E-05	2.6E-04
Chromium (unspecified)	0.0079	0.0021	0.010
Chromium (hexavalent)	2.7E-05	0	2.7E-05
Cobalt	1.1E-04	5.8E-05	1.6E-04
Copper	0.0011	4.3E-04	0.0015
Iron	0.60	0.20	0.79
Lead	0.0023	9.3E-04	0.0032
Lithium	2.26	2.41	4.67
Magnesium	3.00	1.64	4.64
Manganese	0.0048	0.0037	0.0085
Mercury	3.0E-06	8.1E-07	3.9E-06
Molybdenum	1.1E-04	6.0E-05	1.7E-04
Nickel	0.0011	4.9E-04	0.0016
Selenium	3.4E-05	2.5E-05	5.9E-05
Silver	0.010	0.0055	0.015
Sodium	48.7	26.5	75.2
Strontium	0.26	0.14	0.40
Thallium	3.7E-05	9.6E-06	4.6E-05
Tin	8.3E-04	3.3E-04	0.0012
Titanium	0.0027	7.0E-04	0.0034
Vanadium	1.3E-04	7.1E-05	2.0E-04
Yttrium	3.2E-05	1.8E-05	5.0E-05
Zinc	0.0066	0.0019	0.0085
Chlorides (unspecified)	173	94.0	267
Chlorides (methyl chloride)	1.9E-07	1.0E-07	3.0E-07
Calcium	15.4	8.36	23.7
Fluorides	0	7.6E-04	7.6E-04
Nitrates	0	1.2E-04	1.2E-04
Nitrogen (ammonia)	0	4.1E-05	4.1E-05

Table 7-6

Waterborne Emissions for the Production of GPPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Bromide		1.02	0.56	1.58
Boron		0.015	0.0082	0.023
Total Organic Carbon		5.6E-04	0.011	0.012
Cyanide		1.3E-06	1.9E-07	1.5E-06
Hardness		47.3	25.8	73.1
Total Alkalinity		0.38	0.21	0.59
Surfactants		0	0.0025	0.0025
Acetone		4.8E-05	2.6E-05	7.4E-05
Alkylated Benzenes		1.5E-04	4.0E-05	1.9E-04
Alkylated Fluorenes		8.8E-06	2.3E-06	1.1E-05
Alkylated Naphthalenes		2.5E-06	6.5E-07	3.1E-06
Alkylated Phenanthrenes		1.0E-06	2.7E-07	1.3E-06
Benzene		0.0080	0.0044	0.012
Cresols		2.9E-04	1.5E-04	4.4E-04
Cymene		4.8E-07	2.6E-07	7.4E-07
Dibenzofuran		9.1E-07	4.9E-07	1.4E-06
Dibenzothiophene		7.4E-07	4.0E-07	1.1E-06
2,4 dimethylphenol		1.3E-04	7.3E-05	2.1E-04
Ethylbenzene		0.0015	2.5E-04	0.0017
2-Hexanone		3.1E-05	1.7E-05	4.8E-05
Methyl Ethyl Ketone (MEK)		3.8E-07	2.1E-07	5.9E-07
1-methylfluorene		5.4E-07	3.0E-07	8.4E-07
2-methyl naphthalene		7.6E-05	4.1E-05	1.2E-04
4-methyl 2-pentanone		2.0E-05	1.1E-05	3.1E-05
Naphthalene		8.7E-05	4.7E-05	1.3E-04
Pentamethyl benzene		3.6E-07	2.0E-07	5.5E-07
Phenanthrene		1.0E-06	3.9E-07	1.4E-06
Toluene		0.0076	0.0041	0.012
Total Biphenyls		9.9E-06	2.6E-06	1.2E-05
Total Dibenzo-thiophenes		3.0E-08	7.9E-09	3.8E-08
Xylenes		0.0041	0.0022	0.0063
Radionuclides (unspecified)	(1)	0	8.3E-08	8.3E-08
Phosphates		0.0010	0	0.0010
Lead 210		5.0E-13	0	5.0E-13
n-Decane		1.4E-04	0	1.4E-04
n-Docosane		5.1E-06	0	5.1E-06
n-Dodecane		2.6E-04	0	2.6E-04
n-Eicosane		7.3E-05	0	7.3E-05
n-Hexacosane		3.2E-06	0	3.2E-06
n-Hexadecane		2.9E-04	0	2.9E-04
n-Octadecane		7.1E-05	0	7.1E-05
n-Tetradecane		1.2E-04	0	1.2E-04
Styrene		0.0010	0	0.0010
Fluorine		4.5E-06	0	4.5E-06
Radium 226		1.7E-10	0	1.7E-10
Radium 228		8.8E-13	0	8.8E-13

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 6.74 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 8

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR HIPS RESIN

This chapter presents LCI results for the production of high-impact polystyrene (HIPS) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of HIPS resin. Figure 8-1 presents the flow diagram for the production of HIPS resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix H of the Appendices (separate document).

Primary data was collected for olefins and HIPS resin production. The olefins dataset was also used for butadiene, which is a coproduct of the olefins hydrocracker. As of 2002, almost all butadiene is produced as an ethylene steam-cracking coproduct.

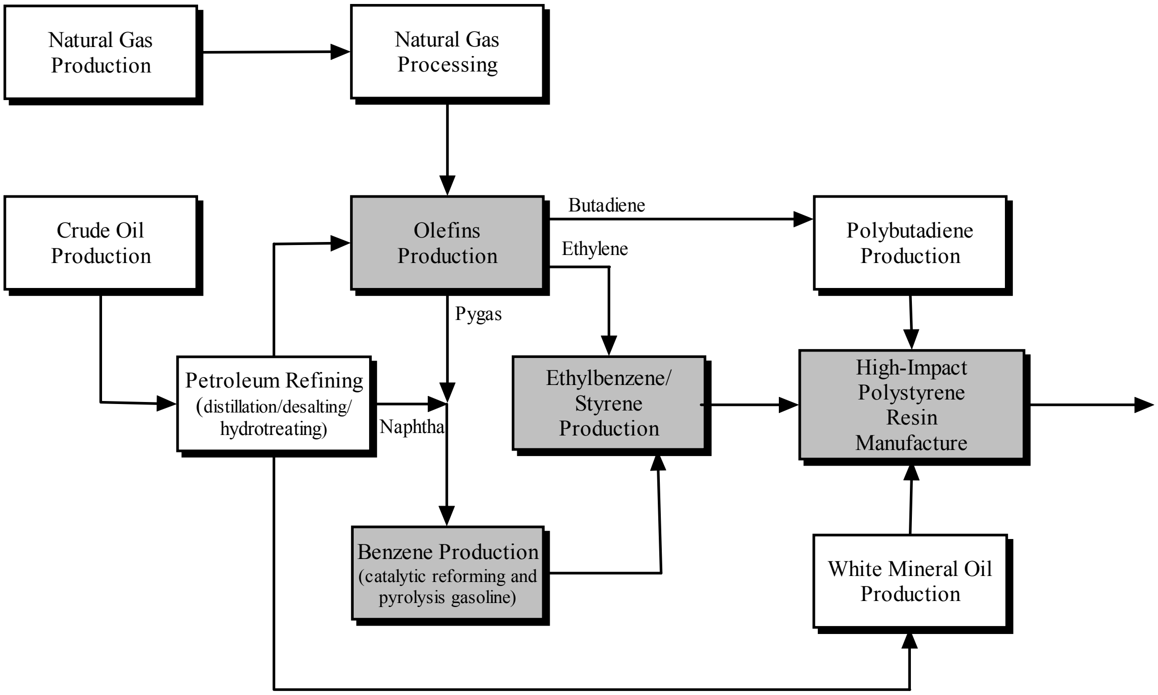

Figure 8-1. Flow diagram for the production of high-impact polystyrene resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

A weighted average using production amounts was calculated from the HIPS production data from six plants collected from four leading producers in North America. As of 2002 there were 12 PS producers and 24 PS plants in the U.S. The captured production amount is approximately 25 percent of the available capacity for all polystyrene production in the U.S. and Canada. Scrap resin (e.g. off-spec) is produced as a coproduct during this process. A mass basis was used to allocate the credit for the scrap.

DESCRIPTION OF TABLES

The average gross energy required to produce HIPS resin is 42.9 million Btu per 1,000 pounds of resin or 99.8 GJ per 1,000 kilograms of resin. Tables 8-1 and 8-2 show the breakdown of energy requirements for the production of HIPS resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table H-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of HIPS resin. Natural gas and petroleum used as raw material inputs for the production of HIPS, reported as energy of material resource in Table 8-1, are included in the totals for natural gas and petroleum energy in Table 8-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 8-2 are used to generate purchased electricity along with the fossil fuels.

Table 8-3 shows the weight of solid waste generated during the production of HIPS resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 8-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 8-1

Energy by Category for the Production of HIPS Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	18.0	42.0
Transportation	1.15	2.69
Energy of Material Resource	23.7	55.1
Total Energy	**42.9**	**99.8**
Energy Category (Percent)		
Process	42%	42%
Transportation	3%	3%
Energy of Material Resource	55%	55%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 8-2

Energy Profile for the Production of HIPS Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	23.8	55.3
Petroleum	17.0	39.6
Coal	1.59	3.71
Hydropower	0.071	0.17
Nuclear	0.38	0.89
Wood	0	0
Other	0.074	0.17
Recovered Energy (1)	-0.0041	-0.0096
Total Energy	**42.9**	**99.8**
Energy Source (Percent)		
Natural Gas	55%	55%
Petroleum	40%	40%
Coal	4%	4%
Hydropower	0%	0%
Nuclear	1%	1%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 8-3

Solid Wastes by Weight for the Production of HIPS Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	41.5	41.5
Incinerated	3.72	3.72
Waste-to-Energy	1.15	1.15
Fuel	67.7	67.7
Total	**114**	**114**
Weight Percent by Category		
Process		
Landfilled	36%	36%
Incinerated	3%	3%
Waste-to-Energy	1%	1%
Fuel	59%	59%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 8-5 provides a greenhouse gas (GHG) summary for the production of HIPS resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 8-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 8-4 are multiplied by their global warming potential and shown in Table 8-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 8-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 8-4

Atmospheric Emissions for the Production of HIPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.22	0.29	0.51
Particulates (PM2.5)	0.0073	0	0.0073
Particulates (PM10)	0.069	0.20	0.27
Nitrogen Oxides	0.42	5.58	6.00
Hydrocarbons (unspecified)	2.41	0.22	2.62
VOC (unspecified)	0.40	0.58	0.97
TNMOC (unspecified)	0	0.0085	0.0085
Sulfur Dioxide	0	14.8	14.8
Sulfur Oxides	14.1	0.99	15.1
Carbon Monoxide	9.94	3.00	12.9
Fossil CO2	318	2,417	2,735
Non-Fossil CO2	0	7.48	7.48
Aldehydes (Formaldehyde)	0	0.0015	0.0015
Aldehydes (Acetaldehyde)	0	6.4E-05	6.4E-05
Aldehydes (Propionaldehyde)	0	1.4E-08	1.4E-08
Aldehydes (unspecified)	0.031	0.0045	0.035
Organics (unspecified)	0.010	4.7E-04	0.010
Ammonia	0.015	0.0022	0.017
Ammonia Chloride	0	5.9E-05	5.9E-05
Methane	9.72	8.11	17.8
Kerosene	0	1.1E-04	1.1E-04
Chorine	1.3E-04	3.0E-05	1.6E-04
HCl	5.2E-07	0.099	0.099
HF	0	0.012	0.012
Metals (unspecified)	0	0.0016	0.0016
Mercaptan	0	7.6E-06	7.6E-06
Antimony	0	1.7E-06	1.7E-06
Arsenic	0	4.4E-05	4.4E-05
Beryllium	0	2.3E-06	2.3E-06
Cadmium	0	1.9E-05	1.9E-05
Chromium (VI)	0	6.1E-06	6.1E-06
Chromium	0	4.2E-05	4.2E-05
Cobalt	0	5.0E-05	5.0E-05
Copper	0	6.2E-07	6.2E-07
Lead	0	5.1E-05	5.1E-05
Magnesium	0	8.5E-04	8.5E-04
Manganese	0	1.2E-04	1.2E-04
Mercury	0	1.0E-05	1.0E-05
Nickel	0	6.2E-04	6.2E-04
Selenium	0	1.1E-04	1.1E-04
Zinc	0	4.1E-07	4.1E-07
Acetophenone	0	5.6E-10	5.6E-10
Acrolein	0	1.8E-04	1.8E-04
Nitrous Oxide	0	0.039	0.039
Benzene	0.048	0.050	0.098
Benzyl Chloride	0	2.6E-08	2.6E-08
Bis(2-ethylhexyl) Phthalate (DEHP)	0	2.7E-09	2.7E-09
1,3 Butadiene	0	1.1E-06	1.1E-06
2-Chloroacetophenone	0	2.6E-10	2.6E-10
Chlorobenzene	0	8.2E-10	8.2E-10
2,4-Dinitrotoluene	0	1.0E-11	1.0E-11
Ethyl Chloride	0	1.6E-09	1.6E-09
Ethylbenzene	0.0060	0.0059	0.012

Table 8-4

Atmospheric Emissions for the Production of HIPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethylene Dibromide	0	4.5E-11	4.5E-11
Ethylene Dichloride	0	1.5E-09	1.5E-09
Hexane	0	2.5E-09	2.5E-09
Isophorone (C9H14O)	0	2.2E-08	2.2E-08
Methyl Bromide	0	6.0E-09	6.0E-09
Methyl Chloride	0	2.0E-08	2.0E-08
Methyl Ethyl Ketone	0.0018	1.5E-08	0.0018
Methyl Hydrazine	0	6.3E-09	6.3E-09
Methyl Methacrylate	0	7.5E-10	7.5E-10
Methyl Tert Butyl Ether (MTBE)	0	1.3E-09	1.3E-09
Naphthalene	0	1.8E-05	1.8E-05
Propylene	0	7.0E-05	7.0E-05
Styrene	0	9.3E-10	9.3E-10
Toluene	0.075	0.077	0.15
Trichloroethane	7.1E-08	1.1E-08	8.1E-08
Vinyl Acetate	0	2.8E-10	2.8E-10
Xylenes	0.043	0.045	0.088
Bromoform	0	1.5E-09	1.5E-09
Chloroform	0	2.2E-09	2.2E-09
Carbon Disulfide	0	4.8E-09	4.8E-09
Dimethyl Sulfate	0	1.8E-09	1.8E-09
Cumene	0	2.0E-10	2.0E-10
Cyanide	0	9.3E-08	9.3E-08
Perchloroethylene	0	3.9E-06	3.9E-06
Methylene Chloride	0	7.0E-05	7.0E-05
Carbon Tetrachloride	8.7E-09	1.7E-06	1.7E-06
Phenols	0	3.0E-05	3.0E-05
Fluorides	0	6.6E-06	6.6E-06
Polyaromatic Hydrocarbons (total)	0	6.3E-06	6.3E-06
Biphenyl	0	1.3E-07	1.3E-07
Acenaphthene	0	3.9E-08	3.9E-08
Acenaphthylene	0	1.9E-08	1.9E-08
Anthracene	0	1.6E-08	1.6E-08
Benzo(a)anthracene	0	6.2E-09	6.2E-09
Benzo(a)pyrene	0	2.9E-09	2.9E-09
Benzo(b,j,k)fluroanthene	0	8.5E-09	8.5E-09
Benzo(g,h,i) perylene	0	2.1E-09	2.1E-09
Chrysene	0	7.7E-09	7.7E-09
Fluoranthene	0	5.5E-08	5.5E-08
Fluorene	0	7.0E-08	7.0E-08
Indeno(1,2,3-cd)pyrene	0	4.7E-09	4.7E-09
Naphthanlene	0	1.0E-06	1.0E-06
Phenanthrene	0	2.1E-07	2.1E-07
Pyrene	0	2.6E-08	2.6E-08
5-Methyl Chrysene	0	1.7E-09	1.7E-09
Dioxins (unspecified)	0	6.4E-08	6.4E-08
Furans (unspecified)	0	3.5E-10	3.5E-10
CFC12	0	1.2E-08	1.2E-08
Radionuclides (unspecified) (1)	0	0.0060	0.0060
HCFC-22	0.0010	0	0.0010
Hydrogen	0.0024	0	0.0024
Acid (unknown)	0.40	0	0.40
F2	1.0E-06	0	1.0E-06

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 490,774 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 8-5

Greenhouse Gas Summary for the Production of HIPS Resin (lb carbon dioxide equivalents per 1,000 lb HIPS or kg carbon dioxide equivalents per 1,000 kg HIPS)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	2,417	318	2,735
Methane	203	243	446
Nitrous oxide	11.6	0	11.6
Methyl bromide	3.0E-08	0	3.0E-08
Methyl chloride	3.2E-07	0	3.2E-07
Trichloroethane	1.5E-06	9.9E-06	1.1E-05
Chloroform	6.6E-08	0	6.6E-08
Methylene chloride	7.0E-04	0	7.0E-04
Carbon tetrachloride	0.0024	1.2E-05	0.0024
CFC-012	1.3E-04	0	1.3E-04
HCFC-22	0	1.81	1.81
Total	2,631	563	3,194

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 8-6

Waterborne Emissions for the Production of HIPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0027	0.0027
Acid (benzoic)	0.0049	0.0026	0.0076
Acid (hexanoic)	0.0010	5.4E-04	0.0016
Dissolved Solids	220	115	335
Suspended Solids	8.88	2.45	11.3
BOD	1.24	0.46	1.70
COD	2.42	0.66	3.08
Phenol/Phenolic Compounds	0.0029	0.0012	0.0041
Sulfur	0	0.0068	0.0068
Sulfates	0.36	0.27	0.62
Sulfides	8.7E-04	2.0E-05	8.9E-04
Oil	0.12	0.051	0.17
Hydrocarbons	0	5.2E-04	5.2E-04
Ammonia	0.078	0.040	0.12
Ammonium	0	4.8E-05	4.8E-05
Aluminum	0.28	0.075	0.35
Antimony	1.7E-04	4.6E-05	2.2E-04
Arsenic	0.0012	5.9E-04	0.0018
Barium	3.91	1.09	4.99
Beryllium	6.3E-05	2.8E-05	9.1E-05
Cadmium	1.8E-04	8.7E-05	2.7E-04
Chromium (unspecified)	0.0079	0.0021	0.010
Chromium (hexavalent)	2.8E-05	0	2.8E-05
Cobalt	1.1E-04	5.7E-05	1.7E-04
Copper	0.0011	4.3E-04	0.0015
Iron	0.60	0.20	0.80
Lead	0.0023	9.2E-04	0.0032
Lithium	2.36	2.37	4.73
Magnesium	3.06	1.62	4.68
Manganese	0.0049	0.0036	0.0086
Mercury	3.1E-06	8.2E-07	3.9E-06
Molybdenum	1.1E-04	5.9E-05	1.7E-04
Nickel	0.0011	4.9E-04	0.0016
Selenium	3.4E-05	2.6E-05	6.0E-05
Silver	0.010	0.0054	0.016
Sodium	49.6	26.3	75.9
Strontium	0.27	0.14	0.41
Thallium	3.7E-05	9.7E-06	4.6E-05
Tin	8.4E-04	3.3E-04	0.0012
Titanium	0.0027	7.0E-04	0.0034
Vanadium	1.3E-04	7.0E-05	2.0E-04
Yttrium	3.3E-05	1.7E-05	5.0E-05
Zinc	0.067	0.0019	0.068
Chlorides (unspecified)	176	93.3	269
Chlorides (methyl chloride)	2.0E-07	1.0E-07	3.0E-07
Calcium	15.6	8.30	23.9
Fluorides	0	7.7E-04	7.7E-04
Nitrates	0	1.2E-04	1.2E-04
Nitrogen (ammonia)	0	4.2E-05	4.2E-05

Table 8-6

Waterborne Emissions for the Production of HIPS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Bromide	1.04	0.55	1.60
Boron	0.015	0.0081	0.023
Total Organic Carbon	5.9E-04	0.011	0.012
Cyanide	1.4E-06	1.9E-07	1.5E-06
Hardness	48.2	25.6	73.8
Total Alkalinity	0.39	0.21	0.59
Surfactants	0	0.0025	0.0025
Acetone	4.9E-05	2.6E-05	7.5E-05
Alkylated Benzenes	1.5E-04	4.0E-05	1.9E-04
Alkylated Fluorenes	8.9E-06	2.3E-06	1.1E-05
Alkylated Naphthalenes	2.5E-06	6.6E-07	3.2E-06
Alkylated Phenanthrenes	1.0E-06	2.7E-07	1.3E-06
Benzene	0.0082	0.0043	0.013
Cresols	2.9E-04	1.5E-04	4.4E-04
Cymene	4.9E-07	2.6E-07	7.4E-07
Dibenzofuran	9.3E-07	4.9E-07	1.4E-06
Dibenzothiophene	7.5E-07	4.0E-07	1.1E-06
2,4 dimethylphenol	1.4E-04	7.2E-05	2.1E-04
Ethylbenzene	0.0014	2.4E-04	0.0016
2-Hexanone	3.2E-05	1.7E-05	4.9E-05
Methyl Ethyl Ketone (MEK)	3.9E-07	2.1E-07	6.0E-07
1-methylfluorene	5.5E-07	2.9E-07	8.5E-07
2-methyl naphthalene	7.7E-05	4.1E-05	1.2E-04
4-methyl 2-pentanone	2.0E-05	1.1E-05	3.1E-05
Naphthalene	8.9E-05	4.7E-05	1.4E-04
Pentamethyl benzene	3.6E-07	1.9E-07	5.6E-07
Phenanthrene	1.0E-06	3.9E-07	1.4E-06
Toluene	0.0078	0.0041	0.012
Total Biphenyls	9.9E-06	2.6E-06	1.2E-05
Total Dibenzo-thiophenes	3.1E-08	8.0E-09	3.9E-08
Xylenes	0.0042	0.0022	0.0063
Radionuclides (unspecified) (1)	0	8.4E-08	8.4E-08
Phosphates	0.0010	0	0.0010
Lead 210	5.1E-13	0	5.1E-13
n-Decane	1.4E-04	0	1.4E-04
n-Docosane	5.2E-06	0	5.2E-06
n-Dodecane	2.7E-04	0	2.7E-04
n-Eicosane	7.4E-05	0	7.4E-05
n-Hexacosane	3.3E-06	0	3.3E-06
n-Hexadecane	2.9E-04	0	2.9E-04
n-Octadecane	7.3E-05	0	7.3E-05
n-Tetradecane	1.2E-04	0	1.2E-04
Styrene	9.4E-04	0	9.4E-04
Fluorine	4.5E-06	0	4.5E-06
Radium 226	1.8E-10	0	1.8E-10
Radium 228	9.0E-13	0	9.0E-13

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 6.86 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 9

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR PVC RESIN

This chapter presents LCI results for the production of polyvinyl chloride (PVC) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of PVC resin. Figure 9-1 presents the flow diagram for the production of PVC resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix I of the Appendices (separate document).

No fillers, additives, or plasticizers are included in this analysis; therefore, no compounding process is included.

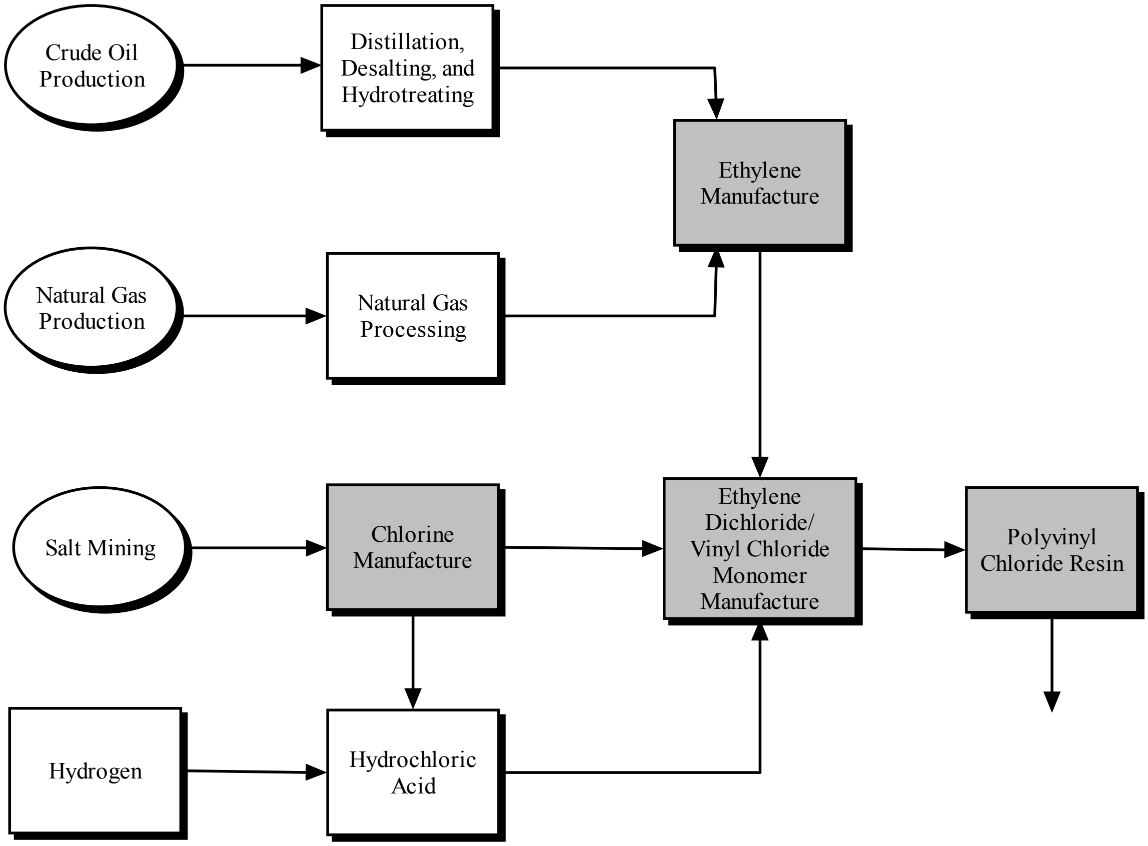

Figure 9-1. Flow diagram for the manufacture of polyvinyl chloride (PVC) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Primary data was collected for olefins, chlorine/caustic soda, EDC/VCM, and PVC resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. According to a study performed by Chemical Market Associates, Inc. (CMAI), the approximate amount of chlorine from mercury cell technology going into EDC production is 1.4 percent. The collected datasets were weighted using 1.4 percent mercury cell technology and 98.6 percent diaphragm/membrane cell technology. As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies. The captured production amount is approximately 30 percent of the available capacity for all chlorine production in the U.S. Caustic soda and hydrogen are the coproducts produced with chlorine. A mass basis was used to allocate the credit to the coproducts.

A weighted average using production amounts was calculated from the EDC/VCM production data from three plants collected from three leading producers in North America. As of 2003, there were 8 VCM producers and 12 VCM plants in the U.S. The captured production amount is approximately 50 percent of the available capacity for VCM production in the U.S. Dichloroethane is produced as a coproduct during this process. A mass basis was used to allocate the credit for the coproduct.

A weighted average using production amounts was calculated from the PVC production data from three plants collected from three leading producers in North America. As of 2003, there were 12 PVC producers and 25 PVC plants in the U.S. The captured production amount is approximately 35 percent of the available capacity for PVC production in the U.S. and Canada. Scrap resin (e.g. off-spec) is produced as a coproduct during this process. A mass basis was used to allocate the credit for the coproduct.

DESCRIPTION OF TABLES

The average gross energy required to produce PVC resin is 25.4 million Btu per 1,000 pounds of resin or 59.0 GJ per 1,000 kilograms of resin. Tables 9-1 and 9-2 show the breakdown of energy requirements for the production of PVC resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table I-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of PVC resin. Natural gas and petroleum used as raw material inputs for the production of PVC, reported as energy of material resource in Table 9-1, are included in the totals for natural gas and petroleum energy in Table 9-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 9-2 are used to generate purchased electricity along with the fossil fuels.

Table 9-3 shows the weight of solid waste generated during the production of PVC resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Table 9-1

Energy by Category for the Production of PVC Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	14.3	33.3
Transportation	0.33	0.78
Energy of Material Resource	10.7	24.9
Total Energy	**25.4**	**59.0**
Energy Category (Percent)		
Process	56%	56%
Transportation	1%	1%
Energy of Material Resource	42%	42%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 9-2

Energy Profile for the Production of PVC Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	19.3	44.9
Petroleum	2.62	6.09
Coal	2.64	6.13
Hydropower	0.107	0.25
Nuclear	0.57	1.33
Wood	0	0
Other	0.11	0.26
Recovered Energy (1)	-0.0054	-0.013
Total Energy	**25.4**	**59.0**
Energy Source (Percent)		
Natural Gas	76%	76%
Petroleum	10%	10%
Coal	10%	10%
Hydropower	0%	0%
Nuclear	2%	2%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

---

(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 9-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 9-3

Solid Wastes by Weight for the Production of PVC Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	16.0	16.0
Incinerated	5.84	5.84
Waste-to-Energy	21.7	21.7
Fuel	94.2	94.2
Total	**138**	**138**
Weight Percent by Category		
Process		
Landfilled	12%	12%
Incinerated	4%	4%
Waste-to-Energy	16%	16%
Fuel	68%	68%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 9-5 provides a greenhouse gas (GHG) summary for the production of PVC resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 9-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 9-4 are multiplied by their global warming potential and shown in Table 9-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 9-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 9-4

Atmospheric Emissions for the Production of PVC Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.13	0.39	0.52
Particulates (PM2.5)	0.0011	0	0.0011
Particulates (PM10)	0.058	0.16	0.22
Nitrogen Oxides	0.066	3.10	3.17
Hydrocarbons (unspecified)	0.24	0.056	0.29
VOC (unspecified)	0.34	0.36	0.70
TNMOC (unspecified)	0	0.014	0.014
Sulfur Dioxide	0	12.5	12.5
Sulfur Oxides	10.7	0.29	11.0
Carbon Monoxide	1.29	1.44	2.73
Fossil CO2	72.6	1,744	1,817
Non-Fossil CO2	0	10.3	10.3
Aldehydes (Formaldehyde)	0	0.0012	0.0012
Aldehydes (Acetaldehyde)	0	7.2E-05	7.2E-05
Aldehydes (Propionaldehyde)	0	3.7E-06	3.7E-06
Aldehydes (unspecified)	0.0040	0.0012	0.0053
Organics (unspecified) (1)	0.046	6.4E-04	0.047
Ammonia	0.0020	5.9E-04	0.0026
Ammonia Chloride	0	8.1E-05	8.1E-05
Methane	6.43	6.14	12.6
Kerosene	0	1.5E-04	1.5E-04
Chorine	0.012	4.2E-05	0.012
HCl	0.0029	0.13	0.14
HF	0	0.017	0.017
Metals (unspecified)	0	0.0023	0.0023
Mercaptan	0	0.0021	0.0021
Antimony	0	2.5E-06	2.5E-06
Arsenic	0	5.1E-05	5.1E-05
Beryllium	0	2.9E-06	2.9E-06
Cadmium	0	1.6E-05	1.6E-05
Chromium (VI)	0	9.1E-06	9.1E-06
Chromium	0	4.3E-05	4.3E-05
Cobalt	0	2.1E-05	2.1E-05
Copper	0	7.9E-07	7.9E-07
Lead	5.9E-09	8.9E-05	8.9E-05
Magnesium	0	0.0013	0.0013
Manganese	0	1.5E-04	1.5E-04
Mercury	1.4E-05	2.4E-05	3.8E-05
Nickel	0	1.7E-04	1.7E-04
Selenium	0	1.5E-04	1.5E-04
Zinc	0	5.3E-07	5.3E-07
Acetophenone	0	1.5E-07	1.5E-07
Acrolein	0	2.5E-04	2.5E-04
Nitrous Oxide	0	0.038	0.038
Benzene	0.041	0.037	0.079
Benzyl Chloride	0	6.8E-06	6.8E-06
Bis(2-ethylhexyl) Phthalate (DEHP)	0	7.1E-07	7.1E-07
1,3 Butadiene	0	6.9E-07	6.9E-07
2-Chloroacetophenone	0	6.8E-08	6.8E-08
Chlorobenzene	0	2.1E-07	2.1E-07
2,4-Dinitrotoluene	0	2.7E-09	2.7E-09
Ethyl Chloride	0	4.1E-07	4.1E-07
Ethylbenzene	0.0052	0.0043	0.0095
Ethylene Dibromide	0	1.2E-08	1.2E-08
Ethylene Dichloride	0	3.9E-07	3.9E-07
Hexane	0	6.5E-07	6.5E-07
Isophorone (C9H14O)	0	5.6E-06	5.6E-06
Methyl Bromide	0	1.6E-06	1.6E-06
Methyl Chloride	0	5.1E-06	5.1E-06
Methyl Ethyl Ketone	0	3.8E-06	3.8E-06

Table 9-4

Atmospheric Emissions for the Production of PVC Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Methyl Hydrazine		0	1.9E-06	1.9E-06
Methyl Methacrylate		0	2.2E-07	2.2E-07
Methyl Tert Butyl Ether (MTBE)		0	3.9E-07	3.9E-07
Naphthalene		0	1.3E-05	1.3E-05
Propylene		0	4.7E-05	4.7E-05
Propylene Oxide		9.2E-05	0	9.2E-05
Styrene		0	2.8E-07	2.8E-07
Toluene		0.065	0.058	0.12
Trichloroethane		9.3E-09	2.3E-07	2.4E-07
Vinyl Acetate		0	8.5E-08	8.5E-08
Xylenes		0.037	0.034	0.071
Bromoform		0	4.4E-07	4.4E-07
Chloroform		0	6.6E-07	6.6E-07
Carbon Disulfide		0	1.5E-06	1.5E-06
Dimethyl Sulfate		0	5.4E-07	5.4E-07
Cumene		0	5.9E-08	5.9E-08
Cyanide		0	2.8E-05	2.8E-05
Perchloroethylene		0	5.7E-06	5.7E-06
Methylene Chloride		0	6.7E-05	6.7E-05
Carbon Tetrachloride		1.2E-04	2.6E-06	1.2E-04
Phenols		0	1.4E-05	1.4E-05
Fluorides		0	5.1E-04	5.1E-04
Polyaromatic Hydrocarbons (total)		0	5.8E-06	5.8E-06
Biphenyl		0	2.2E-07	2.2E-07
Acenaphthene		0	6.5E-08	6.5E-08
Acenaphthylene		0	3.2E-08	3.2E-08
Anthracene		0	2.7E-08	2.7E-08
Benzo(a)anthracene		0	1.0E-08	1.0E-08
Benzo(a)pyrene		0	4.8E-09	4.8E-09
Benzo(b,j,k)fluroanthene		0	1.4E-08	1.4E-08
Benzo(g,h,i) perylene		0	3.4E-09	3.4E-09
Chrysene		0	1.3E-08	1.3E-08
Fluoranthene		0	9.1E-08	9.1E-08
Fluorene		0	1.2E-07	1.2E-07
Indeno(1,2,3-cd)pyrene		0	7.8E-09	7.8E-09
Naphthanlene		0	1.7E-06	1.7E-06
Phenanthrene		0	3.4E-07	3.4E-07
Pyrene		0	4.2E-08	4.2E-08
5-Methyl Chrysene		0	2.8E-09	2.8E-09
Dioxins (unspecified)	(2)	1.1E-10	9.7E-08	9.7E-08
Furans (unspecified)		0	5.3E-10	5.3E-10
CFC12		0	3.3E-09	3.3E-09
Radionuclides (unspecified)	(3)	0	0.0091	0.0091
HCFC-22		0.0010	0	0.0010
HCFC-123		5.6E-05	0	5.6E-05
HFC-134a		5.6E-05	0	5.6E-05
Hydrogen		0.0018	0	0.0018
Acid (unknown)		0.34	0	0.34
Vinyl Chloride	(4)	0.039	0	0.039

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(1) This emission category contains small amounts of EDC and VCM as well as other hydrocarbons which were not separated out by the data providers. These amounts may be overcounting the VCM emissions as the Vinyl Institute provided atmospheric VCM emissions for the production of EDC/VCM/PVC.

(2) This emission was provided by the Vinyl Institute based on 2003 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. The values are based on TM 17 congeners. If these amounts were converted to toxic equivalents, the TEQ would be 200 to 300 times lower.

(3) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 672,639 kBq per 1,000 kgs of product.

(4) This vinyl chloride emission was provided by the Vinyl Institute, based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average. The dioxin amounts shown were calculated as toxic equivalent values (TEQ).

Source: Franklin Associates, A Division of ERG

Table 9-5

Greenhouse Gas Summary for the Production of PVC Resin
(lb carbon dioxide equivalents per 1,000 lb PVC or kg carbon dioxide equivalents per 1,000 kg PVC)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,847	72.6	1,919
Methane	161	161	322
Nitrous oxide	12.4	0	12.4
Methyl bromide	9.0E-06	0	9.0E-06
Methyl chloride	9.5E-05	0	9.5E-05
Trichloroethane	3.2E-05	1.3E-06	3.3E-05
Chloroform	2.0E-05	0	2.0E-05
Methylene chloride	6.7E-04	0	6.7E-04
Carbon tetrachloride	0.0037	0.16	0.17
CFC-012	3.6E-05	0	3.6E-05
HCFC-22	0	1.81	1.81
HCFC-123	0	0.0043	0.0043
HFC-134a	0	0.080	0.080
Total	2,020	235	2,255

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 9-6

Waterborne Emissions for the Production of PVC Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0020	0.0020
Acid (benzoic)	0.0023	0.0018	0.0041
Acid (hexanoic)	4.7E-04	3.7E-04	8.4E-04
Dissolved Solids	128	78.7	207
Suspended Solids	2.39	1.37	3.76
BOD	0.58	0.40	0.98
COD	0.74	0.49	1.23
Phenol/Phenolic Compounds	0.0016	8.0E-04	0.0024
Sulfur	0	0.0047	0.0047
Sulfates	0.17	0.25	0.41
Sulfides	2.3E-05	5.4E-06	2.8E-05
Oil	0.046	0.034	0.080
Hydrocarbons	0	3.6E-04	3.6E-04
Ammonia	0.031	0.027	0.058
Ammonium	0	7.2E-05	7.2E-05
Aluminum	0.067	0.041	0.11
Antimony	4.1E-05	2.4E-05	6.6E-05
Arsenic	5.2E-04	4.0E-04	9.2E-04
Barium	0.98	0.60	1.58
Beryllium	2.5E-05	1.8E-05	4.3E-05
Cadmium	7.6E-05	5.9E-05	1.3E-04
Chromium (unspecified)	0.0020	0.0011	0.0031
Chromium (hexavalent)	3.6E-06	0	3.6E-06
Cobalt	5.0E-05	3.9E-05	8.9E-05
Copper	3.7E-04	2.8E-04	6.5E-04
Iron	0.17	0.12	0.29
Lead	8.1E-04	5.9E-04	0.0014
Lithium	2.04	1.79	3.83
Magnesium	1.42	1.11	2.53
Manganese	0.0023	0.0035	0.0058
Mercury	8.4E-07	4.5E-07	1.3E-06
Molybdenum	5.2E-05	4.1E-05	9.2E-05
Nickel	4.3E-04	3.2E-04	7.5E-04
Selenium	8.1E-06	3.0E-05	3.8E-05
Silver	0.0047	0.0037	0.0084
Sodium	23.0	18.0	41.0
Strontium	0.12	0.10	0.22
Thallium	8.7E-06	5.2E-06	1.4E-05
Tin	2.9E-04	2.1E-04	5.0E-04
Titanium	6.3E-04	3.8E-04	0.0010
Vanadium	6.1E-05	4.8E-05	1.1E-04
Yttrium	1.5E-05	1.2E-05	2.7E-05
Zinc	0.0018	0.0011	0.0028
Chlorides (unspecified)	81.5	63.8	145
Chlorides (methyl chloride)	9.1E-08	7.1E-08	1.6E-07
Calcium	7.25	5.68	12.9
Fluorides	0	0.0012	0.0012
Nitrates	0.010	1.8E-04	0.010
Nitrogen (ammonia)	0	6.3E-05	6.3E-05

Table 9-6

Waterborne Emissions for the Production of PVC Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Bromide		0.48	0.38	0.86
Boron		0.0071	0.0055	0.013
Total Organic Carbon		4.5E-04	0.0084	0.0089
Cyanide		1.2E-06	1.3E-07	1.3E-06
Hardness		22.3	17.5	39.8
Total Alkalinity		0.18	0.14	0.32
Surfactants		0	0.0017	0.0017
Acetone		2.3E-05	1.8E-05	4.0E-05
Alkylated Benzenes		3.6E-05	2.1E-05	5.7E-05
Alkylated Fluorenes		2.1E-06	1.2E-06	3.3E-06
Alkylated Naphthalenes		5.9E-07	3.5E-07	9.4E-07
Alkylated Phenanthrenes		2.5E-07	1.5E-07	3.9E-07
Benzene		0.0038	0.0030	0.0068
Cresols		1.3E-04	1.0E-04	2.4E-04
Cymene		2.3E-07	1.8E-07	4.0E-07
Dibenzofuran		4.3E-07	3.4E-07	7.6E-07
Dibenzothiophene		3.5E-07	2.7E-07	6.2E-07
2,4 dimethylphenol		6.3E-05	4.9E-05	1.1E-04
Ethylbenzene		2.2E-04	1.7E-04	3.8E-04
2-Hexanone		1.5E-05	1.2E-05	2.6E-05
Methyl Ethyl Ketone (MEK)		1.8E-07	1.4E-07	3.2E-07
1-methylfluorene		2.6E-07	2.0E-07	4.6E-07
2-methyl naphthalene		3.6E-05	2.8E-05	6.4E-05
4-methyl 2-pentanone		9.5E-06	7.4E-06	1.7E-05
Naphthalene		4.1E-05	3.2E-05	7.3E-05
Pentamethyl benzene		1.7E-07	1.3E-07	3.0E-07
Phenanthrene		3.4E-07	2.4E-07	5.9E-07
Toluene		0.0036	0.0028	0.0064
Total Biphenyls		2.3E-06	1.4E-06	3.7E-06
Total Dibenzo-thiophenes		7.2E-09	4.3E-09	1.1E-08
Xylenes		0.0019	0.0015	0.0034
Radionuclides (unspecified)	(1)	0	1.3E-07	1.3E-07
Lead 210		2.3E-13	0	2.3E-13
n-Decane		6.6E-05	0	6.6E-05
n-Docosane		2.4E-06	0	2.4E-06
n-Dodecane		1.2E-04	0	1.2E-04
n-Eicosane		3.4E-05	0	3.4E-05
n-Hexacosane		1.5E-06	0	1.5E-06
n-Hexadecane		1.4E-04	0	1.4E-04
n-Octadecane		3.4E-05	0	3.4E-05
n-Tetradecane		5.5E-05	0	5.5E-05
Styrene		4.5E-07	0	4.5E-07
Fluorine		1.2E-06	0	1.2E-06
Radium 226		8.2E-11	0	8.2E-11
Radium 228		4.2E-13	0	4.2E-13
Vinyl Chloride	(2)	0.0010	0	0.0010
Dioxins	(3)	2.9E-10	0	2.9E-10

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 9.40 kBq per 1,000 kgs of product.

(2) This vinyl chloride emission was provided by the Vinyl Institute, based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average. The dioxin amounts shown were calculated as toxic equivalent values (TEQ).

(3) This emission was provided by the Vinyl Institute based on 2003 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. The values are based on TM 17 congeners. If these amounts were converted to toxic equivalents, the TEQ would be 200 to 300 times lower.

Source: Franklin Associates, A Division of ERG

CHAPTER 10

CRADLE-TO-RESIN LIFE CYCLE INVENTORY RESULTS FOR ABS RESIN

This chapter presents LCI results for the production of acrylonitrile-butadiene-styrene (ABS) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of ABS resin. Figure 10-1 presents the flow diagram for the production of ABS resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix J of the Appendices (separate document).

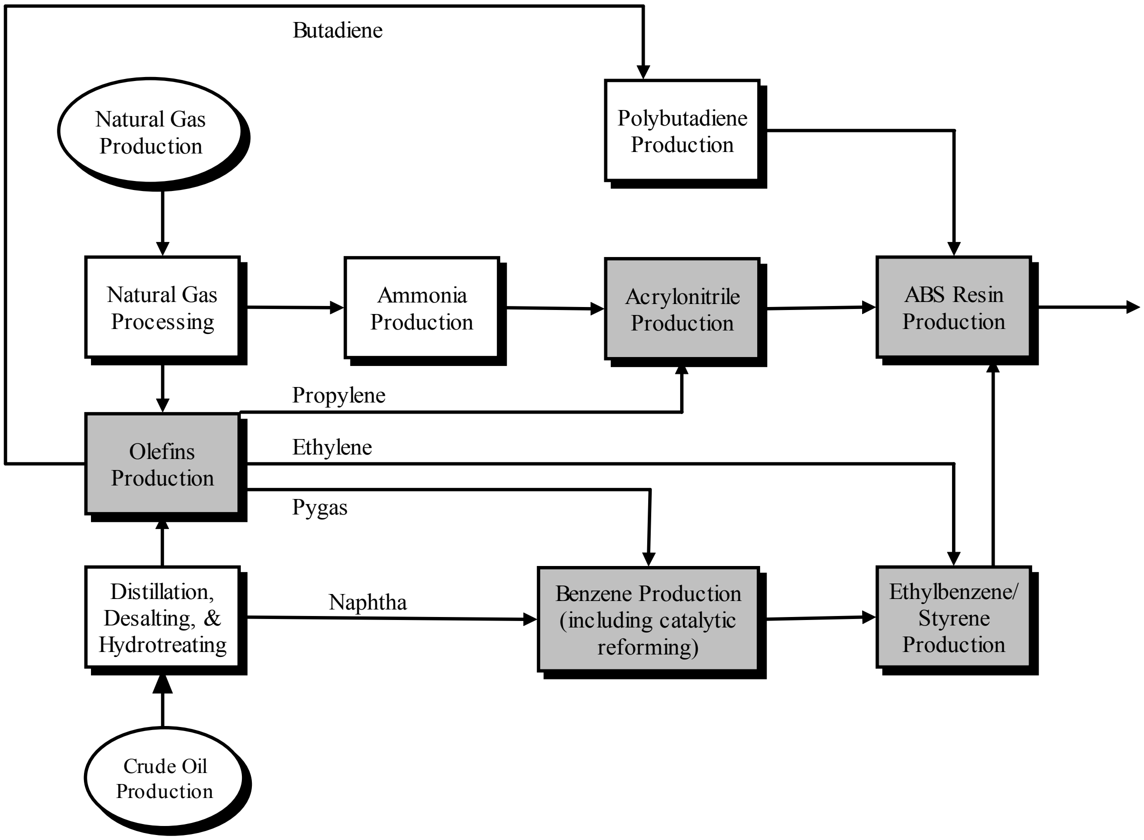

Figure 10-1. Flow diagram for the production of acrylonitrile-butadiene-styrene (ABS) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Primary data was collected for olefins, benzene, ethylbenzene/styrene, acrylonitrile, and ABS resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

It is estimated that one-third of the benzene production is from pyrolysis gasoline and two-thirds are produced from catalytic reforming. These percentages were used to weight the collected datasets for benzene. Catalytic reforming is represented by 2 primary datasets from 1992. The benzene data collected for this analysis represent 1 producer and 1 plant in the U.S. using the pyrolysis gasoline production method. As of 2002 there were 22 benzene producers and 38 benzene plants in the U.S. for the three standard technologies. The captured production amount is approximately 10 percent of the available capacity for benzene production in the U.S. Numerous aromatic coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the reactor, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit the remaining aromatic products.

Two of the three ethylbenzene/styrene datasets were collected for this project and represents 2002-2003 data, while the other dataset comes from 1993. As of 2001 there were 8 styrene producers and 8 styrene plants in the U.S. The styrene data collected for this module represent 2 producers and 2 plants in the U.S. The captured production amount is approximately 25 percent of the available capacity for styrene production in the U.S. Various coproduct streams are produced during this process. A mass basis was used to allocate the credit to the coproducts in the datasets collected during this analysis.

Only one company provided the dataset for the production of acrylonitrile. The company provided ranges for the material inputs and coproducts. The median of these ranges was used in the acrylonitrile dataset. The captured production amount is approximately 30 percent of the available capacity for acrylonitrile production in the U.S. Hydrogen cyanide and acetonitrile are produced as coproducts during the production of acrylonitrile. A mass basis was used to allocate the credit for these coproducts.

A weighted average using production amounts was calculated from the ABS production data from five plants collected from three leading producers in North America. As of 2003, there were 4 ABS producers and 7 ABS plants in the U.S. The captured production amount is approximately 50 percent of the 2004 production amount for ABS production in the U.S., Mexico, and Canada. Scrap resin (e.g. off-spec) and heat are produced as coproducts during the production of ABS. A mass basis was used to allocate the credit for scrap, while the energy amount for the heat was reported separately as recovered energy.

DESCRIPTION OF TABLES

The average gross energy required to produce ABS resin is 46.8 million Btu per 1,000 pounds of resin or 109 GJ per 1,000 kilograms of resin. Tables 10-1 and 10-2 show the breakdown of energy requirements for the production of ABS resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table J-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-resin) for the production of ABS resin. Natural gas and petroleum used as raw material inputs for the production of ABS, reported as energy of material resource in Table 10-1, are included in the totals for natural gas and petroleum energy in Table 10-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 10-2 are used to generate purchased electricity along with the fossil fuels.

Table 10-1

Energy by Category for the Production of ABS Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	21.2	49.4
Transportation	1.06	2.46
Energy of Material Resource	24.5	57.0
Total Energy	**46.8**	**109**
Energy Category (Percent)		
Process	45%	45%
Transportation	2%	2%
Energy of Material Resource	52%	52%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 10-2

Energy Profile for the Production of ABS Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	26.8	62.3
Petroleum	15.2	35.4
Coal	3.95	9.19
Hydropower	0.14	0.34
Nuclear	0.77	1.79
Wood	0	0
Other	0.15	0.35
Recovered Energy (1)	-0.21	-0.48
Total Energy	**46.8**	**109**
Energy Source (Percent)		
Natural Gas	57%	57%
Petroleum	32%	32%
Coal	8%	8%
Hydropower	0%	0%
Nuclear	2%	2%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condensate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 10-3 shows the weight of solid waste generated during the production of ABS resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 10-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 10-3

Solid Wastes by Weight for the Production of ABS Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	52.1	52.1
Incinerated	7.29	7.29
Waste-to-Energy	0.81	0.81
Fuel	139	139
Total	**200**	**200**
Weight Percent by Category		
Process		
Landfilled	26%	26%
Incinerated	4%	4%
Waste-to-Energy	0%	0%
Fuel	70%	70%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 10-5 provides a greenhouse gas (GHG) summary for the production of ABS resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 10-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 10-4 are multiplied by their global warming potential and shown in Table 10-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 10-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 10-4

Atmospheric Emissions for the Production of ABS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.31	0.66	0.97
Particulates (PM2.5)	0.0053	0	0.0053
Particulates (PM10)	0.074	0.37	0.44
Nitrogen Oxides	0.90	6.80	7.70
Hydrocarbons (unspecified)	3.46	0.20	3.66
VOC (unspecified)	0.50	0.57	1.07
TNMOC (unspecified)	0	0.027	0.027
Sulfur Dioxide	0	18.1	18.1
Sulfur Oxides	17.0	1.02	18.0
Carbon Monoxide	9.18	3.11	12.3
Fossil CO2	260	2,965	3,225
Non-Fossil CO2	0	15.2	15.2
Aldehydes (Formaldehyde)	0	0.0019	0.0019
Aldehydes (Acetaldehyde)	0	1.2E-04	1.2E-04
Aldehydes (Propionaldehyde)	0	1.3E-05	1.3E-05
Aldehydes (unspecified)	0.027	0.0041	0.031
Organics (unspecified)	0.14	9.5E-04	0.14
Ammonia	0.11	0.0020	0.11
Ammonia Chloride	0	1.2E-04	1.2E-04
Methane	11.2	8.86	20.1
Kerosene	0	2.2E-04	2.2E-04
Chorine	1.1E-04	6.2E-05	1.7E-04
HCl	5.9E-07	0.21	0.21
HF	0	0.027	0.027
Metals (unspecified)	0	0.0033	0.0033
Mercaptan	0	0.0074	0.0074
Antimony	0	4.0E-06	4.0E-06
Arsenic	0	8.7E-05	8.7E-05
Beryllium	0	4.6E-06	4.6E-06
Cadmium	0	2.6E-05	2.6E-05
Chromium (VI)	0	1.5E-05	1.5E-05
Chromium	0	6.9E-05	6.9E-05
Cobalt	0	5.6E-05	5.6E-05
Copper	0	7.4E-07	7.4E-07
Lead	0	2.1E-04	2.1E-04
Magnesium	0	0.0021	0.0021
Manganese	0	2.4E-04	2.4E-04
Mercury	0	6.2E-05	6.2E-05
Nickel	0	5.9E-04	5.9E-04
Selenium	0	2.5E-04	2.5E-04
Zinc	0	4.9E-07	4.9E-07
Acetophenone	0	5.1E-07	5.1E-07
Acrolein	0	3.7E-04	3.7E-04
Nitrous Oxide	0	0.072	0.072
Benzene	0.060	0.053	0.11
Benzyl Chloride	0	2.4E-05	2.4E-05
Bis(2-ethylhexyl) Phthalate (DEHP)	0	2.5E-06	2.5E-06
1,3 Butadiene	0	1.2E-06	1.2E-06
2-Chloroacetophenone	0	2.4E-07	2.4E-07
Chlorobenzene	0	7.5E-07	7.5E-07
2,4-Dinitrotoluene	0	9.6E-09	9.6E-09
Ethyl Chloride	0	1.4E-06	1.4E-06
Ethylbenzene	0.0075	0.0059	0.013
Ethylene Dibromide	0	4.1E-08	4.1E-08
Ethylene Dichloride	0	1.4E-06	1.4E-06

Table 10-4

Atmospheric Emissions for the Production of ABS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Hexane	0	2.3E-06	2.3E-06
Isophorone (C9H14O)	0	2.0E-05	2.0E-05
Methyl Bromide	0	5.5E-06	5.5E-06
Methyl Chloride	0	1.8E-05	1.8E-05
Methyl Ethyl Ketone	0	1.3E-05	1.3E-05
Methyl Hydrazine	0	5.8E-06	5.8E-06
Methyl Methacrylate	0	6.9E-07	6.9E-07
Methyl Tert Butyl Ether (MTBE)	0	1.2E-06	1.2E-06
Naphthalene	0	2.1E-05	2.1E-05
Propylene	0	8.0E-05	8.0E-05
Styrene	0	8.6E-07	8.6E-07
Toluene	0.094	0.076	0.17
Trichloroethane	6.2E-08	7.0E-07	7.6E-07
Vinyl Acetate	0	2.6E-07	2.6E-07
Xylenes	0.054	0.044	0.099
Bromoform	0	1.3E-06	1.3E-06
Chloroform	0	2.0E-06	2.0E-06
Carbon Disulfide	0	4.5E-06	4.5E-06
Dimethyl Sulfate	0	1.6E-06	1.6E-06
Cumene	0	1.8E-07	1.8E-07
Cyanide	0	8.6E-05	8.6E-05
Perchloroethylene	0	8.7E-06	8.7E-06
Methylene Chloride	0	1.1E-04	1.1E-04
Carbon Tetrachloride	7.7E-09	3.5E-06	3.5E-06
Phenols	0	3.2E-05	3.2E-05
Fluorides	0	0.0015	0.0015
Polyaromatic Hydrocarbons (total)	0	9.3E-06	9.3E-06
Biphenyl	0	3.2E-07	3.2E-07
Acenaphthene	0	9.7E-08	9.7E-08
Acenaphthylene	0	4.8E-08	4.8E-08
Anthracene	0	4.0E-08	4.0E-08
Benzo(a)anthracene	0	1.5E-08	1.5E-08
Benzo(a)pyrene	0	7.2E-09	7.2E-09
Benzo(b,j,k)fluroanthene	0	2.1E-08	2.1E-08
Benzo(g,h,i) perylene	0	5.1E-09	5.1E-09
Chrysene	0	1.9E-08	1.9E-08
Fluoranthene	0	1.4E-07	1.4E-07
Fluorene	0	1.7E-07	1.7E-07
Indeno(1,2,3-cd)pyrene	0	1.2E-08	1.2E-08
Naphthanlene	0	2.5E-06	2.5E-06
Phenanthrene	0	5.1E-07	5.1E-07
Pyrene	0	6.3E-08	6.3E-08
5-Methyl Chrysene	0	4.2E-09	4.2E-09
Dioxins (unspecified)	0	1.3E-07	1.3E-07
Furans (unspecified)	0	7.1E-10	7.1E-10
CFC12	0	1.1E-08	1.1E-08
Radionuclides (unspecified) (1)	0	0.012	0.012
HCFC-22	1.0E-04	0	1.0E-04
Hydrogen	0.0029	0	0.0029
Acid (unknown)	0.50	0	0.50
Hydrogen Cyanide	0.010	0	0.010

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 991,912 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 10-5

Greenhouse Gas Summary for the Production of ABS Resin
(lb carbon dioxide equivalents per 1,000 lb ABS or kg carbon dioxide equivalents per 1,000 kg ABS)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	2,965	260	3,225
Methane	222	281	502
Nitrous oxide	21.5	0	21.5
Methyl bromide	2.7E-05	0	2.7E-05
Methyl chloride	2.9E-04	0	2.9E-04
Trichloroethane	9.7E-05	8.7E-06	1.1E-04
Chloroform	6.1E-05	0	6.1E-05
Methylene chloride	0.0011	0	0.0011
Carbon tetrachloride	0.0049	1.1E-05	0.0049
CFC-012	1.2E-04	0	1.2E-04
HCFC-22	0	0.18	0.18
Total	3,208	541	3,749

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 10-6

Waterborne Emissions for the Production of ABS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0027	0.0027
Acid (benzoic)	0.0052	0.0026	0.0078
Acid (hexanoic)	0.0011	5.3E-04	0.0016
Metal (unspecified)	1.0E-04	0	1.0E-04
Dissolved Solids	230	112	342
Suspended Solids	9.45	2.35	11.8
BOD	1.24	0.54	1.77
COD	5.25	0.65	5.90
Phenol/Phenolic Compounds	0.0032	0.0011	0.0043
Sulfur	0	0.0067	0.0067
Sulfates	0.38	0.34	0.72
Sulfides	6.5E-04	1.8E-05	6.7E-04
Oil	0.23	0.050	0.28
Hydrocarbons	0	5.1E-04	5.1E-04
Ammonia	0.19	0.039	0.22
Ammonium	0	9.6E-05	9.6E-05
Aluminum	0.26	0.071	0.33
Antimony	1.6E-04	4.3E-05	2.1E-04
Arsenic	0.0013	5.8E-04	0.0018
Barium	3.69	1.03	4.73
Beryllium	6.4E-05	2.7E-05	9.2E-05
Cadmium	1.9E-04	8.5E-05	2.7E-04
Chromium (unspecified)	0.0074	0.0020	0.0094
Chromium (hexavalent)	2.4E-05	0	2.4E-05
Cobalt	1.1E-04	5.6E-05	1.7E-04
Copper	0.0011	4.3E-04	0.0015
Iron	0.58	0.19	0.77
Lead	0.0023	8.9E-04	0.0032
Lithium	2.97	2.34	5.32
Magnesium	3.23	1.58	4.81
Manganese	0.0052	0.0050	0.010
Mercury	2.9E-06	7.9E-07	3.7E-06
Molybdenum	1.2E-04	5.8E-05	1.8E-04
Nickel	0.0011	4.7E-04	0.0016
Selenium	3.2E-05	4.2E-05	7.4E-05
Silver	0.011	0.0053	0.016
Sodium	52.3	25.7	78.0
Strontium	0.28	0.14	0.42
Thallium	3.5E-05	9.2E-06	4.4E-05
Tin	8.4E-04	3.2E-04	0.0012
Titanium	0.0025	6.7E-04	0.0032
Vanadium	1.4E-04	6.8E-05	2.1E-04
Yttrium	3.5E-05	1.7E-05	5.2E-05
Zinc	0.0064	0.0018	0.0082
Chlorides (unspecified)	185	91.0	276
Chlorides (methyl chloride)	2.1E-07	1.0E-07	3.1E-07
Calcium	16.5	8.10	24.6
Fluorides	0	0.0016	0.0016
Nitrates	0.010	2.4E-04	0.010
Nitrogen (ammonia)	0	8.4E-05	8.4E-05

Table 10-6

Waterborne Emissions for the Production of ABS Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Bromide		1.10	0.54	1.64
Boron		0.016	0.0079	0.024
Total Organic Carbon		7.4E-04	0.011	0.012
Cyanide		3.7E-07	1.8E-07	5.5E-07
Hardness		50.8	24.9	75.8
Total Alkalinity		0.41	0.20	0.61
Surfactants		0	0.0025	0.0025
Acetone		5.1E-05	2.5E-05	7.7E-05
Alkylated Benzenes		1.4E-04	3.8E-05	1.8E-04
Alkylated Fluorenes		8.3E-06	2.2E-06	1.1E-05
Alkylated Naphthalenes		2.4E-06	6.2E-07	3.0E-06
Alkylated Phenanthrenes		9.8E-07	2.6E-07	1.2E-06
Benzene		0.0086	0.0042	0.013
Cresols		3.1E-04	1.5E-04	4.5E-04
Cymene		5.1E-07	2.5E-07	7.6E-07
Dibenzofuran		9.8E-07	4.8E-07	1.5E-06
Dibenzothiophene		7.9E-07	3.9E-07	1.2E-06
2,4 dimethylphenol		1.4E-04	7.1E-05	2.1E-04
Ethylbenzene		0.0012	2.4E-04	0.0014
2-Hexanone		3.4E-05	1.6E-05	5.0E-05
Methyl Ethyl Ketone (MEK)		4.1E-07	2.0E-07	6.2E-07
1-methylfluorene		5.8E-07	2.9E-07	8.7E-07
2-methyl naphthalene		8.1E-05	4.0E-05	1.2E-04
4-methyl 2-pentanone		2.2E-05	1.1E-05	3.2E-05
Naphthalene		9.3E-05	4.6E-05	1.4E-04
Pentamethyl benzene		3.8E-07	1.9E-07	5.7E-07
Phenanthrene		1.0E-06	3.8E-07	1.4E-06
Toluene		0.0082	0.0040	0.012
Total Biphenyls		9.3E-06	2.5E-06	1.2E-05
Total Dibenzo-thiophenes		2.9E-08	7.6E-09	3.6E-08
Xylenes		0.0044	0.0021	0.0065
Radionuclides (unspecified)	(1)	0	1.7E-07	1.7E-07
Phosphates		0.010	0	0.010
Lead 210		5.3E-13	0	5.3E-13
n-Decane		1.5E-04	0	1.5E-04
n-Docosane		5.5E-06	0	5.5E-06
n-Dodecane		2.8E-04	0	2.8E-04
n-Eicosane		7.8E-05	0	7.8E-05
n-Hexacosane		3.4E-06	0	3.4E-06
n-Hexadecane		3.1E-04	0	3.1E-04
n-Octadecane		7.7E-05	0	7.7E-05
n-Tetradecane		1.2E-04	0	1.2E-04
Styrene		6.7E-04	0	6.7E-04
Fluorine		4.3E-06	0	4.3E-06
Radium 226		1.9E-10	0	1.9E-10
Radium 228		9.5E-13	0	9.5E-13
Other Organics		1.0E-04	0	1.0E-04

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 13.86 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 11

CRADLE-TO-PRECURSOR LIFE CYCLE INVENTORY RESULTS FOR POLYETHER POLYOL USED FOR RIGID FOAM POLYURETHANE

This chapter presents LCI results for the production of polyether polyol used for rigid foam polyurethane (cradle-to-polyol). The results are given on the bases of 1,000 pounds and 1,000 kilograms of the polyol. Figure 11-1 presents the flow diagram for the production of the polyol. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix K of the Appendices (separate document).

Primary data was collected for olefins, chlorine/caustic soda, and polyether polyol production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

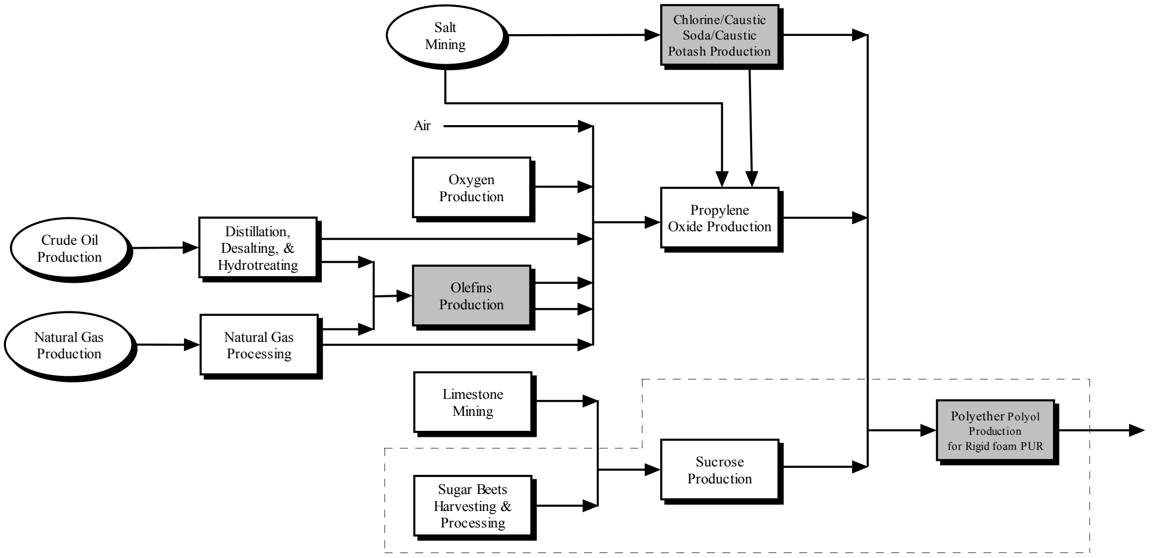

Figure 11-1. Flow diagram for the manufacture of polyether polyol for rigid foam polyurethane. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis. Boxes within the dotted lines are included in an aggregated dataset. Polyol types vary greatly by use. Additives are not included in this analysis of polyether polyols.

The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. The mercury cell technology is more likely to be used to produce high-purity caustic, than chlorine to be used in EDC; however, a small percentage of chlorine used in EDC does still come from mercury cells. For this analysis, it is estimated that 91.4 percent of the cell technology is diaphragm and membrane, while 8.6 percent of the cell technology is mercury. The collected datasets were weighted using these fractions. As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies. The captured production amount is approximately 30 percent of the available capacity for all chlorine production in the U.S. Caustic soda and hydrogen are the coproducts produced with chlorine. A mass basis was used to allocate the credit to the coproducts.

A weighted average using production amounts was calculated from the polyol production data from two plants collected from two leading producers in North America. As of 2002, it is estimated that for all polyurethane applications, there were 7 polyether polyol producers and 9 polyether polyol plants in the U.S. The captured production amount is approximately 40 percent of the available capacity for polyol production in the U.S. and Canada. Heat was a coproduct for one producer. The energy for exported heat was reported separately as recovered energy.

DESCRIPTION OF TABLES

The average gross energy required to produce the polyether polyol for rigid foam polyurethane is 35.4 million Btu per 1,000 pounds or 82.3 GJ per 1,000 kilograms. Tables 11-1 and 11-2 show the breakdown of energy requirements for the production of polyol by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table K-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-polyol) for the production of the polyol. Natural gas and petroleum used as raw material inputs for the production of the polyol, reported as energy of material resource in Table 11-1, are included in the totals for natural gas and petroleum energy in Table 11-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 11-2 are used to generate purchased electricity along with the fossil fuels.

Table 11-1

Energy by Category for the Production of Polyether Polyol for Rigid Foam Polyurethane

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	21.5	50.0
Transportation	0.65	1.50
Energy of Material Resource	13.3	30.9
Total Energy	**35.4**	**82.3**
Energy Category (Percent)		
Process	61%	61%
Transportation	2%	2%
Energy of Material Resource	37%	37%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 11-2

Energy Profile for the Production of Polyether Polyol for Rigid Foam Polyurethane

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	20.7	48.1
Petroleum	9.10	21.2
Coal	4.47	10.4
Hydropower	0.15	0.36
Nuclear	0.82	1.91
Wood	0	0
Other	0.16	0.37
Recovered Energy (1)	-0.0014	-0.0031
Total Energy	**35.4**	**82.3**
Energy Source (Percent)		
Natural Gas	58%	58%
Petroleum	26%	26%
Coal	13%	13%
Hydropower	0%	0%
Nuclear	2%	2%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 11-3 shows the weight of solid waste generated during the production of polyether polyol for rigid foam polyurethane. The process solid waste, those wastes produced directly from the cradle-to-precursor processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 11-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 11-3

Solid Wastes by Weight for the Production of Polyether Polyol for Rigid Foam Polyurethane

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	21.0	21.0
Incinerated	4.57	4.57
Waste-to-Energy	0.0026	0.0026
Fuel	156	156
Total	**182**	**182**
Weight Percent by Category		
Process		
Landfilled	12%	12%
Incinerated	3%	3%
Waste-to-Energy	0%	0%
Fuel	86%	86%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 11-4

Atmospheric Emissions for the Production of Polyether Polyol for Rigid Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.32	0.76	1.08
Particulates (PM2.5)	0.010	0	0.010
Particulates (PM10)	0.11	0.44	0.55
Nitrogen Oxides	0.51	7.89	8.39
Hydrocarbons (unspecified)	5.00	0.40	5.40
VOC (unspecified)	0.35	0.56	0.91
TNMOC (unspecified)	0	0.032	0.032
Sulfur Dioxide	0	17.0	17.0
Sulfur Oxides	11.4	1.47	12.9
Carbon Monoxide	3.44	7.98	11.4
Fossil CO2	63.2	3,038	3,101
Non-Fossil CO2	0	16.2	16.2
Aldehydes (Formaldehyde)	0	0.0029	0.0029
Aldehydes (Acetaldehyde)	0	6.1E-04	6.1E-04
Aldehydes (Propionaldehyde)	0	1.8E-05	1.8E-05
Aldehydes (unspecified)	0.010	0.0084	0.019
Organics (unspecified)	0.11	0.0010	0.11
Ammonia	0.042	0.0042	0.047
Ammonia Chloride	0	1.3E-04	1.3E-04
Methane	8.06	8.41	16.5
Kerosene	0	2.3E-04	2.3E-04
Chorine	0.0022	6.6E-05	0.0023
HCl	2.9E-04	0.24	0.24
HF	0	0.030	0.030
Metals (unspecified)	0	0.0036	0.0036
Mercaptan	0	0.011	0.011
Antimony	0	4.5E-06	4.5E-06
Arsenic	0	1.1E-04	1.1E-04
Beryllium	0	5.9E-06	5.9E-06
Cadmium	0	3.0E-05	3.0E-05
Chromium (VI)	0	1.7E-05	1.7E-05
Chromium	0	8.1E-05	8.1E-05
Cobalt	0	1.1E-04	1.1E-04
Copper	0	2.1E-06	2.1E-06
Lead	9.7E-09	2.8E-04	2.8E-04
Magnesium	0	0.0024	0.0024
Manganese	0	2.8E-04	2.8E-04
Mercury	1.6E-04	8.3E-05	2.4E-04
Nickel	0	0.0014	0.0014
Selenium	0	3.0E-04	3.0E-04
Zinc	0	1.4E-06	1.4E-06
Acetophenone	0	7.3E-07	7.3E-07
Acrolein	0	4.5E-04	4.5E-04
Nitrous Oxide	0	0.083	0.083
Benzene	0.043	0.048	0.090
Benzyl Chloride	0	3.4E-05	3.4E-05
Bis(2-ethylhexyl) Phthalate (DEHP)	0	3.5E-06	3.5E-06
1,3 Butadiene	0	2.6E-05	2.6E-05
2-Chloroacetophenone	0	3.4E-07	3.4E-07
Chlorobenzene	0	1.1E-06	1.1E-06
2,4-Dinitrotoluene	0	1.4E-08	1.4E-08
Ethyl Chloride	0	2.0E-06	2.0E-06
Ethylbenzene	0.73	0.0050	0.74
Ethylene Dibromide	0	5.8E-08	5.8E-08
Ethylene Dichloride	0	1.9E-06	1.9E-06

Table 11-4

Atmospheric Emissions for the Production of Polyether Polyol for Rigid Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Hexane	0	3.3E-06	3.3E-06
Isophorone (C9H14O)	0	2.8E-05	2.8E-05
Methyl Bromide	0	7.8E-06	7.8E-06
Methyl Chloride	0	2.6E-05	2.6E-05
Methyl Ethyl Ketone	0	1.9E-05	1.9E-05
Methyl Hydrazine	0	8.3E-06	8.3E-06
Methyl Methacrylate	0	9.7E-07	9.7E-07
Methyl Tert Butyl Ether (MTBE)	0	1.7E-06	1.7E-06
Naphthalene	0	3.1E-05	3.1E-05
Propylene	0	0.0017	0.0017
Propylene Oxide	0.36	0	0.36
Styrene	0	1.2E-06	1.2E-06
Toluene	0.067	0.065	0.13
Trichloroethane	2.4E-08	9.9E-07	1.0E-06
Vinyl Acetate	0	3.7E-07	3.7E-07
Xylenes	0.039	0.038	0.077
Bromoform	0	1.9E-06	1.9E-06
Chloroform	0	2.9E-06	2.9E-06
Carbon Disulfide	0	6.3E-06	6.3E-06
Dimethyl Sulfate	0	2.3E-06	2.3E-06
Cumene	0	2.6E-07	2.6E-07
Cyanide	0	1.2E-04	1.2E-04
Perchloroethylene	0	1.1E-05	1.1E-05
Methylene Chloride	0	1.7E-04	1.7E-04
Carbon Tetrachloride	1.7E-04	3.7E-06	1.8E-04
Phenols	0	7.1E-05	7.1E-05
Fluorides	0	0.0022	0.0022
Polyaromatic Hydrocarbons (total)	0	1.1E-04	1.1E-04
Biphenyl	0	3.7E-07	3.7E-07
Acenaphthene	0	1.1E-07	1.1E-07
Acenaphthylene	0	5.4E-08	5.4E-08
Anthracene	0	4.5E-08	4.5E-08
Benzo(a)anthracene	0	1.7E-08	1.7E-08
Benzo(a)pyrene	0	8.2E-09	8.2E-09
Benzo(b,j,k)fluroanthene	0	2.4E-08	2.4E-08
Benzo(g,h,i) perylene	0	5.8E-09	5.8E-09
Chrysene	0	2.2E-08	2.2E-08
Fluoranthene	0	1.5E-07	1.5E-07
Fluorene	0	2.0E-07	2.0E-07
Indeno(1,2,3-cd)pyrene	0	1.3E-08	1.3E-08
Naphthanlene	0	2.8E-06	2.8E-06
Phenanthrene	0	5.8E-07	5.8E-07
Pyrene	0	7.1E-08	7.1E-08
5-Methyl Chrysene	0	4.7E-09	4.7E-09
Dioxins (unspecified)	0	1.4E-07	1.4E-07
Furans (unspecified)	0	7.6E-10	7.6E-10
CFC12	0	2.3E-08	2.3E-08
Radionuclides (unspecified) (1)	0	0.013	0.013
HCFC-22	5.9E-07	0	5.9E-07
HCFC-123	8.3E-05	0	8.3E-05
HFC-134a	8.3E-05	0	8.3E-05
Hydrogen	0.0030	0	0.0030
Acid (unknown)	0.35	0	0.35
F2	0.033	0	0.033

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 1,105,836 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 11-5 provides a greenhouse gas (GHG) summary for the production of polyether polyol for rigid foam polyurethane. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 11-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 11-4 are multiplied by their global warming potential and shown in Table 11-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 11-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 11-5

Greenhouse Gas Summary for the Production of Polyether Polyol for Rigid Foam Polyurethane
(lb carbon dioxide equivalents per 1,000 lb Polyol or kg carbon dioxide equivalents per 1,000 kg Polyol)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	3,038	63.2	3,101
Methane	210	202	412
Nitrous oxide	24.7	0	24.7
Methyl bromide	3.9E-05	0	3.9E-05
Methyl chloride	4.1E-04	0	4.1E-04
Trichloroethane	1.4E-04	3.4E-06	1.4E-04
Chloroform	8.6E-05	0	8.6E-05
Methylene chloride	0.0017	0	0.0017
Carbon tetrachloride	0.0052	0.24	0.25
CFC-012	2.5E-04	0	2.5E-04
HCFC-22	0	0.0011	0.0011
HCFC-123	0	0.0064	0.0064
HFC-134a	0	0.12	0.12
Total	3,273	265	3,538

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 11-6

Waterborne Emissions for the Production of Polyether Polyol for Rigid Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	7.56	0.0023	7.56
Acid (benzoic)	0.0029	0.0026	0.0055
Acid (hexanoic)	6.1E-04	5.4E-04	0.0011
Dissolved Solids	169	114	283
Suspended Solids	3.85	3.15	6.99
BOD	1.64	0.49	2.14
COD	1.89	0.58	2.47
Phenol/Phenolic Compounds	1.01	0.0012	1.01
Sulfur	0	0.0068	0.0068
Sulfates	0.21	0.35	0.57
Sulfides	9.1E-05	3.7E-05	1.3E-04
Oil	0.059	0.052	0.11
Hydrocarbons	0.70	5.1E-04	0.70
Ammonia	0.042	0.041	0.083
Ammonium	0	1.0E-04	1.0E-04
Aluminum	0.12	0.10	0.22
Antimony	7.3E-05	6.0E-05	1.3E-04
Arsenic	6.9E-04	6.1E-04	0.0013
Barium	1.68	1.39	3.07
Beryllium	3.4E-05	2.9E-05	6.3E-05
Cadmium	1.0E-04	9.0E-05	1.9E-04
Chromium (unspecified)	0.0033	0.0027	0.0060
Chromium (hexavalent)	9.2E-06	0	9.2E-06
Cobalt	6.4E-05	5.7E-05	1.2E-04
Copper	5.4E-04	4.9E-04	0.0010
Iron	0.28	0.24	0.52
Lead	0.0012	0.0010	0.0022
Lithium	2.12	2.00	4.12
Magnesium	1.82	1.61	3.42
Manganese	0.0029	0.0054	0.0083
Mercury	1.8E-06	1.1E-06	2.9E-06
Molybdenum	6.6E-05	5.9E-05	1.3E-04
Nickel	6.0E-04	5.2E-04	0.0011
Selenium	1.4E-05	4.8E-05	6.2E-05
Silver	0.0061	0.0054	0.011
Sodium	29.4	26.0	55.5
Strontium	0.16	0.14	0.30
Thallium	1.5E-05	1.3E-05	2.8E-05
Tin	4.2E-04	3.6E-04	7.8E-04
Titanium	0.0011	9.2E-04	0.0020
Vanadium	7.8E-05	6.9E-05	1.5E-04
Yttrium	1.9E-05	1.7E-05	3.7E-05
Zinc	0.0029	0.0024	0.0053
Chlorides (unspecified)	104	92.4	197
Chlorides (methyl chloride)	1.2E-07	1.0E-07	2.2E-07
Calcium	9.29	8.22	17.5
Fluorides	0	0.0017	0.0017
Nitrates	0	2.6E-04	2.6E-04
Nitrogen (ammonia)	0.91	9.0E-05	0.91

Table 11-6

Waterborne Emissions for the Production of Polyether Polyol for Rigid Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Bromide		0.62	0.55	1.17
Boron		0.0091	0.0080	0.017
Total Organic Carbon		5.9E-04	0.009	0.010
Cyanide		2.1E-07	1.8E-07	3.9E-07
Hardness		28.6	25.3	53.9
Total Alkalinity		0.23	0.20	0.44
Surfactants		0	0.0024	0.0024
Acetone		2.9E-05	2.6E-05	5.4E-05
Alkylated Benzenes		6.4E-05	5.3E-05	1.2E-04
Alkylated Fluorenes		3.7E-06	3.0E-06	6.8E-06
Alkylated Naphthalenes		1.1E-06	8.6E-07	1.9E-06
Alkylated Phenanthrenes		4.4E-07	3.6E-07	7.9E-07
Benzene		0.0049	0.0043	0.0091
Cresols		1.7E-04	1.5E-04	3.2E-04
Cymene		2.9E-07	2.6E-07	5.4E-07
Dibenzofuran		5.5E-07	4.9E-07	1.0E-06
Dibenzothiophene		4.5E-07	3.9E-07	8.4E-07
2,4 dimethylphenol		8.1E-05	7.2E-05	1.5E-04
Ethylbenzene		2.8E-04	2.4E-04	5.2E-04
2-Hexanone		1.9E-05	1.7E-05	3.6E-05
Methyl Ethyl Ketone (MEK)		2.3E-07	2.1E-07	4.4E-07
1-methylfluorene		3.3E-07	2.9E-07	6.2E-07
2-methyl naphthalene		4.6E-05	4.1E-05	8.6E-05
4-methyl 2-pentanone		1.2E-05	1.1E-05	2.3E-05
Naphthalene		5.3E-05	4.6E-05	9.9E-05
Pentamethyl benzene		2.2E-07	1.9E-07	4.1E-07
Phenanthrene		5.1E-07	4.4E-07	9.5E-07
Toluene		0.0046	0.0041	0.0087
Total Biphenyls		4.2E-06	3.4E-06	7.6E-06
Total Dibenzo-thiophenes		1.3E-08	1.1E-08	2.3E-08
Xylenes		0.0025	0.0022	0.0046
Radionuclides (unspecified)	(1)	0	1.8E-07	1.8E-07
Lead 210		3.0E-13	0	3.0E-13
n-Decane		8.4E-05	0	8.4E-05
n-Docosane		3.1E-06	0	3.1E-06
n-Dodecane		1.6E-04	0	1.6E-04
n-Eicosane		4.4E-05	0	4.4E-05
n-Hexacosane		1.9E-06	0	1.9E-06
n-Hexadecane		1.7E-04	0	1.7E-04
n-Octadecane		4.3E-05	0	4.3E-05
n-Tetradecane		7.0E-05	0	7.0E-05
Styrene		5.9E-07	0	5.9E-07
Fluorine		2.0E-06	0	2.0E-06
Radium 226		1.0E-10	0	1.0E-10
Radium 228		5.3E-13	0	5.3E-13
Sodium Hydroxide		1.08	0	1.08

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 15.45 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 12

CRADLE-TO-PRECURSOR LIFE CYCLE INVENTORY RESULTS FOR POLYETHER POLYOL USED FOR FLEXIBLE FOAM POLYURETHANE

This chapter presents LCI results for the production of polyether polyol used for flexible foam polyurethane (cradle-to-polyol). The results are given on the bases of 1,000 pounds and 1,000 kilograms of the polyol. Figure 12-1 presents the flow diagram for the production of the polyol. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix L of the Appendices (separate document). Although a number of raw materials (coconut oil, palm oil, palm kernel oil, etc.) can be used to produce glycerine, palm kernel oil was chosen in this analysis.

Primary data was collected for olefins, chlorine/caustic soda, and polyether polyol production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

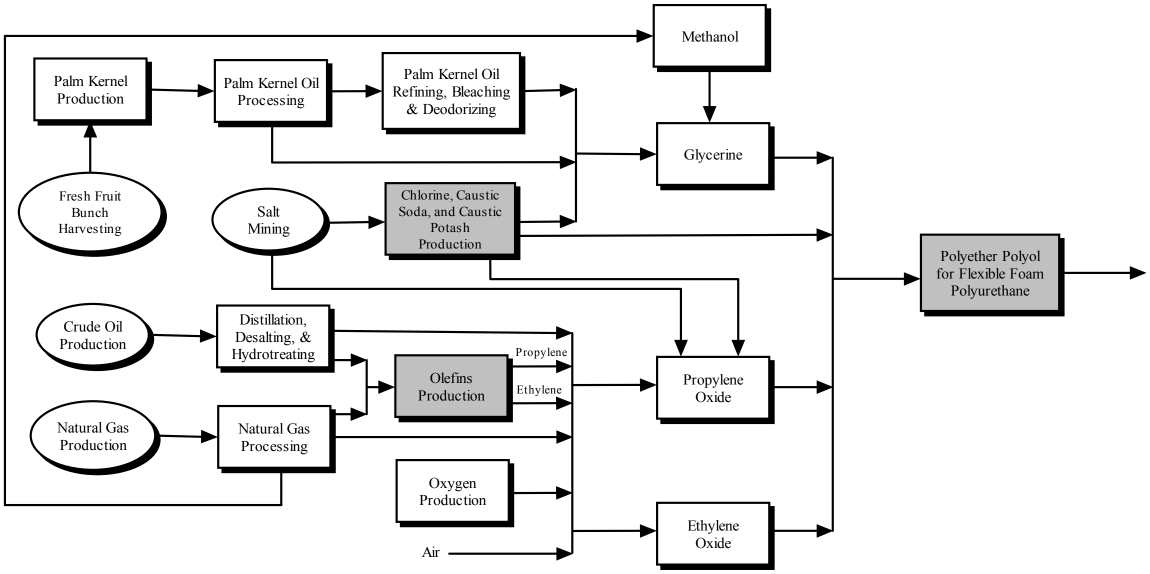

Figure 12-1. Flow diagram for the manufacture of polyether polyol for flexible foam polyurethane. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. The mercury cell technology is more likely to be used to produce high-purity caustic, than chlorine to be used in EDC; however, a small percentage of chlorine used in EDC does still come from mercury cells. For this analysis, it is estimated that 91.4 percent of the cell technology is diaphragm and membrane, while 8.6 percent of the cell technology is mercury. The collected datasets were weighted using these fractions. As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies. The captured production amount is approximately 30 percent of the available capacity for all chlorine production in the U.S. Caustic soda and hydrogen are the coproducts produced with chlorine. A mass basis was used to allocate the credit to the coproducts.

A weighted average using production amounts was calculated from the polyol production data from five plants collected from five leading producers in North America. As of 2002, it is estimated that for all polyurethane applications, there were 7 polyether polyol producers and 9 polyether polyol plants in the U.S. The captured production amount is approximately 45 percent of the available capacity for polyol production in the U.S. and Canada. Heat was a coproduct for two producers. The energy for exported heat was reported separately as recovered energy.

DESCRIPTION OF TABLES

The average gross energy required to produce the polyether polyol for flexible foam polyurethane is 40.9 million Btu per 1,000 pounds or 95.1 GJ per 1,000 kilograms. Tables 12-1 and 12-2 show the breakdown of energy requirements for the production of polyol by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table L-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-polyol) for the production of the polyol. Natural gas and petroleum used as raw material inputs for the production of the polyol, reported as energy of material resource in Table 12-1, are included in the totals for natural gas and petroleum energy in Table 12-2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 12-2 are used to generate purchased electricity along with the fossil fuels.

Table 12-1

Energy by Category for the Production of Polyether Polyol for Flexible Foam Polyurethane

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	23.1	53.8
Transportation	0.66	1.54
Energy of Material Resource	17.1	39.8
Total Energy	**40.9**	**95.1**
Energy Category (Percent)		
Process	57%	57%
Transportation	2%	2%
Energy of Material Resource	42%	42%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 12-2

Energy Profile for the Production of Polyether Polyol for Flexible Foam Polyurethane

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	25.6	59.6
Petroleum	9.85	22.9
Coal	4.25	09.9
Hydropower	0.17	0.39
Nuclear	0.89	2.07
Wood	0	0
Other	0.17	0.40
Recovered Energy (1)	-0.082	-0.19
Total Energy	**40.9**	**95.1**
Energy Source (Percent)		
Natural Gas	63%	63%
Petroleum	24%	24%
Coal	10%	10%
Hydropower	0%	0%
Nuclear	2%	2%
Wood	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 12-3 shows the weight of solid waste generated during the production of polyether polyol for flexible foam polyurethane. The process solid waste, those wastes produced directly from the cradle-to-precursor processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 12-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 12-3

Solid Wastes by Weight for the Production of Polyether Polyol for Flexible Foam Polyurethane

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	30.5	30.5
Incinerated	5.46	5.46
Waste-to-Energy	0.0050	0.0050
Fuel	152	152
Total	**188**	**188**
Weight Percent by Category		
Process		
Landfilled	16%	16%
Incinerated	3%	3%
Waste-to-Energy	0%	0%
Fuel	81%	81%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 12-4

Atmospheric Emissions for the Production of Polyether Polyol for Flexible Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.16	0.73	0.89
Particulates (PM2.5)	0.010	0	0.010
Particulates (PM10)	0.15	0.33	0.49
Nitrogen Oxides	0.17	6.60	6.77
Hydrocarbons (unspecified)	7.93	0.37	8.30
VOC (unspecified)	0.46	0.52	0.99
TNMOC (unspecified)	0	0.027	0.027
Sulfur Dioxide	0	18.2	18.2
Sulfur Oxides	15.1	1.54	16.6
Carbon Monoxide	4.01	4.17	8.17
Fossil CO2	154	3,164	3,317
Non-Fossil CO2	16.9	17.6	34.4
Aldehydes (Formaldehyde)	0	0.0023	0.0023
Aldehydes (Acetaldehyde)	0	1.4E-04	1.4E-04
Aldehydes (Propionaldehyde)	0	9.3E-06	9.3E-06
Aldehydes (unspecified)	0.044	0.0077	0.052
Organics (unspecified)	0.10	0.0011	0.10
Ammonia	0.048	0.0038	0.052
Ammonia Chloride	0	1.4E-04	1.4E-04
Methane	11.5	9.12	20.6
Kerosene	0	2.5E-04	2.5E-04
Chorine	0.0024	7.1E-05	0.0025
HCl	3.3E-04	0.25	0.25
HF	0	0.030	0.030
Metals (unspecified)	0	0.0039	0.0039
Mercaptan	0.0039	0.0053	0.0092
Antimony	0	4.4E-06	4.4E-06
Arsenic	0	1.1E-04	1.1E-04
Beryllium	0	6.1E-06	6.1E-06
Cadmium	0	3.1E-05	3.1E-05
Chromium (VI)	0	1.6E-05	1.6E-05
Chromium	0	8.4E-05	8.4E-05
Cobalt	0	1.2E-04	1.2E-04
Copper	0	2.4E-06	2.4E-06
Lead	1.1E-07	2.0E-04	2.0E-04
Magnesium	0	0.0023	0.0023
Manganese	0	3.0E-04	3.0E-04
Mercury	1.7E-04	5.3E-05	2.3E-04
Nickel	0	0.0015	0.0015
Selenium	0	2.8E-04	2.8E-04
Zinc	0	1.6E-06	1.6E-06
Acetophenone	0	3.7E-07	3.7E-07
Acrolein	0	4.2E-04	4.2E-04
Nitrous Oxide	1.0E-04	0.067	0.068
Benzene	0.057	0.051	0.11
Benzyl Chloride	0	1.7E-05	1.7E-05
Bis(2-ethylhexyl) Phthalate (DEHP)	0	1.8E-06	1.8E-06
1,3 Butadiene	0	1.9E-06	1.9E-06
2-Chloroacetophenone	0	1.7E-07	1.7E-07
Chlorobenzene	0	5.4E-07	5.4E-07
2,4-Dinitrotoluene	0	6.9E-09	6.9E-09
Ethyl Chloride	0	1.0E-06	1.0E-06
Ethylbenzene	0.83	0.0057	0.83
Ethylene Dibromide	0	2.9E-08	2.9E-08
Ethylene Dichloride	0	9.8E-07	9.8E-07

Table 12-4

Atmospheric Emissions for the Production of Polyether Polyol for Flexible Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Hexane		0	1.6E-06	1.6E-06
Isophorone (C9H14O)		0	1.4E-05	1.4E-05
Methyl Bromide		0	3.9E-06	3.9E-06
Methyl Chloride		0	1.3E-05	1.3E-05
Methyl Ethyl Ketone		0	9.6E-06	9.6E-06
Methyl Hydrazine		0	4.2E-06	4.2E-06
Methyl Methacrylate		0	4.9E-07	4.9E-07
Methyl Tert Butyl Ether (MTBE)		0	8.6E-07	8.6E-07
Naphthalene		0	3.5E-05	3.5E-05
Propylene		0	1.2E-04	1.2E-04
Propylene Oxide		0.40	0	0.40
Styrene		0	6.1E-07	6.1E-07
Toluene		0.088	0.074	0.16
Trichloroethane		2.9E-08	5.1E-07	5.4E-07
Vinyl Acetate		0	1.9E-07	1.9E-07
Xylenes		0.051	0.043	0.094
Bromoform		0	9.6E-07	9.6E-07
Chloroform		0	1.4E-06	1.4E-06
Carbon Disulfide		0	3.2E-06	3.2E-06
Dimethyl Sulfate		0	1.2E-06	1.2E-06
Cumene		0	1.3E-07	1.3E-07
Cyanide		0	6.1E-05	6.1E-05
Perchloroethylene		0	1.0E-05	1.0E-05
Methylene Chloride		0	1.8E-04	1.8E-04
Carbon Tetrachloride		2.0E-04	4.1E-06	2.0E-04
Phenols		0	7.9E-05	7.9E-05
Fluorides		0	0.0011	0.0011
Polyaromatic Hydrocarbons (total)		0	1.3E-05	1.3E-05
Biphenyl		0	3.5E-07	3.5E-07
Acenaphthene		0	1.0E-07	1.0E-07
Acenaphthylene		0	5.1E-08	5.1E-08
Anthracene		0	4.3E-08	4.3E-08
Benzo(a)anthracene		0	1.6E-08	1.6E-08
Benzo(a)pyrene		0	7.8E-09	7.8E-09
Benzo(b,j,k)fluroanthene		0	2.3E-08	2.3E-08
Benzo(g,h,i) perylene		0	5.5E-09	5.5E-09
Chrysene		0	2.1E-08	2.1E-08
Fluoranthene		0	1.5E-07	1.5E-07
Fluorene		0	1.9E-07	1.9E-07
Indeno(1,2,3-cd)pyrene		0	1.3E-08	1.3E-08
Naphthanlene		0	2.7E-06	2.7E-06
Phenanthrene		0	5.5E-07	5.5E-07
Pyrene		0	6.8E-08	6.8E-08
5-Methyl Chrysene		0	4.5E-09	4.5E-09
Dioxins (unspecified)		0	1.5E-07	1.5E-07
Furans (unspecified)		0	8.2E-10	8.2E-10
CFC12		0	2.1E-08	2.1E-08
Radionuclides (unspecified)	(1)	0	0.014	0.014
HCFC-22		7.5E-07	0	7.5E-07
HCFC-123		9.2E-05	0	9.2E-05
HFC-134a		9.2E-05	0	9.2E-05
Hydrogen		0.0038	0	0.0038
Acid (unknown)		0.46	0	0.46
F2		0.038	0	0.038
Ethylene Oxide		0.011	0	0.011

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 1,200,939 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 12-5 provides a greenhouse gas (GHG) summary for the production of polyether polyol for flexible foam polyurethane. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 12-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 12-4 are multiplied by their global warming potential and shown in Table 12-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 12-6. Definitions of process and fuel-related emissions are provided in this chapter, as well as in the glossary.

Table 12-5

Greenhouse Gas Summary for the Production of Polyether Polyol for Flexible Foam Polyurethane (lb carbon dioxide equivalents per 1,000 lb Polyol or kg carbon dioxide equivalents per 1,000 kg Polyol)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	3,164	154	3,317
Methane	228	287	515
Nitrous oxide	20.1	0.030	20.1
Methyl bromide	2.0E-05	0	2.0E-05
Methyl chloride	2.1E-04	0	2.1E-04
Trichloroethane	7.1E-05	4.1E-06	7.5E-05
Chloroform	4.3E-05	0	4.3E-05
Methylene chloride	0.0018	0	0.0018
Carbon tetrachloride	0.0057	0.27	0.28
CFC-012	2.3E-04	0	2.3E-04
HCFC-22	0	0.0014	0.0014
HCFC-123	0	0.0071	0.0071
HFC-134a	0	0.13	0.13
Total	3,412	441	3,853

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 12-6

Waterborne Emissions for the Production of Polyether Polyol for Flexible Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	8.52	0.0026	8.52
Acid (benzoic)	0.0038	0.0028	0.0066
Acid (hexanoic)	7.8E-04	5.8E-04	0.0014
Metal (unspecified)	1.00	0	1.00
Dissolved Solids	211	123	334
Suspended Solids	4.84	3.16	8.00
BOD	1.47	0.55	2.03
COD	4.48	0.66	5.14
Phenol/Phenolic Compounds	1.14	0.0013	1.14
Sulfur	0	0.0073	0.0073
Sulfates	0.27	0.38	0.66
Sulfides	1.1E-04	3.3E-05	1.4E-04
Oil	0.078	0.056	0.13
Hydrocarbons	0.89	5.6E-04	0.89
Ammonia	0.063	0.044	0.11
Ammonium	0	1.1E-04	1.1E-04
Aluminum	0.15	0.10	0.24
Antimony	9.1E-05	6.0E-05	1.5E-04
Arsenic	8.8E-04	6.5E-04	0.0015
Barium	2.09	1.39	3.48
Beryllium	4.3E-05	3.1E-05	7.4E-05
Cadmium	1.3E-04	9.6E-05	2.3E-04
Chromium (unspecified)	0.0070	0.0027	0.0097
Chromium (hexavalent)	1.1E-05	0	1.1E-05
Cobalt	8.2E-05	6.1E-05	1.4E-04
Copper	6.8E-04	5.2E-04	0.0012
Iron	0.35	0.25	0.59
Lead	0.0015	0.0011	0.0025
Lithium	2.80	2.29	5.09
Magnesium	2.33	1.74	4.07
Manganese	0.0037	0.0055	0.0093
Mercury	2.1E-06	1.1E-06	3.2E-06
Molybdenum	8.5E-05	6.4E-05	1.5E-04
Nickel	7.6E-04	5.5E-04	0.0013
Selenium	1.8E-05	5.1E-05	6.8E-05
Silver	0.0078	0.0058	0.014
Sodium	37.8	28.2	66.0
Strontium	0.20	0.15	0.35
Thallium	1.9E-05	1.3E-05	3.2E-05
Tin	5.3E-04	3.8E-04	9.1E-04
Titanium	0.0014	9.2E-04	0.0023
Vanadium	1.0E-04	7.5E-05	1.8E-04
Yttrium	2.5E-05	1.9E-05	4.4E-05
Zinc	0.0047	0.0024	0.0071
Chlorides (unspecified)	134	100	234
Chlorides (methyl chloride)	1.5E-07	1.1E-07	2.6E-07
Calcium	11.9	8.91	20.8
Fluorides	2.3E-05	0.0018	0.0018
Nitrates	1.00	2.8E-04	1.00
Nitrogen (ammonia)	0.0025	9.7E-05	0.0026

Table 12-6

Waterborne Emissions for the Production of Polyether Polyol for Flexible Foam Polyurethane
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Bromide	0.79	0.59	1.39
Boron	0.012	0.0087	0.020
Total Organic Carbon	0.011	0.011	0.022
Cyanide	2.7E-07	2.0E-07	4.7E-07
Hardness	36.7	27.4	64.1
Total Alkalinity	0.30	0.22	0.52
Surfactants	0	0.0027	0.0027
Acetone	3.7E-05	2.8E-05	6.5E-05
Alkylated Benzenes	8.0E-05	5.2E-05	1.3E-04
Alkylated Fluorenes	4.6E-06	3.0E-06	7.7E-06
Alkylated Naphthalenes	1.3E-06	8.6E-07	2.2E-06
Alkylated Phenanthrenes	5.4E-07	3.6E-07	9.0E-07
Benzene	0.0062	0.0046	0.011
Cresols	2.2E-04	1.6E-04	3.8E-04
Cymene	3.7E-07	2.8E-07	6.5E-07
Dibenzofuran	7.0E-07	5.3E-07	1.2E-06
Dibenzothiophene	5.7E-07	4.3E-07	1.0E-06
2,4 dimethylphenol	1.0E-04	7.8E-05	1.8E-04
Ethylbenzene	3.6E-04	2.6E-04	6.2E-04
2-Hexanone	2.4E-05	1.8E-05	4.2E-05
Methyl Ethyl Ketone (MEK)	3.0E-07	2.2E-07	5.2E-07
1-methylfluorene	4.2E-07	3.2E-07	7.4E-07
2-methyl naphthalene	5.9E-05	4.4E-05	1.0E-04
4-methyl 2-pentanone	1.6E-05	1.2E-05	2.7E-05
Naphthalene	6.7E-05	5.0E-05	1.2E-04
Pentamethyl benzene	2.8E-07	2.1E-07	4.9E-07
Phenanthrene	6.5E-07	4.6E-07	1.1E-06
Toluene	0.0059	0.0044	0.010
Total Biphenyls	5.2E-06	3.4E-06	8.5E-06
Total Dibenzo-thiophenes	1.6E-08	1.0E-08	2.6E-08
Xylenes	0.0032	0.0023	0.0055
Radionuclides (unspecified) (1)	0	2.0E-07	2.0E-07
Lead 210	3.9E-13	0	3.9E-13
n-Decane	1.1E-04	0	1.1E-04
n-Docosane	4.0E-06	0	4.0E-06
n-Dodecane	2.0E-04	0	2.0E-04
n-Eicosane	5.6E-05	0	5.6E-05
n-Hexacosane	2.5E-06	0	2.5E-06
n-Hexadecane	2.2E-04	0	2.2E-04
n-Octadecane	5.5E-05	0	5.5E-05
n-Tetradecane	9.0E-05	0	9.0E-05
Styrene	7.5E-07	0	7.5E-07
Fluorine	2.5E-06	0	2.5E-06
Radium 226	1.3E-10	0	1.3E-10
Radium 228	6.9E-13	0	6.9E-13
Acetaldehyde	0.011	0	0.011
Sodium Hydroxide	1.22	0	1.22

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 16.78 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 13

CRADLE-TO-PRECURSOR LIFE CYCLE INVENTORY RESULTS FOR MDI

This chapter presents LCI results for the production of pure and polymeric methylene diphenylene diisocyanate (MDI) (cradle-to-MDI). The market split is approximately 80 percent polymeric MDI and 20 percent pure MDI. The results are given on the bases of 1,000 pounds and 1,000 kilograms of MDI. Figure 13-1 presents the flow diagram for the production of MDI. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix M of the Appendices (separate document).

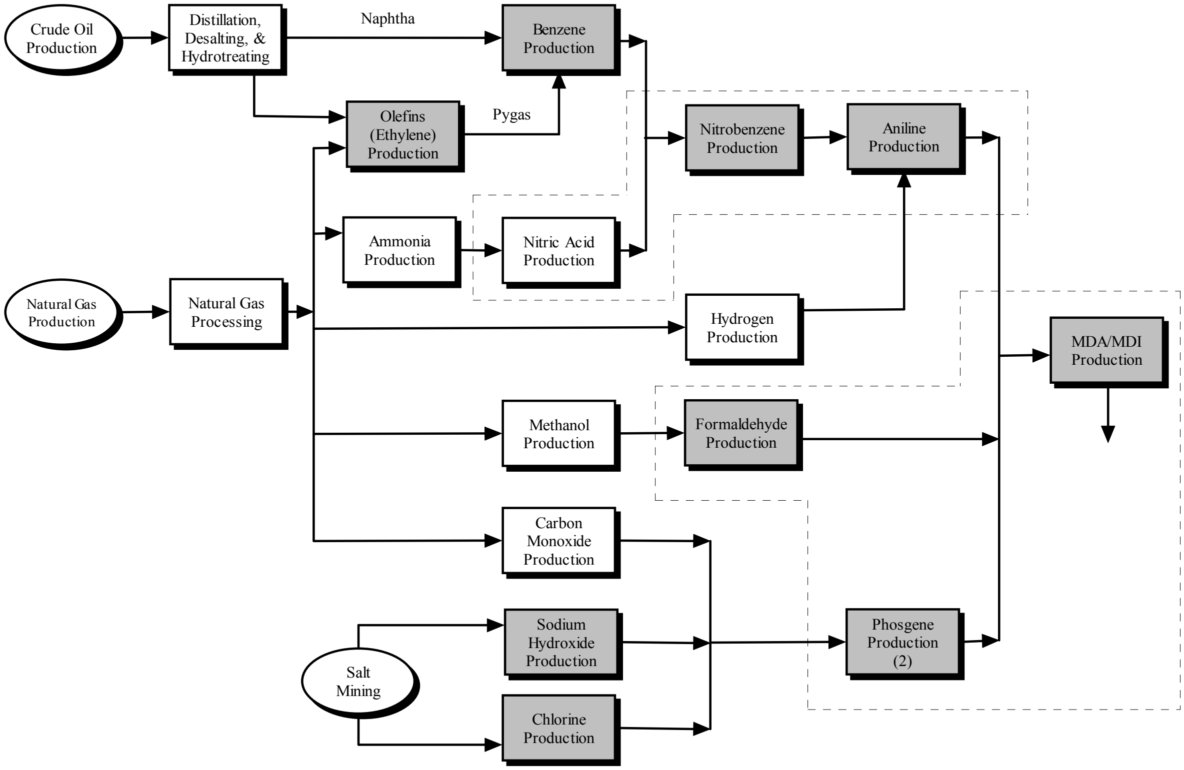

Figure 13-1. Flow diagram for the manufacture of methylene diphenylene diisocyanate (MDI). Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted lines are included in an aggregated dataset.

Primary data was collected for olefins, benzene, chlorine/caustic soda, nitric acid/nitrobenzene/aniline, and formaldehyde/phosgene/MDA/MDI production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

It is estimated that one-third of the benzene production is from pyrolysis gasoline and two-thirds are produced from catalytic reforming. These percentages were used to weight the collected datasets for benzene. Catalytic reforming is represented by 2 primary datasets from 1992. The benzene data collected for this analysis represent 1 producer and 1 plant in the U.S. using the pyrolysis gasoline production method. As of 2002 there were 22 benzene producers and 38 benzene plants in the U.S. for the three standard technologies. The captured production amount is approximately 10 percent of the available capacity for benzene production in the U.S. Numerous aromatic coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the reactor, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit the remaining aromatic products.

The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. The mercury cell technology is more likely to be used to produce high-purity caustic, than chlorine to be used in EDC; however, a small percentage of chlorine used in EDC does still come from mercury cells. For this analysis, it is estimated that 91.4 percent of the cell technology is diaphragm and membrane, while 8.6 percent of the cell technology is mercury. The collected datasets were weighted using these fractions. As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies. The captured production amount is approximately 30 percent of the available capacity for all chlorine production in the U.S. Caustic soda and hydrogen are the coproducts produced with chlorine. A mass basis was used to allocate the credit to the coproducts.

The nitric acid, nitrobenzene and aniline data collected for this module represent 2 producers and 2 plants in the U.S. As of 2002 there were 28 nitric acid producers and 49 nitric acid plants in the U.S. (Reference M-6). The captured production amount is approximately 90 percent of the available capacity for all nitric acid production in the U.S. As of 2002 there were 4 nitrobenzene producers and 5 nitrobenzene plants in the U.S. The captured production amount is more than 50 percent of the available capacity for all nitrobenzene production in the U.S. As of 2002 there were 6 aniline producers and 7 aniline plants in the U.S. The captured production amount is more than 50 percent of the available capacity for all aniline production in the U.S. Steam/heat is produced as a coproduct during the aniline production. The energy for exported steam/heat was reported separately as recovered energy.

A weighted average using production amounts was calculated from the formaldehyde/phosgene/MDA/MDI production data from four plants collected from four leading producers in North America. As of 2003, there were 4 MDI producers and 5 MDI plants in the U.S. The captured production amount is approximately 95 percent of the available capacity for MDI production in the U.S. and Canada. Hydrogen chloride is produced as a coproduct during this process. A mass basis was used to allocate the credit for the coproduct.

DESCRIPTION OF TABLES

The average gross energy required to produce MDI is 26.3 million Btu per 1,000 pounds or 61.2 GJ per 1,000 kilograms. Tables 13-1 and 13-2 show the breakdown of energy requirements for the production of MDI by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table M-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-MDI) for the production of MDI. Natural gas and petroleum used as raw material inputs for the production of MDI, reported as energy of material resource in Table 13-1, are included in the totals for natural gas and petroleum energy in Table 13-2. Petroleum-based fuels (e.g. diesel fuel) is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 13-2 are used to generate purchased electricity along with the fossil fuels.

Table 13-1

Energy by Category for the Production of MDI

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	13.3	30.9
Transportation	0.37	0.86
Energy of Material Resource	12.7	29.4
Total Energy	**26.3**	**61.2**
Energy Category (Percent)		
Process	50%	50%
Transportation	1%	1%
Energy of Material Resource	48%	48%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 13-2

Energy Profile for the Production of MDI

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	16.6	38.6
Petroleum	8.05	18.7
Coal	1.96	4.55
Hydropower	0.080	0.19
Nuclear	0.43	1.00
Wood/Biomass	0	0
Other	0.083	0.19
Recovered Energy (1)	-0.90	-2.09
Total Energy	**26.3**	**61.2**
Energy Source (Percent)		
Natural Gas	61%	61%
Petroleum	30%	30%
Coal	7%	7%
Hydropower	0%	0%
Nuclear	2%	2%
Wood/Biomass	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 13-3 shows the weight of solid waste generated during the production of MDI. The total generated solid waste includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 13-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 13-3

Solid Wastes by Weight for the Production of MDI

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	20.3	20.3
Incinerated	3.26	3.26
Waste-to-Energy	0.75	0.75
Fuel	75.0	75.0
Total	**99**	**99**
Weight Percent by Category		
Process		
Landfilled	20%	20%
Incinerated	3%	3%
Waste-to-Energy	1%	1%
Fuel	76%	76%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 13-4

Atmospheric Emissions for the Production of MDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.093	0.33	0.42
Particulates (PM2.5)	0.010	0	0.010
Particulates (PM10)	0.058	0.18	0.23
Nitrogen Oxides	0.54	3.46	4.00
Hydrocarbons (unspecified)	1.05	0.10	1.16
VOC(unspecified)	0.21	0.44	0.65
TNMOC (unspecified)	1.04	0.012	1.05
Sulfur Dioxide	0	13.6	13.6
Sulfur Oxides	7.66	0.49	8.15
Carbon Monoxide	7.35	1.86	9.21
CO2 (fossil)	95.6	1,885	1,981
CO2 (non-fossil)	0	8.47	8.47
Aldehydes (Formaldehyde)	0.0012	0.0013	0.0025
Aldehydes (Acetaldehyde)	0	6.2E-05	6.2E-05
Aldehydes (Propionaldehyde)	0	2.9E-06	2.9E-06
Aldehydes (unspecified)	0.014	0.0022	0.017
Organics (unspecified)	0.11	5.3E-04	0.11
Ammonia	0.28	0.0011	0.28
Ammonia Chloride	0	6.7E-05	6.7E-05
Methane	5.14	7.07	12.2
Kerosene	0	1.2E-04	1.2E-04
Chorine	6.8E-04	3.4E-05	7.2E-04
HCl	2.8E-04	0.11	0.11
HF	0	0.014	0.014
Metals (unspecified)	0	0.0019	0.0019
Mercaptan	0	0.0017	0.0017
Antimony	0	2.0E-06	2.0E-06
Arsenic	0	4.6E-05	4.6E-05
Beryllium	0	2.6E-06	2.6E-06
Cadmium	0	1.8E-05	1.8E-05
Chromium (VI)	0	7.5E-06	7.5E-06
Chromium	0	4.2E-05	4.2E-05
Cobalt	0	3.3E-05	3.3E-05
Copper	4.8E-05	8.3E-07	4.9E-05
Lead	4.8E-06	7.8E-05	8.3E-05
Magnesium	0	0.0010	0.0010
Manganese	0	1.3E-04	1.3E-04
Mercury	7.0E-05	2.1E-05	9.1E-05
Nickel	4.8E-04	3.6E-04	8.4E-04
Selenium	0	1.3E-04	1.3E-04
Zinc	0	5.5E-07	5.5E-07
Acetophenone	0	1.2E-07	1.2E-07
Acrolein	0	2.0E-04	2.0E-04
Nitrous Oxide	0	0.039	0.039
Benzene	0.026	0.044	0.070
Benzyl Chloride	0	5.4E-06	5.4E-06
Bis(2-ethylhexyl) Phthalate (DEHP)	0	5.7E-07	5.7E-07
1,3 Butadiene	0	6.9E-07	6.9E-07
2-Chloroacetophenone	0	5.4E-08	5.4E-08
Chlorobenzene	0	1.7E-07	1.7E-07
2,4-Dinitrotoluene	0	2.2E-09	2.2E-09

Table 13-4

Atmospheric Emissions for the Production of MDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethyl Chloride	0	3.3E-07	3.3E-07
Ethylbenzene	0.0033	0.0051	0.0084
Ethylene Dibromide	0	9.3E-09	9.3E-09
Ethylene Dichloride	0	3.1E-07	3.1E-07
Hexane	0	5.2E-07	5.2E-07
Isophorone	0	4.5E-06	4.5E-06
Methyl Bromide	0	1.2E-06	1.2E-06
Methyl Chloride	0	4.1E-06	4.1E-06
Methyl Ethyl Ketone	0	3.0E-06	3.0E-06
Methyl Hydrazine	0	1.3E-06	1.3E-06
Methyl Methacrylate	0	1.6E-07	1.6E-07
Methyle Tert Butyl Ether (MTBE)	0	2.7E-07	2.7E-07
Naphthalene	0	1.4E-05	1.4E-05
Propylene	0	4.6E-05	4.6E-05
Styrene	0	1.9E-07	1.9E-07
Toluene	0.041	0.066	0.107
Trichloroethane	3.3E-08	1.6E-07	1.9E-07
Vinyl Acetate	0	5.9E-08	5.9E-08
Xylenes	0.024	0.039	0.063
Bromoform	0	3.0E-07	3.0E-07
Chloroform	0	4.6E-07	4.6E-07
Carbon Disulfide	0	1.0E-06	1.0E-06
Dimethyl Sulfate	0	3.7E-07	3.7E-07
Cumene	0	4.1E-08	4.1E-08
Cyanide	0	1.9E-05	1.9E-05
Perchloroethylene	0	4.4E-06	4.4E-06
Methylene Chloride	0	6.3E-05	6.3E-05
Carbon Tetrachloride	0.010	2.0E-06	0.010
Phenols	0	2.1E-05	2.1E-05
Fluorides	0	3.5E-04	3.5E-04
Polyaromatic Hydrocarbons (total)	0	5.0E-06	5.0E-06
Biphenyl	0	1.6E-07	1.6E-07
Acenaphthene	0	4.8E-08	4.8E-08
Acenaphthylene	0	2.4E-08	2.4E-08
Anthracene	0	2.0E-08	2.0E-08
Benzo(a)anthracene	0	7.6E-09	7.6E-09
Benzo(a)pyrene	0	3.6E-09	3.6E-09
Benzo(b,j,k)fluroanthene	0	1.0E-08	1.0E-08
Benzo(g,h,i) perylene	0	2.6E-09	2.6E-09
Chrysene	0	9.5E-09	9.5E-09
Fluoranthene	0	6.7E-08	6.7E-08
Fluorene	0	8.6E-08	8.6E-08
Indeno(1,2,3-cd)pyrene	0	5.8E-09	5.8E-09
Naphthanlene	0	1.2E-06	1.2E-06
Phenanthrene	0	2.6E-07	2.6E-07
Pyrene	0	3.1E-08	3.1E-08
5-methyl Chrysene	0	2.1E-09	2.1E-09
Dioxins (unspecified)	0	7.3E-08	7.3E-08
Furans (unspecified)	0	4.0E-10	4.0E-10
CFC12	0	5.8E-09	5.8E-09
Radionuclides (unspecified) (1)	0	0.0068	0.0068
Sulfuric Acid	4.8E-06	0	4.8E-06
Methanol	0.0010	0	0.0010
HFC-22	4.8E-04	0	4.8E-04
Hydrogen	7.5E-04	0	7.5E-04
Dimethyl Ether	0.0010	0	0.0010

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 627,988 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 13-5 provides a greenhouse gas (GHG) summary for the production of MDI. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 13-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 13-4 are multiplied by their global warming potential and shown in Table 13-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 13-6. Definitions of process and fuel-related emissions are provided previously in this chapter, as well as in the glossary.

Table 13-5

Greenhouse Gas Summary for the Production of MDI
(lb carbon dioxide equivalents per 1,000 lb MDI or kg carbon dioxide equivalents per 1,000 kg MDI)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,885	95.6	1,981
Methane	163	118	281
Nitrous oxide	11.6	0	11.6
Methyl bromide	6.2E-06	0	6.2E-06
Methyl chloride	6.6E-05	0	6.6E-05
Trichloroethane	2.2E-05	4.6E-06	2.7E-05
Chloroform	1.4E-05	0	1.4E-05
Methylene chloride	6.3E-04	0	6.3E-04
Carbon tetrachloride	0.0027	14.7	14.7
CFC-012	6.3E-05	0	6.3E-05
HFC-22	0	0.87	0.87
HCFC-123	0	1.35	1.35
HFC-134a	0	1.81	1.81
Total	2,060	229	2,289

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 13-6

Waterborne Emissions for the Production of MDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	0	0.0023	0.0023
Acid (benzoic)	0.0025	0.0021	0.0046
Acid (hexanoic)	5.2E-04	4.4E-04	9.6E-04
Dissolved Solids	138	93.1	231
Suspended Solids	4.25	1.73	5.97
BOD	0.75	0.42	1.17
COD	1.24	0.56	1.80
Phenol/Phenolic Compounds	0.0014	9.5E-04	0.0024
Sulfur	0.0065	0.0055	0.012
Sulfates	0.18	0.24	0.42
Sulfides	4.9E-04	9.4E-06	5.0E-04
Oil	0.070	0.041	0.11
Hydrocarbons	0	4.2E-04	4.2E-04
Ammonia	0.065	0.032	0.097
Ammonium	0	5.4E-05	5.4E-05
Aluminum	0.13	0.052	0.19
Antimony	8.3E-05	3.2E-05	1.1E-04
Arsenic	6.1E-04	4.7E-04	0.0011
Barium	1.88	0.76	2.64
Beryllium	3.2E-05	2.2E-05	5.3E-05
Cadmium	9.0E-05	7.0E-05	1.6E-04
Chromium (unspecified)	0.0038	0.0014	0.0052
Chromium (hexavalent)	1.3E-05	0	1.3E-05
Cobalt	5.5E-05	4.6E-05	1.0E-04
Copper	5.3E-04	3.4E-04	8.7E-04
Iron	0.29	0.15	0.44
Lead	0.0011	7.1E-04	0.0018
Lithium	1.31	2.05	3.36
Magnesium	1.55	1.31	2.86
Manganese	0.0025	0.0034	0.0059
Mercury	1.7E-06	5.7E-07	2.3E-06
Molybdenum	5.7E-05	4.8E-05	1.0E-04
Nickel	5.7E-04	3.8E-04	9.5E-04
Selenium	1.6E-05	2.5E-05	4.1E-05
Silver	0.0052	0.0044	0.0095
Sodium	25.1	21.3	46.3
Strontium	0.13	0.11	0.25
Thallium	1.8E-05	6.7E-06	2.4E-05
Tin	4.1E-04	2.5E-04	6.6E-04
Titanium	0.0013	4.8E-04	0.0018
Vanadium	6.7E-05	5.7E-05	1.2E-04
Yttrium	1.7E-05	1.4E-05	3.1E-05
Zinc	0.0032	0.0013	0.0045
Chlorides (unspecified)	88.9	75.4	164
Chlorides (methyl chloride)	9.9E-08	8.4E-08	1.8E-07
Calcium	7.91	6.71	14.6

Table 13-6

Waterborne Emissions for the Production of MDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Fluorine/Fluorides	2.2E-06	8.7E-04	0.0009
Nitrates	1.0E-08	1.3E-04	1.3E-04
Nitrogen/Nitrates (ammonia)	0	4.7E-05	4.7E-05
Bromide	0.53	0.45	0.97
Boron	0.0077	0.0066	0.014
Organic Carbon	0.025	0.0097	0.035
Cyanide	1.2E-06	1.5E-07	1.3E-06
Hardness	24.4	20.7	45.0
Total Alkalinity	0.20	0.17	0.36
Surfactants	0.0022	0.0021	0.0043
Acetone	2.5E-05	2.1E-05	4.5E-05
Alkylated Benzenes	7.3E-05	2.8E-05	1.0E-04
Alkylated Fluorenes	4.2E-06	1.6E-06	5.8E-06
Alkylated Naphthalenes	1.2E-06	4.5E-07	1.7E-06
Alkylated Phenanthrenes	5.0E-07	1.9E-07	6.8E-07
Benzene	0.0041	0.0035	0.0076
Cresols	1.5E-04	1.2E-04	2.7E-04
Cymene	2.5E-07	2.1E-07	4.5E-07
Dibenzofuran	4.7E-07	4.0E-07	8.7E-07
Dibenzothiophene	3.8E-07	3.2E-07	7.0E-07
2,4 dimethylphenol	6.9E-05	5.9E-05	1.3E-04
Ethylbenzene	2.3E-04	2.0E-04	4.3E-04
2-Hexanone	1.6E-05	1.4E-05	3.0E-05
Methyl Ethyl Ketone (MEK)	2.0E-07	1.7E-07	3.7E-07
1-methylfluorene	2.8E-07	2.4E-07	5.2E-07
2-methyl naphthalene	3.9E-05	3.3E-05	7.2E-05
4-methyl 2-pentanone	1.0E-05	8.8E-06	1.9E-05
Naphthalene	4.5E-05	3.8E-05	8.3E-05
Pentamethyl benzene	1.8E-07	1.6E-07	3.4E-07
Phenanthrene	5.1E-07	3.0E-07	8.1E-07
Toluene	0.0039	0.0033	0.0072
Total Biphenyls	4.7E-06	1.8E-06	6.5E-06
Total Dibenzo-thiophenes	1.5E-08	5.5E-09	2.0E-08
Xylenes	0.0021	0.0018	0.0039
Radionuclides (unspecified) (1)	8.9E-11	9.5E-08	9.5E-08
Phosphates	0.0071	0	0.0071
Lead 210	2.6E-13	0	2.6E-13
n-Decane	7.2E-05	0	7.2E-05
n-Docosane	2.6E-06	0	2.6E-06
n-Dodecane	1.4E-04	0	1.4E-04
n-Eicosane	3.7E-05	0	3.7E-05
n-Hexacosane	1.6E-06	0	1.6E-06
n-Hexadecane	1.5E-04	0	1.5E-04
n-Octadecane	3.7E-05	0	3.7E-05
n-Tetradecane	6.0E-05	0	6.0E-05
Styrene	1.4E-07	0	1.4E-07
Chloroform	1.0E-06	0	1.0E-06

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 8.78 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

CHAPTER 14

CRADLE-TO-PRECURSOR LIFE CYCLE INVENTORY RESULTS FOR TDI

This chapter presents LCI results for the production of toluene diisocyanate (TDI) (cradle-to-TDI). The results are given on the bases of 1,000 pounds and 1,000 kilograms of TDI. Figure 14-1 presents the flow diagram for the production of TDI. Process descriptions and individual process tables for each box shown in the flow diagram can be found in Appendix N of the Appendices (separate document).

Primary data was collected for chlorine/caustic soda and DNT/phosgene/TDA/TDI production. The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. For this analysis, it is estimated that 91.4 percent of the cell technology is diaphragm and membrane, while 8.6 percent of the cell technology is mercury. The collected datasets were weighted using these fractions. As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies. The captured production amount is approximately 30 percent of the available capacity for all chlorine production in the U.S. Caustic soda and hydrogen are the coproducts produced with chlorine. A mass basis was used to allocate the credit to the coproducts.

A weighted average using production amounts was calculated from the DNT/phosgene/TDA/TDI production data from three plants collected from three leading producers in North America. As of 2002, there were 5 TDI producers and 6 TDI plants in the U.S. The captured production amount is approximately 55 percent of the available capacity for TDI production in the U.S. and Canada. Hydrogen chloride and exported steam/heat are produced as coproducts during this process. A mass basis was used to allocate the credit for hydrogen chloride. The energy for exported steam/heat was reported separately as recovered energy.

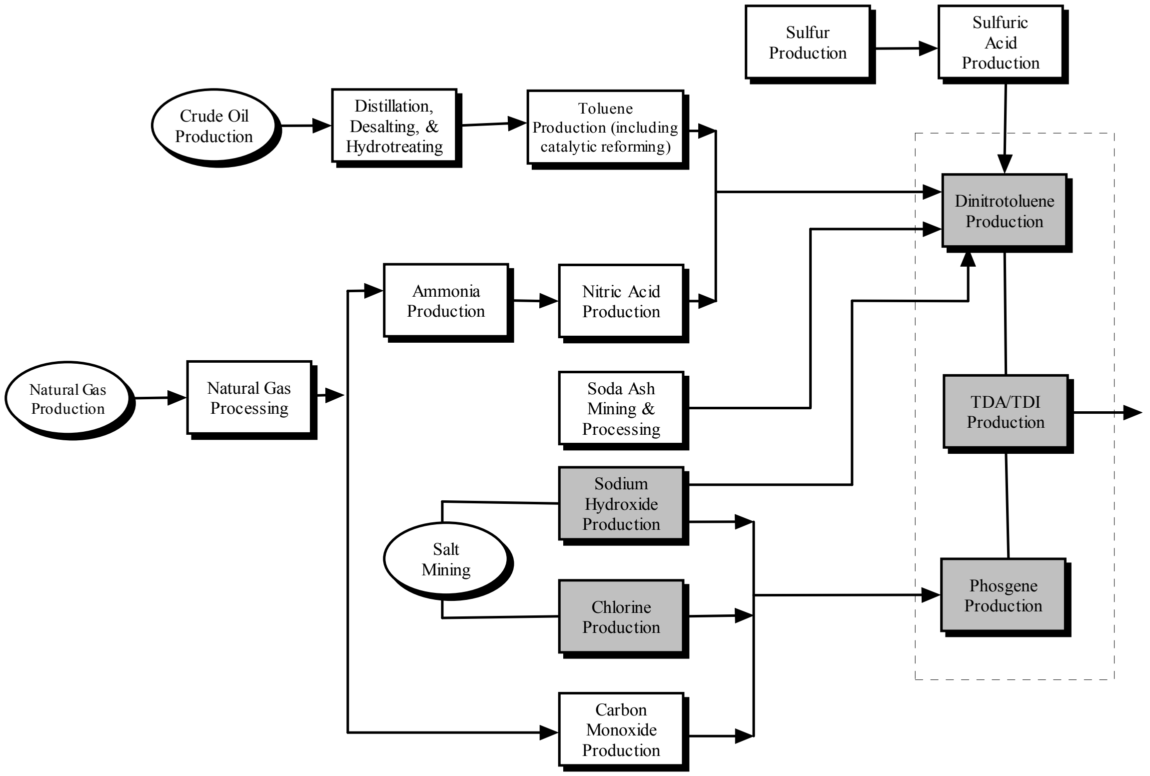

Figure 14-1. Flow diagram for the manufacture of toluene diisocyanate (TDI). Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted rectangle are included in an aggregate dataset.

DESCRIPTION OF TABLES

The average gross energy required to produce TDI is 23.8 million Btu per 1,000 pounds or 55.3 GJ per 1,000 kilograms. Tables 14-1 and 14-2 show the breakdown of energy requirements for the production of TDI by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table N-1 in the Appendices (separate document) provides the aggregated unit process energy (cradle-to-TDI) for the production of TDI. Natural gas and petroleum used as raw material inputs for the production of TDI, reported as energy of material resource in Table 14-1, are included in the totals for natural gas and petroleum energy in Table 14-2. Petroleum-based fuels (e.g. diesel fuel) is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 14-2 are used to generate purchased electricity along with the fossil fuels.

Table 14-1

Energy by Category for the Production of TDI

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process (1)	13.6	31.6
Transportation	0.53	1.22
Energy of Material Resource	9.68	22.5
Total Energy	**23.8**	**55.3**
Energy Category (Percent)		
Process	57%	57%
Transportation	2%	2%
Energy of Material Resource	41%	41%
Total	100%	100%

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(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 14-2

Energy Profile for the Production of TDI

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	14.3	33.3
Petroleum	7.39	17.2
Coal	1.86	4.33
Hydropower	0.075	0.17
Nuclear	0.40	0.93
Wood/Biomass	0	0
Other	0.078	0.18
Recovered Energy (1)	-0.34	-0.79
Total Energy	**23.8**	**55.3**
Energy Source (Percent)		
Natural Gas	59%	59%
Petroleum	31%	31%
Coal	8%	8%
Hydropower	0%	0%
Nuclear	2%	2%
Wood/Biomass	0%	0%
Other	0%	0%
Total	100%	100%

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(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 14-3 shows the weight of solid waste generated during the production of TDI. The total generated solid waste includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately.

Both process and fuel-related, as well as total, atmospheric emissions are shown in Table 14-4. As defined in the report glossary, process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 14-3

Solid Wastes by Weight for the Production of TDI

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	14.5	14.5
Incinerated	1.34	1.34
Waste-to-Energy	34.3	34.3
Fuel	73.3	73.3
Total	**123**	**123**
Weight Percent by Category		
Process		
Landfilled	12%	12%
Incinerated	1%	1%
Waste-to-Energy	28%	28%
Fuel	59%	59%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 14-4

Atmospheric Emissions for the Production of TDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Atmospheric Emissions			
Particulates (unspecified)	0.48	0.31	0.79
Particulates (PM2.5)	0.0011	0	0.0011
Particulates (PM10)	0.020	0.21	0.23
Nitrogen Oxides	0.57	4.44	5.02
Hydrocarbons (unspecified)	0.78	0.13	0.90
VOC(unspecified)	0.11	0.51	0.62
TNMOC (unspecified)	0.81	0.011	0.82
Sulfur Dioxide	0	14.5	14.5
Sulfur Oxides	4.38	0.62	5.00
Carbon Monoxide	5.57	2.15	7.72
CO2 (fossil)	28.2	1,897	1,926
CO2 (non-fossil)	0	7.91	7.91
Aldehydes (Formaldehyde)	0	0.0013	0.0013
Aldehydes (Acetaldehyde)	0	5.8E-05	5.8E-05
Aldehydes (Propionaldehyde)	0	3.4E-06	3.4E-06
Aldehydes (unspecified)	0.013	0.0026	0.016
Organics (unspecified)	1.0E-04	5.0E-04	6.0E-04
Ammonia	0.39	0.0013	0.39
Ammonia Chloride	0	6.2E-05	6.2E-05
Methane	3.46	7.65	11.1
Kerosene	0	1.1E-04	1.1E-04
Chorine	8.1E-04	3.2E-05	8.5E-04
HCl	0.0011	0.11	0.11
HF	0	0.013	0.013
Metals (unspecified)	0	0.0017	0.0017
Mercaptan	0	0.0019	0.0019
Antimony	0	1.9E-06	1.9E-06
Arsenic	0	4.5E-05	4.5E-05
Beryllium	0	2.6E-06	2.6E-06
Cadmium	0	1.8E-05	1.8E-05
Chromium (VI)	0	7.1E-06	7.1E-06
Chromium	0	4.2E-05	4.2E-05
Cobalt	0	3.3E-05	3.3E-05
Copper	0	8.7E-07	8.7E-07
Lead	1.0E-07	8.0E-05	8.0E-05
Magnesium	0	0.0010	0.0010
Manganese	0	1.2E-04	1.2E-04
Mercury	7.8E-05	2.2E-05	1.0E-04
Nickel	0	3.7E-04	3.7E-04
Selenium	0	1.2E-04	1.2E-04
Zinc	0	5.8E-07	5.8E-07
Acetophenone	0	1.3E-07	1.3E-07
Acrolein	0	1.9E-04	1.9E-04
Nitrous Oxide	0	0.042	0.042
Benzene	1.0E-05	0.048	0.048
Benzyl Chloride	0	6.2E-06	6.2E-06
Bis(2-ethylhexyl) Phthalate (DEHP)	0	6.4E-07	6.4E-07
1,3 Butadiene	0	6.2E-07	6.2E-07
2-Chloroacetophenone	0	6.2E-08	6.2E-08
Chlorobenzene	0	1.9E-07	1.9E-07
2,4-Dinitrotoluene	0	2.5E-09	2.5E-09

Table 14-4

Atmospheric Emissions for the Production of TDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Ethyl Chloride	0	3.7E-07	3.7E-07
Ethylbenzene	0	0.0056	0.0056
Ethylene Dibromide	0	1.1E-08	1.1E-08
Ethylene Dichloride	0	3.5E-07	3.5E-07
Hexane	0	5.9E-07	5.9E-07
Isophorone	0	5.1E-06	5.1E-06
Methyl Bromide	0	1.4E-06	1.4E-06
Methyl Chloride	0	4.7E-06	4.7E-06
Methyl Ethyl Ketone	0	3.4E-06	3.4E-06
Methyl Hydrazine	0	1.5E-06	1.5E-06
Methyl Methacrylate	0	1.8E-07	1.8E-07
Methyle Tert Butyl Ether (MTBE)	0	3.1E-07	3.1E-07
Naphthalene	0	1.5E-05	1.5E-05
Propylene	0	4.1E-05	4.1E-05
Styrene	0	2.2E-07	2.2E-07
Toluene	0.049	0.072	0.12
Trichloroethane	3.0E-08	1.8E-07	2.1E-07
Vinyl Acetate	0	6.7E-08	6.7E-08
Xylenes	0	0.042	0.042
Bromoform	0	3.4E-07	3.4E-07
Chloroform	0	5.2E-07	5.2E-07
Carbon Disulfide	0	1.1E-06	1.1E-06
Dimethyl Sulfate	0	4.2E-07	4.2E-07
Cumene	0	4.7E-08	4.7E-08
Cyanide	0	2.2E-05	2.2E-05
Perchloroethylene	0	4.2E-06	4.2E-06
Methylene Chloride	0	6.2E-05	6.2E-05
Carbon Tetrachloride	8.7E-05	1.8E-06	8.9E-05
Phenols	0	2.1E-05	2.1E-05
Fluorides	0	4.0E-04	4.0E-04
Polyaromatic Hydrocarbons (total)	0	4.6E-06	4.6E-06
Biphenyl	0	1.5E-07	1.5E-07
Acenaphthene	0	4.6E-08	4.6E-08
Acenaphthylene	0	2.3E-08	2.3E-08
Anthracene	0	1.9E-08	1.9E-08
Benzo(a)anthracene	0	7.2E-09	7.2E-09
Benzo(a)pyrene	0	3.4E-09	3.4E-09
Benzo(b,j,k)fluroanthene	0	9.9E-09	9.9E-09
Benzo(g,h,i) perylene	0	2.4E-09	2.4E-09
Chrysene	0	9.0E-09	9.0E-09
Fluoranthene	0	6.4E-08	6.4E-08
Fluorene	0	8.2E-08	8.2E-08
Indeno(1,2,3-cd)pyrene	0	5.5E-09	5.5E-09
Naphthanlene	0	1.2E-06	1.2E-06
Phenanthrene	0	2.4E-07	2.4E-07
Pyrene	0	3.0E-08	3.0E-08
5-methyl Chrysene	0	2.0E-09	2.0E-09
Dioxins (unspecified)	0	6.8E-08	6.8E-08
Furans (unspecified)	0	3.7E-10	3.7E-10
CFC12	3.7E-08	7.1E-09	4.4E-08
Radionuclides (unspecified) (1)	0	0.0063	0.0063
Phosgene	1.0E-05	0	1.0E-05
HFC-22	0.010	0	0.010
TDI	1.0E-04	0	1.0E-04
TDA	1.0E-05	0	1.0E-05
ODCB	0.0010	0	0.0010

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 539,509 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 14-5 provides a greenhouse gas (GHG) summary for the production of TDI. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 14-5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in Table 14-4 are multiplied by their global warming potential and shown in Table 14-5.

Both process and fuel-related, as well as the total waterborne emissions are shown in Table 14-6. Definitions of process and fuel-related emissions are earlier previously in this chapter, as well as in the glossary.

Table 14-5

Greenhouse Gas Summary for the Production of TDI
(lb carbon dioxide equivalents per 1,000 lb TDI or kg carbon dioxide equivalents per 1,000 kg TDI)

	Fuel-related CO2 Equiv.	Process CO2 Equiv.	Total CO2 Equiv.
Carbon dioxide (fossil)	1,897	28.2	1,926
Methane	176	79.5	255
Nitrous oxide	12.4	0	12.4
Methyl bromide	7.1E-06	0	7.1E-06
Methyl chloride	7.5E-05	0	7.5E-05
Trichloroethane	2.6E-05	4.2E-06	3.0E-05
Chloroform	1.6E-05	0	1.6E-05
Methylene chloride	6.2E-04	0	6.2E-04
Carbon tetrachloride	0.0026	0.12	0.12
CFC-012	7.7E-05	4.0E-04	4.8E-04
HFC-22	0	18.1	18.1
PFCs (unspecified)	0	0.18	0.18
Total	2,086	126	2,212

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-012--10,900, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 14-6

Waterborne Emissions for the Production of TDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

	Process emissions	Fuel-related emissions	Total emissions
Waterborne Wastes			
Acid (unspecified)	2.5E-04	0.0026	0.0028
Acid (benzoic)	0.0018	0.0023	0.0041
Acid (hexanoic)	3.7E-04	4.8E-04	8.6E-04
Dissolved Solids	99.9	103	203
Suspended Solids	3.61	1.94	5.55
BOD	0.71	0.44	1.16
COD	1.11	0.61	1.73
Phenol/Phenolic Compounds	8.6E-04	0.0010	0.0019
Sulfur	0.0047	0.0061	0.011
Sulfates	0.13	0.25	0.38
Sulfides	0.0011	1.1E-05	0.0011
Oil	0.050	0.045	0.096
Hydrocarbons	0	4.6E-04	4.6E-04
Ammonia	0.056	0.035	0.092
Ammonium	0	5.0E-05	5.0E-05
Aluminum	0.11	0.058	0.17
Antimony	7.1E-05	3.6E-05	1.1E-04
Arsenic	4.5E-04	5.2E-04	0.0010
Barium	1.57	0.86	2.43
Beryllium	2.4E-05	2.4E-05	4.8E-05
Cadmium	6.7E-05	7.7E-05	1.4E-04
Chromium (unspecified)	0.0032	0.0016	0.0048
Chromium (hexavalent)	1.1E-05	0	1.1E-05
Cobalt	3.9E-05	5.1E-05	9.0E-05
Copper	4.2E-04	3.7E-04	7.9E-04
Iron	0.24	0.16	0.40
Lead	8.7E-04	7.9E-04	0.0017
Lithium	0.69	2.24	2.93
Magnesium	1.11	1.45	2.56
Manganese	0.0018	0.0035	0.0053
Mercury	1.5E-06	6.4E-07	2.1E-06
Molybdenum	4.1E-05	5.3E-05	9.4E-05
Nickel	4.2E-04	4.2E-04	8.5E-04
Selenium	1.4E-05	2.5E-05	3.8E-05
Silver	0.0037	0.0048	0.0085
Sodium	18.1	23.5	41.5
Strontium	0.097	0.13	0.22
Thallium	1.5E-05	7.5E-06	2.2E-05
Tin	3.3E-04	2.8E-04	6.0E-04
Titanium	0.0011	5.5E-04	0.0016
Vanadium	4.8E-05	6.3E-05	1.1E-04
Yttrium	1.2E-05	1.6E-05	2.7E-05
Zinc	0.0027	0.0015	0.0042
Chlorides (unspecified)	64.0	83.2	147
Chlorides (methyl chloride)	7.1E-08	9.3E-08	1.6E-07
Calcium	5.70	7.40	13.1

Table 14-6

Waterborne Emissions for the Production of TDI
(lb per 1,000 lb or kg per 1,000 kg)
(page 2 of 2)

		Process emissions	Fuel-related emissions	Total emissions
Fluorine/Fluorides		1.8E-06	8.1E-04	8.1E-04
Nitrates		0	1.2E-04	1.2E-04
Nitrogen/Nitrates (ammonia)		0	4.4E-05	4.4E-05
Bromide		0.38	0.49	0.87
Boron		0.0056	0.0072	0.013
Organic Carbon		0.010	0.011	0.021
Cyanide		3.0E-05	1.7E-07	3.0E-05
Hardness		17.6	22.8	40.3
Total Alkalinity		0.14	0.19	0.33
Surfactants		0.0016	0.0023	0.0038
Acetone		1.8E-05	2.3E-05	4.1E-05
Alkylated Benzenes		6.2E-05	3.1E-05	9.3E-05
Alkylated Fluorenes		3.6E-06	1.8E-06	5.4E-06
Alkylated Naphthalenes		1.0E-06	5.1E-07	1.5E-06
Alkylated Phenanthrenes		4.2E-07	2.1E-07	6.3E-07
Benzene		0.0030	0.0039	0.0068
Cresols		1.1E-04	1.3E-04	2.4E-04
Cymene		1.8E-07	2.3E-07	4.1E-07
Dibenzofuran		3.4E-07	4.4E-07	7.7E-07
Dibenzothiophene		2.7E-07	3.5E-07	6.3E-07
2,4 dimethylphenol		5.0E-05	6.4E-05	1.1E-04
Ethylbenzene		1.7E-04	2.2E-04	3.8E-04
2-Hexanone		1.2E-05	1.5E-05	2.7E-05
Methyl Ethyl Ketone (MEK)		1.4E-07	1.9E-07	3.3E-07
1-methylfluorene		2.0E-07	2.6E-07	4.6E-07
2-methyl naphthalene		2.8E-05	3.6E-05	6.5E-05
4-methyl 2-pentanone		7.5E-06	9.7E-06	1.7E-05
Naphthalene		3.2E-05	4.2E-05	7.4E-05
Pentamethyl benzene		1.3E-07	1.7E-07	3.1E-07
Phenanthrene		4.1E-07	3.3E-07	7.3E-07
Toluene		0.0028	0.0036	0.0065
Total Biphenyls		4.0E-06	2.0E-06	6.0E-06
Total Dibenzo-thiophenes		1.2E-08	6.2E-09	1.9E-08
Xylenes		0.0015	0.0019	0.0035
Radionuclides (unspecified)	(1)	6.4E-11	8.9E-08	8.9E-08
Phosphates		0.0010	0	0.0010
Lead 210		1.8E-13	0	1.8E-13
n-Decane		5.2E-05	0	5.2E-05
n-Docosane		1.9E-06	0	1.9E-06
n-Dodecane		9.8E-05	0	9.8E-05
n-Eicosane		2.7E-05	0	2.7E-05
n-Hexacosane		1.2E-06	0	1.2E-06
n-Hexadecane		1.1E-04	0	1.1E-04
n-Octadecane		2.6E-05	0	2.6E-05
n-Tetradecane		4.3E-05	0	4.3E-05
Chloroform		1.0E-06	0	1.0E-06
ODCB		1.0E-04	0	1.0E-04
Sodium Hydroxide		1.00	0	1.00

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(1) The units for Radionuclides are Curies per 1,000 lbs of product. The total Radionuclides using metric units are 7.55 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

ADDENDUM

DIFFERENCES BETWEEN THE U.S. LCI PLASTICS DATABASE AND THE PLASTICSEUROPE ECO-PROFILES DATABASE

INTRODUCTION

This addendum presents the differences between the U.S. LCI Plastics Database and the PlasticsEurope Eco-Profiles Database. The original purpose of this comparison was to highlight and reconcile the original differences between these two separate databases before the public release of the revised U.S. plastics data into the U.S. LCI Database project. Energy and total greenhouse gases (CO2 equivalents) for each comparable plastic resin and polyurethane precursor in the 2010 report were analyzed in the comparison. After the energy differences were identified in the 2006 draft version of this report, Ian Boustead of Boustead Consulting, Ltd. was contacted by Franklin Associates staff to discuss the differences in results for the two databases. The following sections discuss specific areas where differences were identified between the U.S. and European plastics databases.

The 2010 results have not been reviewed by PlasticsEurope consultants. Both the 2007 and 2010 results for the U.S. LCI Plastics Database have been included in the following tables. Differences between the two sets of results are due to two major factors: (a) intermediate data collection/replacement, and (b) a change in the methodology used for handling fuels produced within the production of a number of intermediate chemicals (including the hydrocracker). This change is consistent with a harmonization of LCA methodologies collaboration that both PlasticsEurope and ACC have undertaken, with a goal of providing a global synchronization of methodologies to conduct polymer LCAs consistent with the ISO 14040 series of standards.

OVERVIEW OF COMPARISON OF PLASTICS AND PRECURSOR ENERGY AND GREENHOUSE GAS RESULTS

Energy Comparison

Table AD-1 presents the total energy for each comparable plastic resin and polyurethane precursor for the 2010 U.S. LCI Plastics Database, the 2007 U.S. LCI Plastics Database, and the current PlasticsEurope Eco-Profiles Database. That table also provides the energy difference between U.S. and European results, and the percent difference between U.S. and European results. The percent differences range from -11 percent to 13 percent for the plastic resins. The percent differences for the polyols (polyurethane precursors) are less meaningful. Polyols have been separated into polyols for rigid foam polyurethane and polyols for flexible foam polyurethane for the U.S. LCI Plastics Database. The PlasticsEurope Eco-Profiles Database does not specify what percentage of the polyols data is for rigid foam polyurethane and flexible foam polyurethane. Therefore, the actual percent difference is within the range of -12 to 2 percent.

One important fact to note is that the ranges of the energy results for the individual plants collected in Europe were large according to various EcoProfiles reports. Individual plant results varied as much as 25 percent on either side of the average total energy. Although individual facility results may be considerably below or above the average, they are part of the population that generated the reported average. The percent differences between the U.S. and European total energy averages shown in Table AD-1 are within the range of the individual plant total energy results in Europe. With greater participation by North American plastic producers, the total energy average for North American resins may increase or decrease. Given the variations in individual U.S. and European plant data, the U.S. 2010 resin averages, while different from the 2007 and European averages, are likely not *statistically* different.

The largest difference is found when the U.S. and European isocyanates data are compared. The U.S. isocyanates data are a little more than half that of the European isocyanates data. The isocyanates results were reviewed by Ian Boustead in 2006. Due to the large differences in energy results for the isocyanates between the two databases, it was decided that Franklin Associates would attempt to collect primary data for the intermediate chemicals to the isocyanates. New primary data was collected for formaldehyde and DNT. The overall difference in the new primary data with the previous data used was very small. One difference found during the review discussions is the allocation of mass for hydrochloric acid as a coproduct during the production of isocyanates. The largest part of this energy difference is due to the hydrochloric acid used as a coproduct in the US, while it was assumed to be incinerated in Europe. During recent discussions with PlasticsEurope contacts, it was discovered that a number of European isocyanate plants are selling the hydrochloric acid. PlasticsEurope is in discussions with ISOPA to update the European isocyanates data to reflect the use of hydrochloric acid as a coproduct, and an update based on mass allocation for HCl as a coproduct is expected to make the US and European isocyanates values more similar. Other differences include methodology differences between the Franklin Associates and Boustead models for feedstock energy/EMR and precombustion energy.

In reviewing the discussion of energy differences, it is useful to understand the terminology used by the consultants in reporting energy results. There are four categories of energy used by Franklin Associates and Boustead Consulting. Within these four categories, there are differences in terminology between the U.S. and European plastics databases. Table AD-2 lists and defines the energy categories.

Greenhouse Gas Comparison

Table AD-3 provides the total greenhouse gases (CO_2 equivalents) for each comparable plastic resin and polyurethane precursor for the 2010 U.S. LCI Plastics Database, the 2007 U.S. LCI Plastics Database, and the current PlasticsEurope Eco-Profiles Database. That table also provides the CO_2 equivalents difference between U.S.

and European results, and the percent difference between U.S. and European results. The greenhouse gases percent differences range from -17 percent to 18 percent for the plastic resins. The results for polyols are also within that range of percent differences. However, the percent difference results for the isocyanates follow the percent differences of energy.

Table AD-1

Total Energy Comparison of ACC Plastics LCI Database and PlasticsEurope Plastics LCI Database (MJ per 1 kg of resin/precursor)

	2010 ACC Database	2007 final ACC Database	PlasticsEurope Database	2007 Difference*		2010 Difference*	
HDPE	83.2	68.9	76.7	-7.8	-11%	6.5	8%
LDPE	88.6	74.0	78.1	-4.1	-5%	10.5	13%
LLDPE	83.0	68.5	72.7	-4.2	-6%	10.3	13%
PP	81.3	63.4	73.4	-10.0	-15%	7.9	10%
PET	74.2	69.1	82.7	-13.6	-18%	-8.5	-11%
GPPS	98.7	84.6	86.5	-1.9	-2%	12.3	13%
HIPS	99.8	85.6	87.4	-1.8	-2%	12.4	13%
PVC	59.0	52.4	56.7	-4.3	-8%	2.3	4%
ABS	109.0	93.3	95.3	-2.0	-2%	13.7	13%
Polyol--Rigid Polyurethane	82.3	74.3	93.2	-18.9	-23%	-10.9	-12%
Polyol--Flexible Polyurethane	95.1	85.2	93.2	-8.0	-9%	1.9	2%
MDI	61.2	NA	91.0	NA	NA	-29.8	-39%
TDI	55.3	NA	108.2	NA	NA	-52.9	-65%

Note: Polyols are one category in the PlasticsEurope database

* Difference = ACC energy - PlasticsEurope energy
% difference = (difference between ACC and PE results)/(average of ACC and PE results)

Updated with June 2010 ACC DB & EcoProfiles as of January 2010

Table AD-2

Energy Categories: Terminology and Definition

U.S. Terminology	European Terminology
Process Energy--Energy used for any/all processes that extract, transform, fabricate or otherwise effect changes on a material or product	**Energy Content of Delivered Fuel**--the energy that is received by the final operator who consumes energy
Transportation Energy--the energy used to move materials or products from location to location during the journey from raw material extraction through end of life disposition [note: the resin database boundaries end at the resin production step]	**Transport Energy**--the energy associated with fuels consumed directly by the transport operations as well as any energy associated with the production of non-fuel bearing materials, such as steel, that are taken into the transport process.
Energy of Material Resource--the energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as inputs for materials such as plastic resins	**Feedstock Energy**--the energy of the fuel bearing materials that are taken into the system but used as materials rather than fuels
Precombustion Energy--the energy required for the production and processing of energy fuels, starting with their extraction from the ground, up to the point of delivery to the customer	**Fuel Production and Delivery Energy**--the energy that is used by the fuel producing industries in extracting the primary fuel from the earth, processing it and delivering it to the ultimate consumer

The greenhouse gas results were not compared with the European results in 2006. One difference may lie in the hydrocracker results. It is unknown if the European Eco-Profiles include greenhouse gases released from the combustion of the offgas used within the hydrocrackers. Franklin Associates did take this into account using the plant data collected.

DATA SOURCES

All primary data for the U.S. plastics LCI database were collected between 2003 and 2005. These data represent the year 2003 for the most part. One exception is the formaldehyde data, which represents 2007 data. Franklin Associates and ACC were diligent in finding at least three companies to participate in collecting data for each resin and precursor studied. However, in some cases, there were fewer numbers of companies participating due to confidentiality concerns and issues for U.S. companies. The data collection effort focused on the resin production step, as well as intermediate chemicals that the resin producers manufactured.

Table AD-3

Total CO2 Equivalent Comparison of ACC Plastics LCI Database and PlasticsEurope Plastics LCI Database (kg CO2 equivalents per 1 kg of resin/precursor)

	2010 ACC Database**	2007 final ACC Database	PlasticsEurope Database	2007 Difference*		2010 Difference*	
HDPE	1.890	1.478	1.930	-0.452	-27%	-0.040	-2%
LDPE	2.210	1.477	2.080	-0.603	-34%	0.130	6%
LLDPE	1.924	1.479	1.824	-0.345	-21%	0.100	5%
PP	1.868	1.343	1.964	-0.621	-38%	-0.096	-5%
PET	2.798	2.538	3.318	-0.780	-27%	-0.520	-17%
GPPS	3.175	2.763	3.432	-0.669	-22%	-0.257	-8%
HIPS	3.194	2.757	3.424	-0.667	-22%	-0.230	-7%
PVC	2.255	2.029	1.889	0.140	7%	0.366	18%
ABS	3.749	3.149	3.760	-0.611	-18%	-0.011	0%
Polyol--Rigid Polyurethane	3.538	3.377	3.547	-0.170	-5%	-0.009	0%
Polyol--Flexible Polyurethane	3.853	3.633	3.547	0.086	2%	0.306	8%
MDI	2.289	NA	3.947	NA	NA	-1.658	-53%
TDI	2.212	NA	6.264	NA	NA	-4.052	-96%

Note: Polyols are one category in the PlasticsEurope database

* Difference = ACC CO2 - PlasticsEurope CO2
% difference = (difference between ACC and PE results)/(average of ACC and PE results)
** 2010 Numbers are reported with updated global warming potentials

Updated with June 2010 ACC DB & EcoProfiles as of January 2010

Boustead Consulting has been collecting and updating various plastic Eco-Profiles for PlasticsEurope for 15 years. Boustead Consulting, in most cases, receives a significant response by most of the European plastics industry in providing datasets for resin production as well as the upstream unit processes. At this time, much of the intermediates and ancillary materials used in the polymer production of the European plastics LCI database are primary datasets.

Another difference between the data sources of these two databases is the fuel data. The fuels information for the European database is based on statistics published by the International Energy Agency (IEA). Country specific fuel data is used for each primary dataset. Fuel production data for the U.S. were based on Department of Energy national statistics and data. The national average U.S. electricity grid (from the U.S. LCI Database) was used.

Other data source differences include:

- <u>Transportation differences.</u> Distances for some transportation steps are higher in North America compared to Europe.

- Different feedstock mixes. Differences in the mix of crude oil and natural gas used as resin material feedstocks in the U.S. and in Europe lead to different feedstock energy (energy of material resource). This comes about due to the difference in calorific values for natural gas (54 MJ/kg) and crude oil (45 MJ/kg).
- Different material sources. Differences in the source of an intermediate chemical/material may make a difference in raw materials, energy, and/or emissions. One example is the glycerine used in the polyols used in flexible foam polyurethane. It may be produced from a number of sources, including palm oil, animal fat, and from propylene.
- Accuracy/types of collected data. The collected U.S. data (including a few Canadian and Mexican plants) was taken from a variety of sources within each company providing data (ranging from estimates to calculations from utility records).
- Differences of the size and age of plants providing data. Production quantities were used to weight the provided data; therefore smaller plants were weighted lower than the larger plants.
- Differences in plant sites. Coproducts that may be regarded as wastes on a small site or stand-alone plant may be regarded as inputs to other processes on large sites.
- Differences in system boundaries. The European plastics LCI database includes waste incineration facilities within its system boundaries. No waste incineration facilities are included within the system boundaries of the U.S. plastics LCI database. Many U.S. plants had wastes sent to incineration facilities; however, these were commonly off-site and mixed with wastes from other plants, and so data were unavailable for the specific materials of interest. In some cases, large amounts of chemicals that were incinerated as wastes at European plants were actually coproducts (sold for profit) at corresponding U.S. plants.

METHODOLOGICAL DIFFERENCES

Averaging Data. Using PlasticsEurope LCI terminology, horizontal and vertical averaging are two different methods of producing average data. A detailed description of each method is given in the PlasticsEurope Methodology pdf document found at http://www.lca.plasticseurope.org/methodol.htm under the heading "Calculating Averages".

Based on Boustead Consulting's description, Franklin Associates averages the primary data collected using the horizontal averaging method. Boustead Consulting uses the vertical averaging method for the primary data collected in Europe. Franklin Associates is not able to use the vertical method of averaging due to fewer data providers and the fact that much of the intermediate chemicals data used by Franklin Associates were unavailable from primary sources.

Figure AD-1 and AD-2 provide flow diagrams showing the use of horizontal and vertical averaging. Using these flow diagrams as an example, Figure AD-1 shows how this analysis utilized horizontal averaging to calculate averages for each unit process for which primary data was received, including intermediate materials and the final material. The average unit process datasets are then linked to calculate the average cradle-to-resin dataset. Figure AD-2 shows how vertical averaging, utilized by PlasticsEurope's database, calculates averages after calculating a cradle-to-product dataset for each company and their supply chain.

Boustead Consulting and Franklin Associates agree that the vertical averaging is the most accurate method of calculating average primary data. However, this method requires that data be available for each resin producer's complete supply chain. Figure AD-2 shows the difficulty that arises when complete supply chain data is not available. In this figure, Company C has provided ethylene data, but the resin producer that they supply to did not provide data for the analysis. Also, Company D provided LDPE resin data, but its supplier of ethylene did not provide data. This is the challenge that Franklin Associates faced as, in most cases, only a small percentage of companies within the specific material industry were participating, and even fewer companies provided intermediate chemical data. However, these limitations can be accommodated using horizontal averaging (see Figure AD-1). Company C's data can be averaged into an industry-average ethylene dataset, and the same is true for Company D's LDPE data.

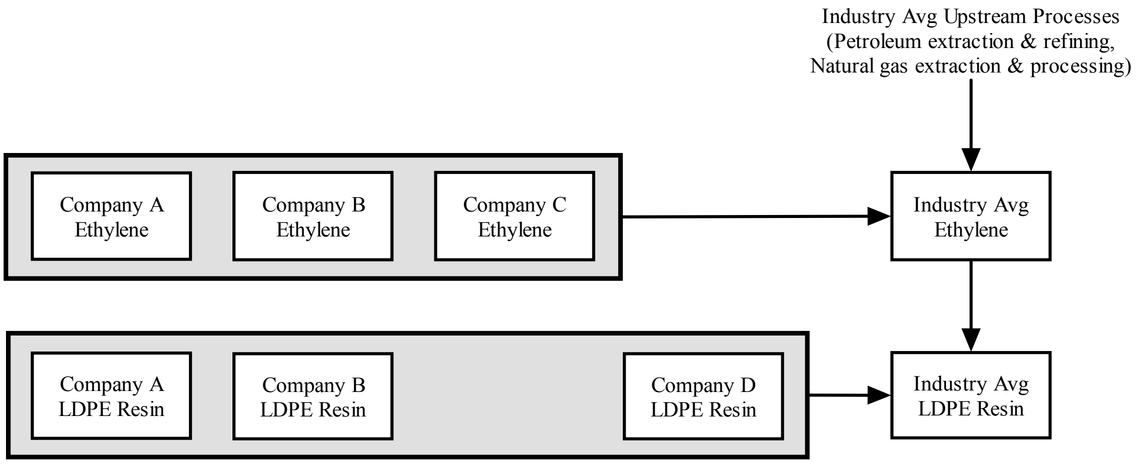

Figure AD-1. Flow diagram of the use of horizontal averaging to calculate primary average LDPE data.

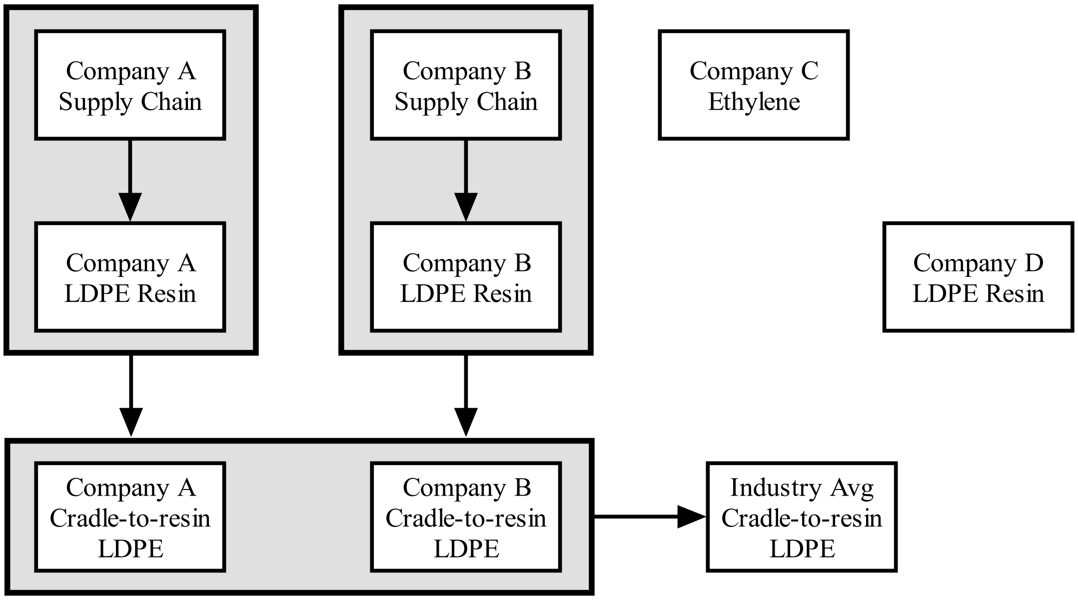

Figure AD-2. Flow diagram of the use of vertical averaging to calculate primary average LDPE data.

Boustead Consulting analyzed the difference in cradle-to-resin results obtained by each of these two methods, using hydrocrackers (ethylene output) as a case study. The total energy using vertical averaging was approximately 5 percent greater than the total energy using horizontal averaging. Considering the differences in Table AD-1, if sufficient data could be collected to do vertical averaging this would bring the total energy differences closer in many cases.

Cogeneration of Steam and Electricity. Boustead Consulting considered the efficiencies of electricity and steam used by Franklin Associates for cogeneration to be "optimistic." An expert from a participating company provided a range of efficiencies for the electricity and steam generation for the cogeneration process. The electricity generation efficiency is 50% and steam efficiency is 80% for cogeneration in the U.S. plastics LCI database. Franklin Associates performed a sensitivity analysis on these efficiencies and found that any changes to these efficiencies would result in very small differences in the overall results of the resins/precursors.

Coproduct Allocation Method. Simple mass allocation is a common type of allocation used for coproducts in LCI/LCA. Franklin Associates has used this allocation method to allocate resources for the production of chlorine and sodium hydroxide from salt. The chemistry of the reaction determines the relative masses of the coproducts chlorine and sodium hydroxide that are produced from a given quantity of salt. It is not possible to control the cell to increase or decrease the amount of chlorine or caustic soda resulting from this given input of salt. Furthermore, sodium hydroxide cannot be obtained without producing the valuable coproducts chlorine and hydrogen.

While stoichiometric allocation tracks the masses of individual ions from the input salt, the fact remains that the output of the reaction is chlorine gas and sodium hydroxide rather than sodium ions and chlorine ions. The relative masses of the output <u>products</u> are different than the relative masses of the sodium and chlorine <u>ions</u> in the salt. The chemistry of the reaction determines the types and relative masses of the output products that are formed from the component ions of the input salt. Thus, the inputs are allocated based on the relative masses of output <u>products</u> formed.

Boustead Consulting uses stoichiometric allocation for the salt input to the chlorine/caustic production. Hydrochloric acid inputs, sulfuric acid inputs, and chlorine emissions are allocated to chlorine production. Hydrogen emissions are allocated to hydrogen production. Sodium hydroxide inputs are allocated to sodium hydroxide production. The electricity, steam, and the remaining emissions are allocated on a simple mass basis.

Franklin Associates performed a sensitivity analysis on the polyols results using stoichiometric allocation for chlorine/caustic production. The polyols use the largest amount of sodium hydroxide of all the resins/precursors, so these results are most sensitive to the choice of allocation method. The total energy for each of the polyols would increase by approximately 1 MJ/kg of polyol if stoichiometric allocation were used. This amount is approximately 1 percent of the total energy for the polyol. It should be noted that use of stoichiometric allocation by Franklin Associates for sodium hydroxide production would decrease the difference between the North American and European polyol total energy results by 1 percent.

Fuel Infrastructure. In the PlasticsEurope LCI database, plant data are calculated using fuel infrastructure from the country where the plant is located. An overall average U.S. electricity grid is used for the plastics LCI database. While it is true that U.S. regional grids differ, the use of horizontal averaging makes the use of regional grids difficult. For example, the ABS plants are from two different U.S. regions. To produce a regional average electricity grid for each average dataset would have required significantly more modeling effort.

Table AD-4 displays the differences between the North American regional grids and the North American average grid. Most of the plants where data was collected are in the Texas and Eastern regions with only a few from the Western region. This leads us to believe that if regional grids were used, it is likely total energy of the resins/precursors would increase by a small percentage, likely **<u>less</u> than two percent** by our estimates. Although the energy total for the Texas regional grid is approximately 20 percent greater than for the North American average grid, the energy total for the Eastern regional grid is approximately 1 percent greater than for the North American average grid, and the energy total for the Western regional grid is approximately 14 percent less than for the North American average grid. Franklin Associates estimates that the primary data collected was about 55 percent in the Texas region, 40 percent in the Eastern region and 5 percent in the Western region. Electricity use generally makes up in the order of 10-20 percent of the total energy of the cradle-to-gate resin production. From these figures, we can estimate:

20% * 55% + 1% * 40% + -14% * 5% = 10.7% increase in electrical energy

10.7% * 20% of total energy from electricity = 2.1% increase in total energy as estimate.

Thus, the small estimated change in total energy does not appear to justify the level of effort that would be required for regional grid modeling.

Table AD-4

Comparison of Regional and Average Electricity Grids for North America

	Percent of kWh					
Grid	**Coal**	**Oil**	**Natural Gas**	**Nuclear**	**Hydro**	**Other**
North American Average Grid	52.2%	2.8%	15.7%	19.6%	7.1%	2.6%
Texas Grid	35.5%	0.9%	50.1%	11.9%	0.2%	1.6%
Eastern U.S. Grid (1)	58.9%	3.3%	10.1%	22.6%	2.9%	2.2%
Western U.S. Grid (2)	32.4%	0.6%	23.2%	11.1%	28.1%	4.6%

	MM Btu/1,000 kWh						
Grid	**Coal**	**Oil**	**Natural Gas**	**Nuclear**	**Hydro**	**Other**	**Total**
North American Average Grid	2.06	0.55	6.07	0.27	1.45	0.28	10.68
Texas Grid	6.77	0.33	4.55	0.01	0.95	0.18	12.80
Eastern U.S. Grid (1)	1.35	0.63	6.81	0.11	1.66	0.24	10.81
Western U.S. Grid (2)	2.94	0.20	3.71	1.04	0.81	0.48	9.17

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(1) The Eastern U.S. Grid includes states/provinces from the Atlantic Ocean as far west as Oklahoma, Kansas, Nebraska, South Dakota, North Dakota, and Saskatchewan.

(2) The Western grid includes states/provinces west of those listed in the Eastern grid.

CONCLUSION

Based on careful and thorough analysis of each area where differences were identified between the Plastics Division of the ACC and PlasticsEurope databases, it has been agreed by the Plastics Division of the ACC and PlasticsEurope that the differences in results (shown in Table AD-1) are justified and acceptable as of 2007. The 2010 ACC results are consistent with the additional data collection efforts and the methodology differences for handling fuels produced within the production of a number of intermediate chemicals (including the hydrocracker) that were the basis for the 2007 data collection

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GLOSSARY

TERMS USED IN THE LCI REPORT AND APPENDICES

Biochemical Oxygen Demand (BOD). An indication of the amount of organic material present in water or wastewater.

Biomass. The total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unit of the Earth's surface. As an energy source, the Energy Information Administration defines biomass as organic non-fossil material of biological origin constituting a renewable energy source.

Btu (British thermal unit). A standard unit for measuring the quantity of heat energy equal to the quantity of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit.

Carbon Cycle, Natural. The process by which carbon dioxide is taken up by trees and released at a later time when these trees, or products made from them, decompose or are burned. The U.S. EPA uses the convention that carbon dioxide releases from wood-derived materials do not constitute a net contribution to global carbon dioxide, because the carbon dioxide removed from the atmosphere during the trees' growth cycle is simply being returned to the atmosphere.

Carbon Dioxide Equivalents. A greenhouse gas's potential to contribute to global warming, relative to carbon dioxide, which is assigned a global warming potential of 1.

Carbon Dioxide. A naturally occurring gas and also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1[7].

Carbon Dioxide, Fossil. Carbon dioxide associated with the combustion of fossil fuels.

Carbon Dioxide, Non-fossil. Carbon dioxide associated with natural sources or combustion of biomass.

Chemical Oxygen Demand (COD). The amount of oxygen required for the oxidation of compounds in water, as determined by a strong oxidant such as dichromate.

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[7] Definition from the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report - **Climate Change 2001.**

Coal. A black or brownish-black solid, combustible substance formed by the partial decomposition of vegetable matter without access to air. The rank of coal, which includes anthracite, bituminous coal, subbituminous coal, and lignite, is based on fixed carbon, volatile matter, and heating value. Coal rank indicates the progressive alteration, or coalification, from lignite to anthracite.

Combustion Energy. The high heat value directly released when coal, fuel oil, natural gas, or wood are burned for energy consumption.

Combustion Emissions. The environmental emissions directly emitted when coal, fuel oil, natural gas, or wood are burned for energy consumption.

Crude Oil. A mixture of hydrocarbons that exists in liquid phase in underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities.

Curie (Ci). The metric unit of radioactive decay. The quantity of any radioactive nuclide that undergoes $3.7x10^{10}$ disintegrations/sec.

Distillate Fuel Oil. A general classification for one of the petroleum fractions produced in conventional distillation operations. It is used primarily for space heating, on-and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation. Included are products known as No. 1, No. 2, and No. 4 diesel fuels.

Energy of Material Resource. The energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as material inputs for materials such as plastic resins. Alternative terms used by other LCI practitioners include "Feedstock Energy" and "Inherent Energy."

Fossil Fuel. Carbon-based fuel from fossil carbon deposits such as oil, natural gas, and coal.

Fuel-related Emissions. Emissions (atmospheric, waterborne, and solid waste) associated with the combustion of fuel, including carbon dioxide emissions, products of incomplete combustion, residual ash, etc.

Fugitive Emissions. Unintended leaks of substances that escape to the environment without treatment. These are typically from the processing, transmission, and/or transportation of fossil fuels, but may also include leaks and spills from reaction vessels, other chemical processes, etc.

Geothermal Energy. Energy from the internal heat of the earth, which may be residual heat, friction heat, or a result of radioactive decay. The heat is found in rocks and fluids at various depths and can be extracted by drilling and/or pumping.

Global Warming Potential (GWP). An index, describing the radiative characteristics of well-mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide[8].

Greenhouse Effect. The entrapment of heat within the Earth's surface-troposphere system due to the absorption of infrared radiation by greenhouse gases[9].

Greenhouse Gas. Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorbs and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane, and ozone are the primary greenhouse gases in the Earth's atmosphere[10].

Heat Content of a Quantity of Fuel, Gross. The total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce carbon dioxide and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat but is not counted as part of net content. Also referred to as the higher heating value. Btu conversion factors typically used by EIA represent gross heat content. Called combustion energy in this appendix.

Heat Content of a Quantity of Fuel, Net. The amount of usable heat energy released when a fuel is burned under conditions similar to those in which it is normally used. Also referred to as the lower heating value. Btu conversion factors typically used by EIA represent gross heat content.

Hydrocarbons. A subcategory of organic compounds that contain only hydrogen and carbon. These compounds may exist in either the gaseous, liquid, or solid phase, and have a molecular structure that varies from the simple to the very heavy and very complex. The category Non-Methane Hydrocarbons (NMHC) is sometimes used when methane is reported separately.

Liquefied Petroleum Gases (LPG). Ethane, ethylene, propane, propylene, normal butane, butylene, isobutane, and isobutylene produced at refineries or natural gas processing plants, including plants that fractionate raw natural gas plant liquids.

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[8] Definition from the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report **- Climate Change 2001.**

[9] Adapted from the definition in the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report **- Climate Change 2001.**

[10] Partial definition for this term from the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report **- Climate Change 2001.**

Methane (CH_4). A hydrocarbon that is a greenhouse gas produced through anaerobic (without oxygen) decomposition of waste in landfills, animal digestion, decomposition of animal wastes, production and distribution of natural gas and oil, coal production, and incomplete fossil fuel combustion[11]. Methane is the principal constituent of natural gas.

(**Motor) Gasoline.** A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, that has been blended to form a fuel suitable for use in spark-ignition engines. "Motor gasoline" includes reformulated gasoline, oxygenated gasoline, and other finished gasoline.

Natural Gas. A mixture of hydrocarbons (principally methane) and small quantities of various nonhydrocarbons existing in the gaseous phase or in solution with crude oil in underground reservoirs.

Nitrogen Oxides (NO_X). Compounds of nitrogen and oxygen produced by the burning of fossil fuels, or any other combustion process taking place in air. The two most important oxides in this category are nitrogen oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide (N_2O), however, is not included in this category and is considered separately.

Nitrous Oxide (N_2O). A greenhouse gas emitted through soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning[12].

Non-Methane Volatile Organic Compounds (NMVOC). Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Other Organics. Compounds containing carbon combined with hydrogen and other elements such as oxygen, nitrogen, sulfur or others. Compounds containing only carbon and hydrogen are classified as hydrocarbons and are not included in this category.

Particulate Matter (Particulates). Small solid particles or liquid droplets suspended in the atmosphere, ranging in size from 0.005 to 500 microns.

Particulates are usually characterized as primary or secondary. Primary particulates, usually 0.1 to 20 microns in size, are those injected directly into the atmosphere by chemical or physical processes. Secondary particulates are produced as a result of chemical reactions that take place in the atmosphere. In our reports, particulates refer only to primary particulates.

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[11] Adapted from the definition in the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report **- Climate Change 2001.**

[12] Adapted from the definition in the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report **- Climate Change 2001.**

Particulates reported by Franklin Associates are not limited by size range, and are sometimes called total suspended particulates (TSP). The category PM-10 refers to all particulates less than 10 microns in (aerodynamic) diameter. This classification is sometimes used when health effects are being considered, since the human nasal passages will filter and reject any particles larger than 10 microns. PM 2.5 (less than 2.5 microns in diameter) is now considered the size range of most concern for human health effects.

Petroleum. A generic term applied to oil and oil products in all forms, such as crude oil, lease condensate, unfinished oils, petroleum products, natural gas plant liquids, and nonhydrocarbon compounds blended into finished petroleum products.

Postconsumer Waste. Product or material that has served its intended use and is discarded by the consumer.

Precombustion Energy. The energy required for the production and processing of energy fuels, such as coal, fuel oil, natural gas, or uranium, starting with their extraction from the ground, up to the point of delivery to the customer.

Precombustion Fuel-related Emissions. The environmental emissions due to the combustion of fuels used in the production and processing of the primary fuels; coal, fuel oil, natural gas, and uranium.

Precombustion Process Emissions. The environmental emissions due to the production and processing of the primary fuels; coal, fuel oil, natural gas, and uranium, that are process rather than fuel-related emissions.

Process Emissions. Emissions (atmospheric, waterborne, and solid waste) that result from a process, such as gases given off during a chemical reaction, residual material remaining in the bottom of a reaction vessel, unrecycled trim scrap from fabrication processes, etc.

Process Energy. Energy used for any/all processes that extract, transform, fabricate or otherwise effect changes on a material or product during its life cycle.

Residual Fuel Oil. The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Included are No. 5, No. 6, and Navy Special. It is used for commercial and industrial heating, electricity generation, and to power ships.

Sulfur Oxides (SO_X). Compounds of sulfur and oxygen, such as sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Total Dissolved Solids (TDS). The TDS in water consists of inorganic salts, minute organic particles, and dissolved materials. In natural waters, salts are chemical compounds composed of anions such as carbonates, chlorides, sulfates, and nitrates, and cations such as potassium, magnesium, calcium, and sodium.

Total Suspended Solids (TSS). TSS gives a measure of the turbidity of the water. Suspended solids cause the water to be milky or muddy looking due to the light scattering from very small particles in the water.

Transportation Energy. The energy used to move materials or products from location to location during the journey from raw material extraction through end of life disposition.

Volatile Organic Compounds (VOCs). Organic compounds that participate in atmospheric chemical reactions.

FINAL APPENDICES

CRADLE-TO-GATE LIFE CYCLE INVENTORY OF NINE PLASTIC RESINS AND FOUR POLYURETHANE PRECURSORS

Prepared for

PLASTICS DIVISION OF THE AMERICAN CHEMISTRY COUNCIL (ACC)

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APPENDIX A

ENERGY REQUIREMENTS AND ENVIRONMENTAL EMISSIONS FOR FUEL CONSUMPTION

INTRODUCTION

This appendix provides detailed information about the energy requirements and environmental emissions associated with the production and use of various types of fuels and energy sources. Specifically, this appendix describes production of fuels and generation of electrical power, and is presented in terms of precombustion and combustion components. Precombustion components include the resources consumed, energy used, and environmental emissions that result from mining, refining, and transporting fuels, and includes all steps up to, but not including, their end use, or consumption. The combustion components are the energy and environmental releases from the combustion of fuels used for heat, process energy, and electricity generation. This appendix also develops a standard method for relating electricity consumption to actual fuel usage.

The energy and environmental emissions data shown in this appendix can be used in the evaluation of products or processes using a life cycle approach. For example, if it is known that a particular manufacturing process requires the use of a certain amount of electricity, the data presented in this appendix can be used to allocate the fuel usage and the environmental emissions for generating this amount of electricity. In addition, the data in this appendix can be used to calculate the fuel usage and environmental emissions for producing the fuels used to generate this electricity. In this way, the total amount of fuel consumed as well as all of the environmental emissions that result from electricity being used in a particular manufacturing process can be accounted for. Fuel usage by other processes in the manufacture of a product under investigation can be evaluated in a similar manner using the data in this appendix.

While determination of the energy and environmental emissions is logically straightforward, it is complicated by the iterative nature of some of the calculations. For this reason, a roadmap is included for the discussion that follows.

The two main topics in this appendix are a) primary fuel production, and b) primary fuel combustion.

Primary Fuel Production

Primary fuels are the fuels used to produce electricity, generate heat and power, and provide energy for transportation. They include coal, natural gas, residual and distillate fuel oil, and uranium.

The objective is to know both a) the energy (in terms of electricity and primary fuels) required to deliver these fuels to a customer, and b) the environmental emissions resulting from the delivery of these fuels to a customer. (Use of these fuels by a customer is discussed in the section on primary fuel combustion.)

The energy requirements and environmental emissions, starting from the extraction of raw materials from the earth, and ending with the delivery of the processed and refined primary fuels to the customer, are known as **precombustion energy** and **precombustion emissions**. The energy and emissions due to the combustion of these primary fuels by the customer, to produce electricity, to generate heat and power for industrial processes, or to provide energy for transportation are called **combustion energy** and **combustion emissions**.

The energy requirements for the production and processing of primary fuels can be found from industry sources, government surveys, or in the published and unpublished literature. They typically are given in terms of electricity, coal, natural gas, and fuel oil (residual and distillate).

The environmental emissions can be divided into two sources:

a) the emissions due to the combustion of fuels used in the production of primary fuels. This includes emissions from such sources as motor vehicles used in the transportation steps, or natural gas compressor engines used to move natural gas through pipelines. These emissions are called **fuel-related precombustion emissions**.

b) the process-related emissions *not* due to the combustion of fuel, which include such sources as fugitive dust, natural gas vented at the wellhead, waste rock from coal cleaning, etc. These emissions are called **precombustion process emissions**.

Transportation occurs at several stages along the path to delivering primary fuels for consumption, and must be included in the precombustion components. Coal, for example, is moved from the mine to the utility plant primarily by railroad and barge; oil is transported from the well to the refinery to the customer primarily by pipeline; uranium is transported from the mine to the mill to the enrichment facility to the power plant primarily by truck; and so on.

Data needed are, therefore: a) the fuels used by various modes of transportation (assuming that the modes and distances involved are known), and b) the fuel-related emissions (fuel-related) put out by the transportation steps involved in the stages along the path of delivering primary fuels for consumption.

The fuels used in transportation are included in the **precombustion (process) energy** requirements. The fuel-related transportation emissions are included in the **precombustion fuel-related emissions** determined in this appendix.

The electricity and fuel used to produce the primary fuels require electricity and fuels for their production. Similarly, the fuels used to produce the fuels used to produce the primary fuels also require electricity and fuels for their production. Theoretically, an infinite set of iterations is necessary to account for the electricity and fuels required to deliver the primary fuels for use by a customer.

To account accurately for the fuels used in production and processing of primary fuels, the fuel mix for electricity production in the U.S. must be known, that is, how much coal, natural gas, fuel oil, and uranium are needed to produce one kilowatt-hour of electricity. This is called the composite kilowatt-hour. Knowing the composite kilowatt-hour, the fuels used to generate electricity used in the production of primary fuels can be determined. Then, the total amount of fuels needed to produce the primary fuels can be calculated by an iterative process.

Emissions to the environment occur whenever fuel is combusted. These **fuel-related precombustion emissions** occur during the production of primary fuels and are determined only after the total fuel requirements for the production of primary fuels have been determined.

Primary Fuel Combustion

The energy and emissions released when fuels are burned are only one part of the energy and emissions associated with the use of a fuel. This part is known as the **combustion components** (i.e., the **combustion energy** and the **combustion emissions**). There are many steps in the production and processing of a fuel before it is usable, and the energy and emissions resulting from these production steps are known as the **precombustion components** (i.e., **precombustion energy** and **precombustion (fuel-related** and **process) emissions)**.

When accounting for the energy and emissions released when fuels are burned, the precombustion components must be added to the combustion components, in order to account for the full environmental burdens associated with the use of the fuels.

Combustion emissions for a given primary fuel will vary according to how it is combusted; for example, coal burned in utility boilers will have a different emissions factor from coal burned in industrial boilers. Major types of combustion sources for the primary fuels, both stationary and mobile, are included in this appendix.

To summarize, the topics included in this appendix are:

- Primary fuel production (precombustion process energy requirements and precombustion process emissions data)
    - Coal
    - Natural gas
    - Petroleum fuels
    - Nuclear fuel

- Energy for transportation
- Energy sources for electricity generation
  - EGRID sorting procedures
  - Calculation of the U.S. composite kilowatt-hour
  - Electricity/heat cogeneration
- Precombustion energy and emissions for primary fuels
- Primary fuel combustion
  - Energy content of fuels
  - Total environmental emissions for process, utility, and transportation fuels
    - Coal
      - Utility boilers
      - Industrial boilers
    - Residual fuel oil
      - Utility boilers
      - Industrial boilers
    - Distillate fuel oil
      - Utility boilers
      - Industrial boilers
    - Natural gas
      - Utility boilers
      - Industrial boilers
      - Industrial equipment
    - Diesel - Industrial equipment
    - Gasoline - Industrial equipment
    - Liquefied petroleum gases (LPG) - Industrial equipment
    - Fuel grade uranium
    - Wood wastes
    - Mobile sources
      - Truck
      - Locomotive
      - Barges
      - Ocean freighters
      - Cargo plane

Most of the data included in this appendix were developed by Franklin Associates in 2003 and are based 2000 values. There are exceptions to this time range: Combustion energy values depend on the fuel type and range from 1995 to 2000 data. Crude oil production data are 1997 values, while refinery data are 1995 values.

Data Quality Indicators

Life Cycle Inventories (LCIs) are an attempt to determine all of the inputs (in terms of energy and natural resource use) and all of the outputs (in terms of products, co-products, and environmental emissions to the air, water, and soil) over the entire life of a product or service. Thousands of data points are needed in a typical LCI, including values for the extraction of raw materials, the manufacturing of intermediate materials, the fabrication of the product, the use/reuse/maintenance of the product, and the ultimate disposal or recycling of the product.

In the best of possible worlds, we could use classical statistics to determine the uncertainties in Life Cycle Inventories. Classical statistics, however, requires that the data conform to several restrictive assumptions such as independence, randomness, and representativeness.

In LCIs, as in many areas of complex assessments, data often do not meet the stringent requirements of classical statistics. There may be no option to control the representativeness of samples, the number of data points, or the randomness of the data collected. In that case, expert judgment becomes important. Recent research has shown that expert judgment can be translated into quantifiable statements about data quality and uncertainty with high reproducibility. While this introduces some subjectivity into the uncertainty analysis, it is presently the best available methodology. It brings to LCI assessments valuable information that has historically been missing. It has the potential of greatly increasing the credibility of comparative LCI results, and making the database in a research project as sound as possible.

Franklin Associates has developed methodologies to deal with the issues of uncertainty and data quality in Life Cycle Analysis. In traditional LCIs, single point estimates of input variables (such as fuel requirements) are used to determine single point estimates for the output variables (such as total energy used or solid waste generated). These point estimates contain no information about the uncertainty of the data; therefore they give a false sense of precision.

The Franklin Associates methodology involves the assignment of data quality indicators (DQIs) to the variables used as inputs to our computer models. This allows the determination of a distribution of input values, rather than a single point estimate. This distribution more accurately reflects the level of confidence in the values. The deterministic model is thus changed to a stochastic model. This also means that the output of the model is a distribution of values, rather than a single point estimate. It is then easier to judge, for example, whether two values for total solid waste are the same or different.

A DQI of A is given to data that is of the highest quality possible. It may represent recent industrial data collected by experts and based on verified measurements on a comprehensive sample of the specific process or product under study.

A DQI of B would be assigned to data of very good quality. A DQI of B is based on verified data partly based on assumptions or non-verified data based on measurements. It would be data based on a representative, but smaller, sample of specific processes or products under study.

A DQI of C is assigned to data that is of average quality. It may be based on non-verified data based partly on assumptions and may be from a representative sample of similar processes of products under study.

A DQI of D is given to data of fair quality. This may be a qualified estimate by an industry representative and representative of a small number of processes or products related to those under study.

A DQI of E is assigned to data of poor quality. This would be a non-qualified estimate from a sample that is incomplete or whose representativeness is unknown. It would be based on old data and only on related processes or products.

PRIMARY FUEL PRODUCTION

Precombustion Energy and Process Emissions

The fuel production section of this appendix describes the precombustion process and transportation energy requirements and the precombustion process emissions for the production and processing (extraction, beneficiation, refining, and transportation) of the various primary fuels. These fuels are used to generate electricity, to provide direct process energy, or to provide energy for transportation. These precombustion process energy requirements include the use of electricity and primary fuels to provide heat and/or power for industrial processes.

Precombustion process emissions include all environmental emissions that are released as a direct result of activities associated with producing the primary fuels. The process emissions listed in this fuel production section do not, however, include emissions from the combustion of fuels used to produce process energy. These fuel-related process emissions are calculated and presented in a different section of this appendix. The energy values presented in Tables A-1 through A-5 are the basis for these fuel-related precombustion emissions calculations.

Coal

Coal is used as a fuel for electric power generation and industrial heating and steam generation. Energy is required and environmental consequences are incurred in acquiring coal for fuel. The production and distribution of coal is discussed below. Aspects of coal production and distribution specific to each type coal are noted when necessary.

Anthracite Coal Production

Anthracite is hard and very brittle, dense, shiny black, and homogeneous with no marks or layers (Reference A-1). Unlike the lower rank coals, it has a high percentage of fixed carbon and a low percentage of volatile matter (Reference A-1). All anthracite is mined from coal deposits in the eastern United States. The leading coal deposits in the eastern United States are in the Appalachian Region, an area encompassing more than 72,000 square miles and parts of nine states (Reference A-16). The region contains the nation's principal deposits of anthracite (in northeastern Pennsylvania) as well as large deposits of bituminous coal (Reference A-16). A small region of anthracite is present in Arkansas (Reference A-16).

Table A-1a

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF ANTHRACITE COAL

Energy Usage			**DQI**
Process Energy			
Electricity	9.61	kwh	B
Natural Gas	3.72	cubic feet	B
Residual Oil	0.16	gal	C
Distillate Oil	0.44	gal	C
Gasoline	0.032	gal	C
Anthracite Coal	0.38	lb	B
Transportation Energy			
Combination Truck	80.4	ton-miles	C
Diesel	0.84	gal	C
Process Atmospheric Emissions			
Particulates (unspecified)	2.10	lb	D
VOC	0.032	lb	D
Methane	1.59	lb	B
Process Waterborne Emissions			
Suspended Solids	0.26	lb	E
Manganese	0.015	lb	E
Iron	0.022	lb	E
Process Solid Wastes	271	lbs	C

References: A-3, A-5, A-11 through A-20, A-105 through A-109.

Source: Franklin Associates, A Division of ERG

Table A-1b

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF BITUMINOUS AND SUBBITUMINOUS COAL

Energy Usage			**DQI**
Process Energy			
Electricity	17.6	kwh	B
Natural Gas	2.59	cubic feet	B
Residual Oil	0.10	gal	C
Distillate Oil	1.05	gal	C
Gasoline	0.10	gal	C
Bituminous Coal	0.43	lb	B
Transportation Energy			
Combination Truck	2.14	ton-miles	C
Diesel	0.022	gal	C
Rail	324	ton-miles	C
Diesel	0.80	gal	C
Barge	39.3	ton-miles	D
Diesel	0.031	gal	D
Residual Oil	0.10	gal	D
Pipeline-coal slurry	1.56	ton-miles	C
Electricity	0.37	kwh	C
Process Atmospheric Emissions			
Particulates (unspecified)	1.63	lb	D
VOC	0.026	lb	D
Methane	3.99	lb	B
Process Waterborne Emissions			
Suspended Solids	0.10	lb	E
Manganese	0.0058	lb	E
Iron	0.0086	lb	E
Process Solid Wastes	235	lbs	C

References: A-3, A-5, A-9 through A-20, A-106, A-107, A-110, and A-111.

Source: Franklin Associates, A Division of ERG

Table A-1c

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF LIGNITE COAL

Energy Usage			**DQI**
Process Energy			
Electricity	24.2	kwh	B
Natural Gas	4.03	cubic feet	B
Residual Oil	1.79	gal	C
Distillate Oil	0.17	gal	C
Gasoline	0.17	gal	C
Lignite Coal	0.36	lb	B
Transportation Energy			
Combination Truck	3.42	ton-miles	C
Diesel	0.036	gal	C
Rail	0.32	ton-miles	C
Diesel	7.9E-04	gal	C
Process Atmospheric Emissions			
Particulates (unspecified)	0.098	lb	D
Methane	1.13	lb	B
Process Waterborne Emissions			
Suspended Solids	0.0020	lb	E
Manganese	1.8E-04	lb	E
Iron	2.6E-05	lb	E

References: A-3, A-5, A-10 through A-19, A-21 through A-23, A-106, A-107, A-111 through A-113.

Source: Franklin Associates, A Division of ERG

Table A-2

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 CUBIC FEET OF NATURAL GAS

Energy Usage			**DQI**
Process Energy			
Electricity	1.28	kwh	B
Natural Gas	50.3	cubic feet	B
Residual Oil	0.0048	gallons	B
Distillate Oil	0.0076	gallons	B
Gasoline	0.0041	gallons	B
Transportation Energy			
Natural Gas Pipeline	23.0	ton-miles	C
Natural Gas	15.9	cu ft	C
Combination Truck	0.23	ton-miles	D
Diesel	0.0024	gallons	D
Rail	0.23	ton-miles	D
Diesel	5.7E-04	gallons	D
Process Atmospheric Emissions			
Methane	0.65	lb	D
Sulfur Dioxide	1.12	lb	A
VOC	0.035	lb	B
Benzene	0.0044	lb	B
Ethylbenzene	5.3E-04	lb	B
Toluene	0.0068	lb	B
Xylenes	0.0040	lb	B
Process Waterborne Emissions			
1-Methylfluorene	2.3E-08	lb	B
2,4-Dimethylphenol	5.7E-06	lb	B
2-Methylnapthalene	3.2E-06	lb	B
2-Hexanone	1.3E-06	lb	B
4-Methyl-2-Pentanone	8.5E-07	lb	B
Acetone	2.0E-06	lb	B
Acid (unspecified)	2.5E-04	lb	B
Alkylated benzenes	2.0E-06	lb	B
Alkylated fluorenes	1.2E-07	lb	B
Alkylated naphthalenes	3.3E-08	lb	B
Alkylated phenanthrenes	1.4E-08	lb	B
Aluminum	0.0037	lb	B
Nitrogen (as ammonia)	0.0030	lb	B
Arsenic	4.5E-05	lb	B
Barium	0.058	lb	B
Benzene	3.4E-04	lb	B
Benzoic acid	2.1E-04	lb	B
Beryllium	2.0E-06	lb	B
BOD	0.035	lb	C
Boron	6.4E-04	lb	B
Bromide	0.044	lb	A
Cadmium	6.5E-06	lb	B
Calcium	0.65	lb	B
Chlorides	7.34	lb	B
Chromium (unspecified)	1.0E-04	lb	B
Cobalt	4.5E-06	lb	B
COD	0.058	lb	C

Table A-2 (Cont'd)

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 CUBIC FEET OF NATURAL GAS

Energy Usage		**DQI**
Copper	2.9E-05 lb	B
Cresols	1.2E-05 lb	B
Cyanide	1.5E-08 lb	B
Cymene	2.0E-08 lb	B
Dibenzofuran	3.9E-08 lb	B
Dibenzothiophene	3.1E-08 lb	B
Ethylbenzene	1.9E-05 lb	B
Fluorine	7.1E-08 lb	B
Hardness	2.01 lb	A
Hexanoic acid	4.3E-05 lb	B
Hydrocarbons	4.1E-05 lb	B
Iron	0.012 lb	B
Lead	6.5E-05 lb	B
Lithium	0.22 lb	A
Magnesium	0.13 lb	B
Manganese	2.1E-04 lb	B
Mercury	4.0E-08 lb	B
Methylchloride	8.2E-09 lb	B
Methyl Ethyl Ketone	1.6E-08 lb	B
Molybdenum	4.7E-06 lb	B
Naphthalene	3.7E-06 lb	B
Nickel	3.6E-05 lb	B
Oil and grease	0.0039 lb	B
Organic carbon	0.0010 lb	B
Pentamethylbenzene	1.5E-08 lb	B
Phenanthrene	2.6E-08 lb	B
Phenolic compounds	9.1E-05 lb	B
Radionuclides (unspecified)	7.6E-12 lb	B
Selenium	4.5E-07 lb	B
Silver	4.3E-04 lb	B
Sodium	2.07 lb	A
Strontium	0.011 lb	B
Sulfates	0.015 lb	A
Sulfur	5.4E-04 lb	B
Surfactants	2.0E-04 lb	A
Thallium	4.8E-07 lb	B
Tin	2.2E-05 lb	B
Titanium	3.5E-05 lb	B
Toluene	3.2E-04 lb	B
Total alkalinity	0.016 lb	A
Total biphenyls	1.3E-07 lb	B
Total dibenzothiophenes	4.0E-10 lb	B
Total dissolved solids	9.05 lb	A
Total suspended solids	0.13 lb	B
Vanadium	5.5E-06 lb	B
Xylene	1.7E-04 lb	A
Yttrium	1.4E-06 lb	B
Zinc	1.0E-04 lb	B
Process Solid Waste	1.23 lb	B

References: A-24 through A-30, A-32 through A-36.

Source: Franklin Associates, A Division of ERG

Table A-3

DATA FOR THE EXTRACTION OF 1,000 POUNDS OF CRUDE OIL

Energy Usage			**DQI**
Process Energy			
Electricity	17.7	kwh	B
Natural Gas	525	cubic feet	B
Residual Oil	0.096	gallons	B
Distillate Oil	0.15	gallons	B
Gasoline	0.082	gallons	B
Transportation Energy			
Petroleum Pipeline	196	ton-miles	B
Electricity	4.27	kwh	B
Barge	0.37	ton-miles	C
Diesel	3.0E-04	gallons	C
Residual Oil	0.0010	gallons	C
Ocean Freighter	1,472	ton-miles	C
Diesel	0.29	gallons	C
Residual Oil	2.50	gallons	C
Process Atmospheric Emissions			
Methane	3.53	lb	C
Process Waterborne Emissions			
1-Methylfluorene	4.0E-07	lb	B
2,4-Dimethylphenol	1.0E-04	lb	B
2-Hexanone	2.3E-05	lb	B
2-Methylnaphthalene	5.6E-05	lb	B
4-Methyl-2-Pentanone	1.5E-05	lb	B
Acetone	3.6E-05	lb	B
Alkylated benzenes	1.7E-04	lb	B
Alkylated fluorenes	1.0E-05	lb	B
Alkylated naphthalenes	2.9E-06	lb	B
Alkylated phenanthrenes	1.2E-06	lb	B
Aluminum	0.32	lb	B
Ammonia	0.053	lb	B
Antimony	2.0E-04	lb	B
Arsenic	9.8E-04	lb	B
Barium	4.36	lb	B
Benzene	0.0060	lb	B
Benzoic acid	0.0036	lb	B
Beryllium	5.5E-05	lb	B
BOD	0.62	lb	C
Boron	0.011	lb	B
Bromide	0.76	lb	B
Cadmium	1.5E-04	lb	B
Calcium	11.4	lb	B
Chlorides	128	lb	B
Chromium (unspecified)	0.0085	lb	B
Cobalt	7.9E-05	lb	B
COD	1.02	lb	C
Copper	0.0010	lb	B
Cyanide	2.6E-07	lb	B
Dibenzofuran	6.8E-07	lb	B
Dibenzothiophene	5.5E-07	lb	B
Ethylbenzene	3.4E-04	lb	B
Fluorine	5.0E-06	lb	B

Table A-3 (Cont'd)

DATA FOR THE EXTRACTION OF 1,000 POUNDS OF CRUDE OIL

Energy Usage		**DQI**
Hardness	35.2 lb	B
Hexanoic acid	7.5E-04 lb	B
Iron	0.63 lb	B
Lead	0.0021 lb	B
Lead 210	3.7E-13 lb	B
Lithium	0.0038 lb	B
Magnesium	2.23 lb	B
Manganese	0.0036 lb	B
Mercury	3.5E-06 lb	B
Methychloride	1.4E-07 lb	B
Methyl Ethyl Ketone	2.9E-07 lb	B
Molybdenum	8.2E-05 lb	B
m-Xylene	1.1E-04 lb	B
Naphthalene	6.5E-05 lb	B
n-Decane	1.0E-04 lb	B
n-Docosane	3.8E-06 lb	B
n-Dodecane	2.0E-04 lb	B
n-Eicosane	5.4E-05 lb	B
n-Hexacosane	2.4E-06 lb	B
n-Hexadecane	2.1E-04 lb	B
Nickel	9.8E-04 lb	B
n-Octadecane	5.3E-05 lb	B
n-Tetradecane	8.6E-05 lb	B
o + p-Xylene	7.8E-05 lb	B
o-Cresol	1.0E-04 lb	B
Oil and grease	0.072 lb	B
p-Cresol	1.1E-04 lb	B
p-Cymene	3.6E-07 lb	B
Pentamethylbenzene	2.7E-07 lb	B
Phenanthrene	1.0E-06 lb	B
Phenol	0.0016 lb	B
Radium 226	1.3E-10 lb	B
Radium 228	6.6E-13 lb	B
Selenium	3.9E-05 lb	B
Silver	0.0075 lb	B
Sodium	36.2 lb	B
Strontium	0.19 lb	B
Sulfates	0.26 lb	B
Sulfur	0.0094 lb	B
Surfactants	0.0030 lb	B
Thallium	4.2E-05 lb	B
Tin	8.0E-04 lb	B
Titanium	0.0031 lb	B
Toluene	0.0056 lb	B
Total alkalinity	0.28 lb	B
Total biphenyls	1.1E-05 lb	B
Total dibenzothiophenes	3.5E-08 lb	B
Total dissolved solids	158 lb	B
TSS	9.77 lb	B
Vanadium	9.7E-05 lb	B
Xylene	0.0028 lb	B
Yttrium	2.4E-05 lb	B
Zinc	0.0073 lb	B
Process Solid Waste	26.1 lb	B

References: A-24, A-25, A-34 through A-37, A-42, A-43, A-114 through A-117.

Source: Franklin Associates, A Division of ERG

Table A-4a

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF RESIDUAL FUEL OIL (Does not include crude oil extraction)

Raw Materials			
Crude Oil	8,150	lb	
Energy Usage			**DQI**
Process Energy			
Electricity	512	kwh	B
Natural Gas	1,402	cu ft	B
Residual Oil	25.7	gal	B
LPG	1.09	gal	B
Transportation Energy			
Combination Truck	108	ton-miles	C
Diesel	1.13	gal	C
Rail	68.6	ton-miles	C
Diesel	0.17	gallons	C
Barge	581	ton-miles	C
Diesel	0.46	gal	C
Residual Oil	1.55	gal	C
Process Atmospheric Emissions			
Aldehydes	0.33	lb	B
Ammonia	0.17	lb	B
Carbon monoxide	105	lb	B
Carbon tetrachloride	9.2E-08	lb	B
CFC12	9.1E-07	lb	B
Hydrocarbons (other than methane)	16.0	lb	B
Methane	0.56	lb	B
NOx	2.62	lb	B
Particulates (unspecified PM)	1.90	lb	B
SOx (unspecified)	18.5	lb	B
Trichloroethane	7.7E-07	lb	B
Process Waterborne Emissions			
BOD5	0.27	lb	D
COD	1.84	lb	D
Chromium (hexavalent)	2.9E-04	lb	D
Chromium (unspecified)	0.0045	lb	D
Nitrogen (as ammonia)	0.12	lb	D
Oil and Grease	0.084	lb	D
Phenolic Compounds	0.0018	lb	D
Sulfide	0.0015	lb	D
Total Suspended Solids	0.22	lb	D
Process Solid Waste	44.2	lb	C

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4b

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF DISTILLATE FUEL OIL (Not including crude oil extraction)

			DQI
Raw Materials			
Crude Oil	7,482	lb	B
Energy Usage			
Process Energy			
Electricity	470	kwh	B
Natural Gas	1,288	cu ft	B
Residual Oil	23.6	gal	B
LPG	1.00	gal	B
Transportation Energy			
Combination Truck	98.8	ton-miles	C
Diesel	1.04	gal	C
Rail	63.0	ton-miles	C
Diesel	0.16	gallons	C
Barge	534	ton-miles	C
Diesel	0.43	gal	C
Residual Oil	1.42	gal	C
Petroleum Pipeline	775	ton-miles	C
Electricity	16.9	kwh	C
Process Atmospheric Emissions			
Aldehydes	0.30	lb	B
Ammonia	0.15	lb	B
Carbon monoxide	96.3	lb	B
Carbon tetrachloride	8.4E-08	lb	B
CFC12	8.3E-07	lb	B
Hydrocarbons (other than methane)	14.7	lb	B
Methane	0.52	lb	B
NOx	2.40	lb	B
Particulates (unspecified PM)	1.74	lb	B
SOx (unspecified)	17.0	lb	B
Trichloroethane	7.0E-07	lb	B
Process Waterborne Emissions			
BOD5	0.25	lb	D
COD	1.69	lb	D
Chromium (hexavalent)	2.6E-04	lb	D
Chromium (unspecified)	0.0041	lb	D
Nitrogen (as ammonia)	0.11	lb	D
Oil and Grease	0.077	lb	D
Phenolic Compounds	0.0016	lb	D
Sulfide	0.0013	lb	D
Total Suspended Solids	0.20	lb	D
Process Solid Waste	40.6	lb	C

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4c

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF GASOLINE
(Not including crude oil extraction)

			DQI
Raw Materials			
Crude Oil	6,376	lb	B
Energy Usage			
Process Energy			
Electricity	400	kwh	B
Natural Gas	1,097	cu ft	B
Residual Oil	20.1	gal	B
LPG	0.85	gal	B
Transportation Energy			
Combination Truck	84.2	ton-miles	C
Diesel	0.88	gal	C
Rail	53.7	ton-miles	C
Diesel	0.13	gallons	C
Barge	455	ton-miles	C
Diesel	0.36	gal	C
Residual Oil	1.21	gal	C
Petroleum Pipeline	661	ton-miles	C
Electricity	14.4	kwh	C
Process Atmospheric Emissions			
Aldehydes	0.26	lb	B
Ammonia	0.13	lb	B
Carbon monoxide	82.0	lb	B
Carbon tetrachloride	7.2E-08	lb	B
CFC12	7.1E-07	lb	B
Hydrocarbons (other than methane)	12.5	lb	B
Methane	0.44	lb	B
NOx	2.05	lb	B
Particulates (unspecified PM)	1.49	lb	B
SOx (unspecified)	14.5	lb	B
Trichloroethane	6.0E-07	lb	B
Process Waterborne Emissions			
BOD5	0.21	lb	D
COD	1.44	lb	D
Chromium (hexavalent)	2.3E-04	lb	D
Chromium (unspecified)	0.0035	lb	D
Nitrogen (as ammonia)	0.095	lb	D
Oil and Grease	0.066	lb	D
Phenolic Compounds	0.0014	lb	D
Sulfide	0.0011	lb	D
Total Suspended Solids	0.17	lb	D
Process Solid Waste	34.6	lb	C

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4d

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF LPG
(Not including crude oil extraction)

Raw Materials			**DQI**
Crude Oil	4,677	lb	B
Energy Usage			
Process Energy			
Electricity	294	kwh	B
Natural Gas	805	cu ft	B
Residual Oil	14.8	gal	B
LPG	0.62	gal	B
Transportation Energy			
Combination Truck	61.8	ton-miles	C
Diesel	0.65	gal	C
Rail	39.4	ton-miles	C
Diesel	0.098	gallons	C
Barge	334	ton-miles	C
Diesel	0.27	gal	C
Residual Oil	0.89	gal	C
Petroleum Pipeline	485	ton-miles	C
Electricity	10.6	kwh	C
Process Atmospheric Emissions			
Aldehydes	0.19	lb	B
Ammonia	0.095	lb	B
Carbon monoxide	60.2	lb	B
Carbon tetrachloride	5.3E-08	lb	B
CFC12	5.2E-07	lb	B
Hydrocarbons (other than methane)	9.20	lb	B
Methane	0.32	lb	B
NOx	1.50	lb	B
Particulates (unspecified PM)	1.09	lb	B
SOx (unspecified)	10.6	lb	B
Trichloroethane	4.4E-07	lb	B
Process Waterborne Emissions			
BOD5	0.15	lb	D
COD	1.05	lb	D
Chromium (hexavalent)	1.7E-04	lb	D
Chromium (unspecified)	0.0026	lb	D
Nitrogen (as ammonia)	0.069	lb	D
Oil and Grease	0.048	lb	D
Phenolic Compounds	0.0010	lb	D
Sulfide	8.4E-04	lb	D
Total Suspended Solids	0.13	lb	D
Process Solid Waste	25.4	lb	C

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-4e

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF KEROSENE (Not including crude oil extraction)

Raw Materials			**DQI**
Crude Oil	6,980	lb	B
Energy Usage			
Process Energy			
Electricity	438	kwh	B
Natural Gas	1,201	cu ft	B
Residual Oil	22.0	gal	B
LPG	0.93	gal	B
Transportation Energy			
Combination Truck	92.2	ton-miles	C
Diesel	0.97	gal	C
Rail	58.8	ton-miles	C
Diesel	0.15	gallons	C
Barge	498	ton-miles	C
Diesel	0.40	gal	C
Residual Oil	1.32	gal	C
Petroleum Pipeline	723	ton-miles	C
Electricity	15.8	kwh	C
Process Atmospheric Emissions			
Aldehydes	0.28	lb	B
Ammonia	0.14	lb	B
Carbon monoxide	89.8	lb	B
Carbon tetrachloride	7.9E-08	lb	B
CFC12	7.8E-07	lb	B
Hydrocarbons (other than methane)	13.7	lb	B
Methane	0.48	lb	B
NOx	2.24	lb	B
Particulates (unspecified PM)	1.63	lb	B
SOx (unspecified)	15.9	lb	B
Trichloroethane	6.6E-07	lb	B
Process Waterborne Emissions			
BOD5	0.23	lb	D
COD	1.57	lb	D
Chromium (hexavalent)	2.5E-04	lb	D
Chromium (unspecified)	0.0038	lb	D
Nitrogen (as ammonia)	0.10	lb	D
Oil and Grease	0.072	lb	D
Phenolic Compounds	0.0015	lb	D
Sulfide	0.0013	lb	D
Total Suspended Solids	0.19	lb	D
Process Solid Waste	37.8	lb	C

References: A-36, A-43 through A-49.

Source: Franklin Associates, A Division of ERG

Table A-5

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL GRADE URANIUM
(includes mining and milling, conversion, enrichment, and fuel fabrication)

Energy Usage			**DQI**
Process Energy			
Electricity	1,851,871	kwh	C
Bituminous Coal	22,730	pounds	C
Natural Gas	2,940,070	cu ft	C
Residual Oil	13.3	gal	C
Distillate Oil	2,470	gallons	C
Transportation Energy			
Combination Truck	8,676	ton-miles	D
Diesel	91.1	gal	D
Ocean Freighter	24,518	ton-miles	D
Diesel	4.66	gallons	D
Residual Oil	41.9	gallons	D
Process Atmospheric Emissions			
Aldehydes	2.12	lb	B
Ammonia	44.6	lb	B
Ammonium chloride	154	lb	B
Carbon dioxide (fossil)	17,490	lb	B
Carbon monoxide	466	lb	B
Fluoride	13.0	lb	B
Hydrocarbons	3,336	lb	B
Kerosene	277	lb	B
NOx	13,209	lb	B
Organic acids	2.12	lb	B
Particulates (unspecified)	16,908	lb	B
Radionuclides	15,477	lb	B
SOx (unspecified)	17.7	lb	B
SO2	49,723	lb	B
Process Waterborne Emissions			
Aluminum	1,211	lb	D
Ammonium	124	lb	D
Arsenic	3.44	lb	D
Cadmium	1.89	lb	D
Calcium	76.8	lb	D
Chloride	298	lb	D
Copper	30.3	lb	D
Fluoride	2,002	lb	D
Iron	5,689	lb	C
Lead	4.24	lb	D
Manganese	557	lb	C
Mercury	0.042	lb	D
Nitrates	308	lb	D
Nitrogen (as ammonia)	108	lb	D
Radionuclides	0.22	lb	C
Selenium	43.3	lb	C
Sodium	358	lb	D
Sulfates	200,582	lb	C
TSS	7,656	lb	D
Zinc	60.3	lb	D
Process Solid Waste	4,884,834	lb	C

References: A-54 through A-59.

Source: Franklin Associates, A Division of ERG

Coal may be obtained by surface mining of outcrops and seams near the earth's surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is generally returned to the mine (eventually) and is not considered as a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining.

After coal is mined, it goes through various preparation processes before it is used as fuel. 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, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-2).

Surface mining is used to extract 95 percent of the U.S. supply anthracite coal, while underground mining extracts 5 percent (Reference A-13). Approximately 64 percent of anthracite coal is cleaned (References A-9 and A-10). Small amounts of solid waste are produced from underground mining, while the remainder of solid waste comes from cleaning. New Source Performance Standards (Reference A-11) are used to estimate the water emissions from mining and cleaning bituminous/subbituminous coal. The lower standards for suspended solids recently set for the western (low precipitation) states were also taken into account.

The coal industry depends heavily on the transportation network for delivering coal to domestic customers. The flow of coal is carried by railroads, barges, ships, trucks, conveyors, and a slurry pipeline. Coal deliveries are usually handled by a combination of transportation modes before finally reaching the consumer (Reference A-1).

The primary air emissions from coal mining are particulates and methane. Particulate emissions arise from coal dust and other debris from stock piles, loaded railroad cars, crushers, conveyors, and other coal processing equipment (References A-4, A-6, and A-7). Methane is released from coal mining operations and continues to be released by coal while it is transported and cleaned (Reference A-8). Factors that influence the extent of particulate and methane emissions include the mining method (surface or underground), the size and location of the mine, and the type of coal.

Bituminous Coal Production

Bituminous coal is the most abundant rank of coal; it is soft and contains high levels of volatile compounds. Subbituminous coal is softer than bituminous coal. Bituminous and subbituminous are the main types of coal used for electric power generation in the U.S. These types of coal come from 21 states across the U.S. The three top producing states are Wyoming, West Virginia, and Kentucky. Since the properties and uses of subbituminous coal are similar to those for bituminous coal, this appendix aggregates bituminous and subbituminous coals into one category.

Surface mining is used to extract 58 percent of the U.S. supply of coal, while underground mining extracts 42 percent (Reference A-13). Approximately 58 percent of coal is cleaned (References A-9 and A-10). Small amounts of solid waste are produced from underground mining, while the remainder of solid waste comes from cleaning. New Source Performance Standards (Reference A-11) are used to estimate the water emissions from mining and cleaning bituminous/subbituminous coal. The lower standards for suspended solids recently set for the western (low precipitation) states were also taken into account.

Coal can be obtained by surface mining of outcrops and seams that are near the earth's surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is usually returned to the mine and is thus not considered a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining.

After coal is mined, it goes through various preparation processes before it is used as fuel. 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, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-2).

The coal industry depends heavily on the transportation network for delivering coal to domestic customers. The flow of coal is carried by railroads, barges, ships, trucks, conveyors, and a slurry pipeline. Coal deliveries are usually handled by a combination of transportation modes before finally reaching the consumer (Reference A-1).

The primary air emissions from coal mining are particulates and methane. Particulate emissions arise from coal dust and other debris from stock piles, loaded railroad cars, crushers, conveyors, and other coal processing equipment (References A-4, A-6, and A-7). Methane is released from coal mining operations and continues to be released by coal while it is transported and cleaned (Reference A-8). Factors that influence the extent of particulate and methane emissions include the mining method (surface or underground), the size and location of the mine, and the type of coal.

Lignite Coal Production

Lignite coal is comprised of remnants of woody fibers, giving it a brown color and laminar structure. Lignite coal is not hard, but lignite deposits are tough and require heavy force to break up. There are large deposits of lignite in the southern region of the Gulf Coastal Plain that have been used for electricity generation in Texas since the 1970s and in Louisiana since the 1980s (Reference A-16). The most important lignite beds are in a succession of strata known as the Wilcox Group and are generally 3 to 10 feet thick (Reference A-16). The western part of the United States also has lignite deposits. The largest lignite deposit in the U.S. is in the northern Great Plains, underlying parts of North Dakota, South Dakota, and Montana (Reference A-16). Based on data from the 2001 Coal Industry Annual (Reference A-13) 61 percent of lignite coal is mined in Texas, 34 percent is mined in North Dakota, 4 percent is mined in Louisiana, and less than one percent is mined in Montana.

Coal may be obtained by surface mining of outcrops and seams that are near the earth’s surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is usually returned to the mine and is thus not considered a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining. Unlike other ranks of coal, which are extracted by both surface and underground mining, all lignite is extracted by surface mining.

After coal is mined, it goes through various preparation processes before it is used as fuel. 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, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-2). Due to the relatively low value of lignite coal, mining companies do not clean it, but merely crush and screen it before being sent to a power plant (References A-13, A-21, A-22, and A-23).

The coal industry depends heavily on the transportation network for delivering coal to domestic customers. The flow of coal is carried by railroads, barges, ships, trucks, conveyors, and a slurry pipeline. Coal deliveries are usually handled by a combination of transportation modes before finally reaching the consumer (Reference A-1). The low value of lignite coal, however, does not justify long transportation distances from mine to consumption. Thus, the transportation demands for lignite are less than for other ranks of coal.

The primary air emissions from coal mining are particulates and methane. Particulate emissions arise from coal dust and other debris from stock piles, loaded railroad cars, crushers, conveyors, and other coal processing equipment (References A-4, A-6, and A-7). Methane is released from coal mining operations and continues to be released by coal while it is transported and cleaned (Reference A-8). Factors that influence the extent of particulate and methane emissions include the mining method (surface or underground), the size and location of the mine, and the type of coal.

New Source Performance Standards (Reference A-11) are used in this appendix to estimate the water emissions from mining and cleaning bituminous/subbituminous coal. The lower standards for suspended solids recently set for the western (low precipitation) states were also taken into account.

Natural Gas

Natural gas is a widely used energy resource, since it is a relatively clean and versatile fuel. The major component of natural gas is methane (CH_4). Other components of natural gas include ethane, propane, butane, and heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen, and hydrogen sulfides. Table A-2 contains the combined energy requirements and environmental emissions for producing, processing, and transporting natural gas used as a fuel.

Natural Gas Production. Natural gas is extracted from deep underground wells and is usually co-produced with crude oil. Because of its gaseous nature, natural gas flows freely from wells that produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. An estimated 80 percent of natural gas is extracted onshore and 20 percent is extracted offshore (Reference A-25).

Atmospheric emissions from natural gas production result primarily from unflared venting. Waterborne wastes result from brines that occur when natural gas is produced in combination with oil. In cases where data represent both crude oil and natural gas extraction, this appendix allocates environmental emissions based on the percent weight of natural gas produced. This appendix also apportions environmental emissions according to the percent share of onshore and offshore extraction.

Energy data for natural gas production were calculated from fuel consumption data for the crude oil and natural gas extraction industry (Reference A-34).

Natural Gas Processing. Once raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG). Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the natural gas has a high hydrogen sulfide content, it is considered “sour.” Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as “sweetening.”

Atmospheric emissions result from the flaring of hydrogen sulfide (H2S), the regeneration of glycol solutions, and fugitive emissions of methane. Hydrogen sulfide is a natural component of natural gas and is converted to sulfur dioxide (SO_2) when flared; sulfur dioxide emissions were calculated from EPA emission factors (Reference A-26) and the known hydrogen sulfide content of domestic natural gas (Reference A-27). Glycol solutions are used to dehydrate natural gas, and the regeneration of these solutions result in the release of BTEX (benzene, toluene, ethylbenzene, and xylene) as well as a variety of less toxic organics (Reference A-28). Methane emissions result from fugitive releases as well as venting (Reference A-29). Negligible particulate emissions are produced from natural gas plants, and the relatively low processing temperatures (<1,200 degrees Fahrenheit) prevent the formation of nitrogen oxides (NOx).

Energy data for natural gas processing were calculated from fuel consumption data for the natural gas liquids extraction industry (Reference A-34).

Natural gas is transported primarily by pipeline, but a small percentage is compressed and transported by insulated railcars and tankers (References A-30 and A-33). Transportation data were calculated from the net annual quantities of natural gas imported and exported by each state (Reference A-31).

Petroleum Fuels

Crude Oil Extraction. 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 a steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although pumps are usually required to bring oil to the surface. Once oil is on the surface, it is separated from water and stored in tanks before being transported to a refinery. In some cases it is immediately transferred to a pipeline that 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 in order to remove the oil from the water. These separators are very efficient and leave minimal oil in the water.

According to the American Petroleum Institute, 17.9 billion barrels of brine were produced from crude oil extraction in 1995 (Reference A-37). This equates to a ratio of 5.4 barrels of water per barrel of oil. The majority of this brine (85 percent) is produced by onshore oil production facilities and, since such facilities are prohibited from discharging to surface water (Reference A-38), is injected into wells specifically designed for production-related waters. The remaining 15 percent of brine discharges are from offshore oil production facilities and are assumed to be released to the ocean. Therefore, all waterborne wastes from crude oil production are attributable to the brine released from offshore production (Reference A-39). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (Reference A-37).

Evolving technologies are reducing the amount of brine that is extracted during crude oil extraction and minimizing the environmental impact of discharged brine. For example, downhole separation is a technology that separates brine from oil before bringing it to the surface; the brine is injected into subsurface injection zones. The freeze-thaw evaporation (FTE) process is another technology that reduces the discharge of brine by using a freeze crystallization process in the winter and a natural evaporation process in the summer to extract fresh water from brine; the fresh water can be used for horticulture or agricultural applications (Reference A-40).

The second source of waste is gas produced from oil wells. The majority of this gas is recovered for sale, but some is released to the atmosphere. 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 amount of methane released from crude oil production was calculated from EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks, which has data specific to oil field emissions (Reference A-43).

The requirements for transporting crude oil from the extraction site to the Gulf Coast of the United States (where most petroleum refining in the United States occurs) were calculated from foreign and domestic supply data, port-to-port distance data, and domestic petroleum movement data (References A-41 and A-42). Based on 2001 foreign and domestic supply data, 62 percent of the United States crude oil supply is from foreign sources, 6 percent is from Alaska, and the remaining 32 percent is from the lower 48 states. These percentages were used to apportion transportation requirements among different transportation modes. With the exception of Canada, which transports crude oil to the United States by pipeline, foreign suppliers transport crude oil to the United States by ocean tanker. (In 2001, Saudi Arabia, Mexico, Canada, Venezuela, and Nigeria were the top five foreign suppliers of crude oil to the United States.) The transportation of crude oil from Alaska to the lower 48 states is accomplished by ocean tanker; other domestic transportation of crude oil is accomplished by pipeline and barge.

Petroleum Refining. Gasoline and diesel are the primary outputs from refineries; however, other major products include kerosene, aviation fuel, residual oil, lubricating oil, and feedstocks for the petrochemical industry. Data specific to the production of each type of refinery product are not available. Such data would be difficult to characterize because there are many types of conversion processes in oil refineries that are altered depending on market demand, quality of crude input, and other variables. Thus, the following discussion is applicable to all refinery products.

A petroleum refinery processes crude oil into thousands of products using physical and/or chemical processing technology. A petroleum refinery receives crude oil, which is comprised of mixtures of many hydrocarbon compounds and uses distillation processes to separate out pure product streams. Because the crude oil is contaminated (to varying degrees) with compounds of sulfur, nitrogen, oxygen, and metals, cleaning operations are common in all refineries. Also, the natural hydrocarbon components that comprise crude oil are often chemically changed to yield products for which there is higher demand. These processes, such as polymerization, alkylation, reforming, and visbreaking, are used to convert light or heavy crude oil fractions into intermediate weight products, which are more easily handled and used as fuels and/or feedstocks (Reference A-51).

Air pollution is caused by various petroleum refining processes, including vacuum distillation, catalytic cracking, thermal cracking, and sulfur recovery. Fugitive emissions are also significant contributors to air emissions. Fugitive emissions include leaks from valves, seals, flanges, and drains, as well as leaks escaping from storage tanks or during transfer operations. The wastewater treatment plant for a refinery is also a source of fugitive emissions (Reference A-50).

The petroleum refining data represents 1,000 pounds of general refinery product as well as data allocated to specific refinery products. The data are allocated to specific refinery products based on the percent by mass of each product in the refinery output. The mass allocation method assigns energy requirements and environmental emissions equally to all refinery products -- equal masses of different refinery products are assigned equal energy and emissions.

Mass allocation is not the only method that can be used for assigning energy and emissions to refinery products. Heat of combustion and economic value are two additional methods for co-product allocation. Using heat of combustion of refinery products yields allocation factors similar to those derived by mass allocation, demonstrating the correlation between mass and heat of combustion. Economic allocation is complicated because market values fluctuate with supply and demand, and market data are not available for refinery products such as asphalt. This appendix does not apply the heat of combustion or economic allocation methods because they have no apparent advantage over mass allocation. However, if the data user prefers to use an alternative allocation method, it can be applied to the data provided in this appendix.

Nuclear Fuel

As with other fuels used for the generation of electricity, uranium ore must undergo a series of processing and refining steps before being used in utility plants. These steps include mining, milling, conversion, enrichment, and fuel fabrication. The following sections describe the operations required to process fuel grade uranium for use by the U.S. nuclear power industry.

Mining. Uranium ore can be extracted from the earth by open-pit or underground mining; these methods are referred to as “conventional” mining. Significant amounts of concentrated uranium-containing material can also be produced from solution mining (in-situ leaching), and as a byproduct of phosphate, copper, and beryllium production. Conventional mining ceased in the United States in 1992 when in situ leach (ISL) mining became predominant in Wyoming and Texas (Reference A-60). However, conventional uranium mining is prevalent in Canada, where high-grade uranium deposits can be mined at relatively low costs (Reference A-61).

In 1984, the United States relinquished its role as the principal world producer of uranium to Canada, and Canada has led ever since (Reference A-60). The free trade agreement between the United States and Canada in 1998 has also had an adverse impact on the U.S. uranium industry because U.S. producers cannot compete with Canada's low cost uranium resources (Reference A-60).

Milling. Uranium ore is processed in mills where uranium oxide (U_3O_8, also known as yellowcake) is extracted from the ore by a series of crushing, grinding, and concentration operations. Uranium mills are located near uranium mines due to the large quantities of ore that must be milled to produce concentrated uranium oxide. The most significant waste stream from milling operations is called "tailings." Tailings are liquid sludge from concentration operations. The solids portion of the tailings is separated from the liquid and usually returned to the earth.

Since 1993, all conventional uranium mills in the United States are either inactive, are being decommissioned, or are permanently closed. Only non-conventional uranium plants (in-situ leaching or phosphate byproduct) are currently producing uranium concentrate in the United States.

Conversion. Subsequent to milling, uranium oxide is combined with fluorine gas to form uranium hexafluoride gas (UF_6). In this form, the uranium is ready for enrichment to fuel grade uranium.

Enrichment. Gaseous diffusion and gas centrifuge are the two most common methods used to commercially produce enriched uranium. These enrichment processes increase the fissionable portion of the fuel (U_{235}) from its natural abundance of 0.7 percent to a fuel-grade abundance of approximately 3 percent. Gaseous diffusion is currently used in the United States, while in Europe the gas centrifuge is the prevalent enrichment process. The majority of energy consumption and environmental emissions released in the front-end of the nuclear fuel cycle are due to the enrichment step. (The front-end of the nuclear fuel cycle includes all steps, from mining to fuel fabrication, preceding the consumption of the nuclear fuel.)

In the gaseous diffusion process, gaseous UF_6 is passed through a series of porous membrane filters. In the filtering process, UF_6 molecules containing the U_{235} isotope diffuse through the filters more readily than the molecules containing the larger U_{235} isotope. A typical gaseous diffusion enrichment process requires more than 1,200 stages to produce uranium enriched to 3 percent. Enrichment is necessary for uranium used as fuel in light-water nuclear reactors, because the amount of fissile U_{235} in natural uranium is too low to sustain a nuclear chain reaction.

Fuel Fabrication. Enriched UF_6 is next taken to a fuel fabrication plant, where it is converted to uranium dioxide (UO_2) powder. The powder is compressed into small, cylindrical pellets, which are loaded and sealed into hollow rods made of a zirconium-stainless steel alloy, and then shipped to nuclear power plants. This appendix assumes that the production of the zirconium-stainless steel alloy is insignificant when compared to the uranium fuel itself.

Unlike utilities that require a daily or hourly supply of fuel (such as coal-fired utilities), the fuel for nuclear reactors does not need to be continuously recharged. A fuel load in a nuclear reactor can last up to three years (Reference A-60). This makes the environmental releases and energy requirements of transportation a negligible contributor to the overall environmental profile of the nuclear fuel cycle. It also explains why the sites of uranium mining, milling, conversion, enrichment, and fuel fabrication do not need to be close to the site of consumption.

Energy for Transportation

Transportation, an important step, occurs often in the production of primary fuels. The energy requirements associated with the transportation of products are shown in Table A-6. Transportation modes included are: truck, rail, barge, ocean transport, wide body aircraft, and pipeline. Energy requirements are reported as the quantity of fuel required per 1,000 ton-miles. Statistical data were used for rail, barge, and pipeline transportation energy (References A-88 and A-89).

Energy Sources for Electricity Generation

Utility power plants generate electricity from five basic energy sources: coal, fuel oil, natural gas, uranium, and hydropower. A small percentage of electricity is also generated by unconventional sources such as biomass, solar energy, wind energy, and geothermal energy. Wood and wood byproducts are also used to generate electricity, primarily within the forest products industry.

The electricity production and distribution systems in the United States are interlinked and are difficult, if not impossible, to separate from one another. Data are available for the types of fuels used for electricity in each NERC (North American Electricity Reliability Council) region in the United States. However, this appendix profiles electricity for the average U.S. electricity grid as shown in Table A-7.

The main data source for the U.S. electricity grid was EGRID (Emissions & Generation Resource Integrated Database). EGRID is a compilation of 24 different data sources from the EPA, Energy Information Administration (EIA), and the Federal Energy Regulatory Commission (FERC). EGRID includes data for individual power plants, generating companies, states, and regions of the electricity grid.

EGRID Sorting Procedures

EGRID is a large database that organizes data for electricity generation according to many criteria, including plant-level generation, generator-level generation, state-level generation, NERC region, year, and fuel types. The following discussion describes the methods that were used to sort the EGRID data and adapt it to the energy and emissions data in this appendix.

Table A-6

2000 TRANSPORTATION FUEL REQUIREMENTS

		Fuel Consumed per 1,000 Ton-Miles	**Energy Consumed (1) (Btu/ton-mile)**	**DQI**
Combination truck (tractor trailer)				
Diesel	gal	10.5	1,667	B
Gasoline	gal	10.5	1,493	B
Single unit truck				
Diesel	gal	22.5	3,573	B
Gasoline	gal	22.5	3,200	B
Rail				
Diesel	gal	2.5	394	B
Barge (2)				
Diesel	gal	0.8	127	C
Residual	gal	2.7	456	C
Total			583	C
Ocean freighter (2)				
Diesel	gal	0.2	30	C
Residual	gal	1.7	293	C
Total			324	C
Pipeline - natural gas				
Natural gas	cuft	690	773	C
Pipeline - petroleum products				
Electricity	kwh	21.8	231	C
Pipeline - coal slurry				
Electricity	kwh	240	2,553	C
Air Carrier				
Jet fuel	gal	8.1	1,249	C

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(1) Includes precombustion energy for fuel acquisition.

(2) An average ratio of diesel and residual fuels is used to represent barge and ocean freighter transportation energy.

References: A-88 through A-90, and A-100 through A-104.

Source: Franklin Associates, A Division of ERG

Coal Generation by Type (U.S. Total). Several types of coal (including anthracite, bituminous, and lignite) are used to generate electricity. This appendix contains data for the production of anthracite, bituminous, and lignite coals. In order to model the percentage of electricity generation from each type of coal, the following procedure was used:

The EGRID PLNT worksheet was sorted by the fields PLFFLCTG (fossil fuel category) and PLPRIMFL (plant primary fuel). The primary fuel categories classified as coal generation are BFG (blast furnace gas), BIT (bituminous), COL (unspecified coal), LIG (lignite), SUB (subbituminous), and WOC (waste other coal). Of the total coal generation reported in PLNT, almost 84 percent of generation was reported as COL.

The EGRID GEN worksheet reports coal generation in greater detail than the PLNT worksheet. GEN was sorted by the field FUELG1 (primary generator fuel). Total generation by specific coal type reported in GEN was compared to the total generation from coal reported in PLNT. GEN accounted for 97 percent of the total generation from coal reported in PLNT.

When generation by each coal type in GEN was summed, the percentages by each coal type were as follows: 68.7 percent bituminous, 25.7 percent subbituminous, 5.0 percent lignite, 0.48 percent waste other coal, and 0.16 percent blast furnace gas. Subbituminous was grouped with bituminous, for an overall coal generation profile of 94.4 percent bituminous/subbituminous, 5 percent lignite, and 0.6 percent other coal.

Coal Generation by Type (NERC Region). To determine the percentage of coal generation by type (anthracite, bituminous/subbituminous, lignite) for individual NERC regions, the following procedure was used:

The EGRID GEN worksheet was sorted by state and primary fuel type to develop a generation profile for each state, including details on coal type. The EGRID PLNT worksheet was then sorted by state and primary fuel type. The GEN profile on coal generation by type (percent of generation from each type of coal) for each state was applied to the unspecified coal generation COL in the PLNT generation profiles for each state. The detailed coal generation profiles for the generation in each state belonging to each NERC region were then totaled to arrive at the coal generation profile for each NERC region.

Oil Generation by Type (U.S. Total). As with coal, several types of oil are used to generate electricity. In order to determine the percentage of electricity generation from each type of oil, the following process was used:

The EGRID PLNT worksheet was sorted by the fields PLFFLCTG (fossil fuel category) and PLPRIMFL (plant primary fuel). The primary fuel categories classified as oil generation are DFO (distillate or diesel fuel oil), JF (jet fuel), KER (kerosene), OIL (unspecified oil), PC (petroleum coke), and RFO (residual fuel oil). Of the total oil generation reported in PLNT, 72 percent of generation was reported as OIL (residual accounted for 21 percent).

The EGRID GEN worksheet reports oil generation in more detail than the PLNT worksheet. GEN was sorted by the field FUELG1 (primary generator fuel). Total generation by specific oil type reported in GEN was compared to the total generation from oil reported in PLNT. GEN accounted for 76 percent of the total generation from oil reported in PLNT.

When generation by each oil type in GEN was summed, the percentages by each oil type were as follows: 90 percent residual fuel oil, 7 percent petroleum coke, and 3 percent distillate oil. Based on the high percentage of residual reported in both the GEN and PLNT worksheets, the decision was made to model all oil generation as residual fuel oil.

Calculation of the U.S. Composite Kilowatt-hour

A composite kilowatt-hour is defined as a kilowatt-hour of electrical energy produced using the average fuel mix for electricity production for an electricity grid. It is based on the amount of electricity that can be produced from a given quantity of fuel and the percentage of each type of fuel consumed by an electricity grid. The quantities of fuel required to generate one kilowatt-hour are shown in Table A-8. The methods for calculating the amount of electricity that can be produced from each type of fuel in the U.S. electricity grid are discussed below.

The amount of electricity produced per unit of a given fossil fuel (coal, distillate oil, residual oil, and natural gas) can be calculated from the fuel inputs and net electricity production for U.S. utilities (Reference A-63). For example, U.S. utilities produced 1.61 billion megawatt-hours of net electricity from 784 million short tons of bituminous coal in 2000. This translates to 0.97 pounds of bituminous coal per kilowatt-hour of net electricity production. Using the same calculation, the net electricity produced per unit of the other types of fossil fuels were 0.79 pounds per kilowatt-hour for anthracite coal, 1.72 pounds per kilowatt-hour for lignite coal, 0.088 gallons per kilowatt-hour for distillate fuel oil, 0.070 gallons per kilowatt-hour for residual fuel oil, and 10.5 cubic feet per kilowatt-hour for natural gas. (Net electricity is the total amount of electricity produced by a utility minus the amount of generated electricity that is consumed by the utility itself.)

For nuclear energy in the U.S., the quantity of uranium fuel (UO_2) consumed per kilowatt-hour of net electricity production was calculated by comparing the quantity of uranium fuel loaded into U.S. nuclear reactors to the kilowatt-hours of electricity produced by U.S. nuclear reactors (References A-92 and A-93). From 1999 through 2001, an annual average of 54.3 million pounds of uranium concentrate (U_3O_8) was used to produce uranium fuel (UO_2) used in U.S. nuclear reactors (Reference A-92). During the same time period, an annual average of 750 billion kilowatt-hours of electricity was generated by U.S. nuclear reactors (Reference A-93). Using a conversion of 10.89 pounds of uranium concentrate per production of one pound of uranium fuel (Reference A-94), 0.0067 pounds of uranium fuel are required for the production of 1,000 kilowatt-hours of electricity. Multiplying this value by the percent of total electricity generated by the nuclear energy results in the quantity of energy contributed by nuclear fuel to the generation of the composite kilowatt-hour.

Efficiency calculations for energy sources other than fossil or nuclear are less meaningful. The quantity of water needed to produce one kilowatt-hour of electricity using hydropower is not an issue in this study. Water for hydropower is a finite, yet renewable, resource. Assigning an efficiency factor to this source of electricity would be an arbitrary procedure. Therefore, the portion of the composite kilowatt-hour from hydropower is determined using the standard conversion of 3,414 Btu per kilowatt-hour and multiplying by the percentage of total electricity generated from hydropower.

Table A-7

CALCULATION OF ENERGY CONSUMPTION FOR THE GENERATION AND DELIVERY OF ONE COMPOSITE KILOWATT-HOUR, 2000

	Total Energy (1)				Quantity of Each Fuel to Generate One Kwh		Percent of Composite Kwh	Btu of Fuel Consumed per Composite Kwh
Utility Sources								
Bituminous/	Pre-Combustior	530	Btu/lb					
Subbituminous	Combustion	10,655	Btu/lb					
Coal	Total Energy	11,185	Btu/lb		0.97	lb	49.6	5,381
Lignite Coal	Pre-Combustior	590	Btu/lb					
	Combustion	6,455	Btu/lb					
	Total Energy	7,045	Btu/lb		1.72	lb	2.60	315
Natural gas	Pre-Combustior	89	Btu/cuft					
	Combustion	1,022	Btu/cuft					
	Total Energy	1,111	Btu/cuft		10.5	cuft	15.7	1,831
Residual fuel oil	Pre-Combustior	21,900	Btu/gal					
	Combustion	149,700	Btu/gal					
	Total Energy	171,600	Btu/gal		0.070	gal	2.80	336
Other fossil (2)	Total Energy	10,350	Btu/kwh	(3)	--		0.61	63.1
Subtotal (fossil fuels)							71.3	7,927
Uranium	Pre-Combustior	20,400,000	Btu/lb					
	Combustion	985,321,000	Btu/lb					
	Total Energy	1,005,721,000	Btu/lb		6.7E-06	lb	19.6	1,321
Hydropower	Total energy	3,414	Btu/kwh		--		7.10	242
Other non-fossil								
Biomass/wood	Total energy	10,350	Btu/kwh	(3)	--		1.40	145
Geothermal	Total energy	10,350	Btu/kwh	(3)	--		0.36	37.3
Wind	Total energy	3,414	Btu/kwh		--		0.15	5.12
Solar	Total energy	3,414	Btu/kwh		--		0.020	0.68
TOTAL (U.S. AVERAGE)							**99.9**	**9,678**
Line loss adjustment: (4)	**Multiply by 1.0991**							**10,638**

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(1) From Table 9.

(2) This is defined by E-GRID (Reference A-62) as including tires, chemicals, batteries, hydrogen, sulfur, and waste heat.

(3) 3,413 Btu/kwh divided by 0.33 thermal efficiency

(4) Adjusts energy requirements to account for power losses in transmission lines (i.e., the difference between net electricity generation and sales.) Reference A-62.

Source: Franklin Associates, A Division of ERG

Table A-8

MIX OF FUEL REQUIRED TO GENERATE ONE KILOWATT-HOUR
(2000 U.S. average)

			DQI
Bituminous/Subbituminus coal	0.48	lb	A
Lignite coal	0.045	lb	A
natural gas	1.65	cuft	A
Residual oil	0.0020	gal	A
Other fossil	63.0	Btu	A
Fuel grade uranium (1)	1.3E-06	lb	A
Hydroelectric	242	Btu	A
Other non-fossil (2)	188	Btu	A

Includes line loss adjustment
(1) Calculated.
(2) Other non-fossil includes biomass/wood, geothermal, wind, solar, and other small sources of electricity.

Source: Calculated from data presented in Table A-7

Electricity from wind energy and photovoltaic cells (solar energy) falls into the same category as hydroelectric energy. The standard conversion of 3,414 Btu per kilowatt-hour is used to measure energy produced from these sources. Currently, very little electricity is actually being produced using wind energy or photovoltaic cells.

Unconventional energy sources, such as geothermal energy, solar energy for steam generation, and biomass energy, currently produce less than one percent of the total electricity generated in the U.S. The contribution from these energy sources is calculated by using the standard conversion factor of 3,414 Btu per kilowatt-hour and assuming an average thermal efficiency of 33 percent for converting the steam produced by these energy sources to electricity. This gives an energy factor of 10,350 Btu per kilowatt-hour of generated electricity. This energy factor is then multiplied by the percentage of total electricity generated from unconventional energy sources.

The composite kilowatt-hour for an electricity grid is calculated from the percent representation of each fuel in the electricity grid and the amount of electricity that can be produced per unit of each type of fuel. For example, to calculate the quantity of natural gas in the U.S. composite kilowatt-hour, the percentage of electricity produced from natural gas in the U.S. (15.7 percent) is multiplied by the amount of natural gas required to produce one kilowatt-hour (10.5 cubic feet). Thus, the U.S. composite kilowatt-hour consists of 1.65 cubic feet of natural gas. This calculation is applied to the remaining fuels and energy sources in order to calculate the total U.S. composite kilowatt-hour.

Electricity/Heat Cogeneration

Cogeneration is the use of steam for generation of both electricity and heat. The most common configuration is to generate high temperature steam in a cogeneration boiler and use that steam to generate electricity. The steam exiting the electricity turbines is then used as a process heat source for other operations. Significant energy savings occur because in a conventional operation, the steam exiting the electricity generation process is condensed, and the heat is dissipated to the environment.

For LCI purposes, the fuel consumed and the emissions generated by the cogeneration boiler need to be allocated to the two energy-consuming processes: electricity generation and subsequent process steam. Because these are both energy-consuming processes, the logical basis for allocation is Btu of energy.

In order to allocate fuel consumption and environmental emissions to both electricity and steam generation, the share of the two forms of energy (electrical and thermal) produced must be correlated to the quantity of fuel consumed by the boiler. Data on the quantity of fuel consumed and the associated environmental emissions from the combustion of the fuel, the amount of electricity generated, and the thermal output of the steam exiting electricity generation must be known in order to allocate fuel consumption and environmental emissions accordingly. These three types of data are discussed below.

3. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2003 industry statistics, natural gas accounted for 59 percent of industrial cogeneration, while coal and waste gases accounted for 28 percent and 13 percent, respectively (References A-111 through A-113). For this analysis, the data for the combustion of natural gas in industrial boilers was used to determine the environmental emissions from natural gas combustion in cogeneration boilers. For cases in which coal is used in cogeneration boilers, the data for the combustion of bituminous coal in industrial boilers is recommended. For cases in which waste gas is used in cogeneration boilers, the data for the combustion of LPG (liquefied petroleum gas) in industrial boilers is recommended.

4. **Kilowatt-Hours of Electricity Generated:** In this analysis, the data providers reported the kilowatt-hours of electricity from cogeneration. The Btu of fuel required for this electricity generation was calculated by multiplying the kilowatt-hours of electricity by 6,826 Btu/kWh (which utilizes a thermal to electrical conversion efficiency of 50 percent) (Reference A-110). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the electricity allocation factor. Note that the kilowatt-hours of electricity generation and consumption of fuel must be on the same production basis, whether a common unit of time or a specified quantity of fuel consumption.

3. **Thermal Output of Steam Exiting Electricity Generation:** In this analysis, the data providers stated the pounds and pressure of steam from cogeneration. The thermal output (in Btu) of this steam was calculated from enthalpy tables (in most cases steam ranged from 1,000 to 1,200 Btu/lb). An efficiency of 80 percent was used for the industrial boiler to calculate the amount of fuel used (Reference A-110). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the steam allocation factor. Note that the thermal output of steam and consumption of fuel must be on the same production basis, whether a common unit of time or a specified quantity of fuel consumption.

Precombustion Energy and Emissions for Primary Fuels

The energy requirements and environmental emissions, starting from the extraction of raw materials from the earth and ending with the delivery of processed and refined primary fuels to the customer, are known as precombustion energy and precombustion emissions.

Precombustion energy is the sum of all energy inputs into the production of a fuel that is subsequently used as a source of energy. Calculation of precombustion energy requires the tabulation of the fuel requirements for each of the energy sources used in fuel production. Each of these fuel inputs also had energy requirements for production and transportation. This series of inputs creates a complex and technically infinite set of interdependent steps. Iterative calculations were employed to evaluate this interdependency.

Precombustion emissions are the sum of the process emissions from fuel production, the combustion of fuels required for fuel production, and the combustion of fuels required for transportation of fuels. Calculation of precombustion emissions requires the tabulation of process emissions along each step in the precombustion cycle, as well as the tabulation of fuel combustion emissions throughout the precombustion cycle. As is the case with precombustion energy, the calculation of precombustion emissions require iterative calculations.

Precombustion energy and emissions for primary fuels were calculated using the process and transportation energy requirements already presented in this appendix. The energy data shown in this appendix represent the fuel types and quantities used in the production and delivery of each type of fuel. The emission data shown in this appendix represent the emissions that result from fuel production processes, fuel combustion required for fuel production, and fuel combustion required for transportation.

Precombustion energy requirements for primary fuels were calculated using the process and transportation energy requirements presented in Tables A-1 through A-5, the transportation energy requirements in Table A-6, and the electricity production data presented in Tables A-7 and A-8, and the energy factors in Table A-9. The results of these iterative calculations are presented in Tables A-10a through A-10c, A-11, A-12a through A-12e, and A-13 for coal, natural gas, petroleum fuels, and nuclear fuels, respectively. The energy requirements shown in Tables A-10 through A-13 include both the process and precombustion energy to produce the fuel.

The environmental emissions that result from producing and combusting fuels used for energy to produce other fuels are also presented in Tables A-10 through A-13. The emissions shown in these tables include the precombustion emissions and the process emissions.

PRIMARY FUEL COMBUSTION

Energy Content of Fuels

The precombustion, combustion, and total energy associated with the consumption of 1,000 units of the various types of fuels used by mobile and stationary sources are reported in Table A-9. Stationary sources include industrial and utility boilers, and other types of stationary industrial equipment such as compressors and pumps. Mobile sources include various modes of transportation such as truck, rail, barge, and ocean freighter.

Table A-9

ENERGY FACTORS FOR VARIOUS FUELS
2003

		Fuel Density (lb/gal)	**Pre-Combustion Energy** (Million Btu)	**Combustion Energy** (Million Btu)	**Total Energy** (Million Btu)
Mobile Sources					
Diesel	1,000 gal	7.237	20.1	139	159
Gasoline	1,000 gal	6.167	17.1	125	142
Residual fuel oil	1,000 gal	7.882	21.9	150	172
Jet fuel (Kerosene)	1,000 gal	6.751	18.7	135	154
Industrial Heating					
Anthracite Coal	1,000 lb	–	0.33	12.4	12.8
Bit/Subbit Coal	1,000 lb	–	0.53	10.7	11.2
Lignite Coal	1,000 lb	–	0.59	6.46	7.05
Diesel	1,000 gal	7.237	20.1	139	159
Distillate fuel oil	1,000 gal	7.237	20.1	139	159
Gasoline	1,000 gal	6.167	17.1	125	142
LPG	1,000 gal	4.524	12.6	95.5	108
Natural gas	1,000 cuft	0.046 (1)	0.089	1.03	1.12
Residual fuel oil	1,000 gal	7.882	21.9	150	172
Utility Heating					
Anthracite Coal	1,000 lb	–	0.33	12.4	12.8
Bit/Subbit Coal	1,000 lb	–	0.53	10.7	11.2
Lignite Coal	1,000 lb	–	0.59	6.46	7.05
Natural gas	1,000 cuft	0.046 (1)	0.089	1.02	1.11
Residual fuel oil	1,000 gal	7.882	21.9	150	172
Distillate fuel oil	1,000 gal	7.237	20.1	139	159
Fuel grade uranium	1,000 lb	–	20,400	985,320	1,005,720

References: A-48, A-81, and A-85.

(1) Natural gas is shown as lb/cu ft.

Source: Franklin Associates, A Division of ERG

Table A-10a

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF ANTHRACITE COAL

Total Precombustion Fuel Use and Process Energy			**DQI**
	United States		
Coal - Anthracite	0.38	lb	B
Coal - Bituminous	5.77	lb	B
Coal - Lignite	0.54	lb	B
Natural gas	36.4	cuft	B
Residual oil	0.26	gal	C
Distillate oil	1.30	gal	C
Gasoline	0.034	gal	C
Liquefied petroleum gas	0.0017	gal	B
Uranium (nuclear power)	1.6E-05	lb	B
Hydropower	2,924	Btu	B
Other renewable energy	1,281	Btu	B
Wood and wood wastes	1,798	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	2.11	lb	D
Particulates (PM10)	0.0060	lb	D
Nitrogen Oxides	0.25	lb	C
Hydrocarbons (unspecified)	0.024	lb	D
VOC (unspecified)	0.042	lb	D
TNMOC (unspecified)	3.7E-04	lb	C
Sulfur Dioxide	0.15	lb	C
Sulfur Oxides	0.051	lb	C
Carbon Monoxide	0.24	lb	C
Fossil CO2	58.1	lb	C
Non-Fossil CO2	0.35	lb	D
Aldehydes (Formaldehyde)	2.7E-05	lb	C
Aldehydes (Acetaldehyde)	4.9E-06	lb	D
Aldehydes (Propionaldehyde)	6.5E-10	lb	D
Aldehydes (unspecified)	5.0E-04	lb	C
Organics (unspecified)	1.9E-05	lb	D
Ammonia	2.5E-04	lb	D
Ammonia Chloride	2.4E-06	lb	D
Methane	1.69	lb	B
Kerosene	4.4E-06	lb	D
Chlorine	1.4E-06	lb	D
HCl	0.0043	lb	C
HF	6.6E-04	lb	C
Metals (unspecified)	7.7E-05	lb	D
Mercaptan	3.5E-07	lb	D
Antimony	7.1E-08	lb	C
Arsenic	1.9E-06	lb	C
Beryllium	2.9E-07	lb	C
Cadmium	5.0E-07	lb	C
Chromium (VI)	2.5E-07	lb	C
Chromium	4.0E-06	lb	D
Cobalt	1.7E-06	lb	C
Copper	3.7E-07	lb	D
Lead	3.4E-06	lb	C
Magnesium	3.5E-05	lb	C
Manganese	5.9E-06	lb	C

Table A-10a (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF ANTHRACITE COAL

Atmospheric Emissions (cont)		**DQI**
Mercury	7.5E-07 lb	C
Nickel	2.3E-05 lb	C
Selenium	5.4E-06 lb	C
Zinc	2.5E-07 lb	D
Acetophenone	2.6E-11 lb	D
Acrolein	8.5E-06 lb	D
Nitrous Oxide	0.0011 lb	C
Benzene	2.1E-04 lb	D
Benzyl Chloride	1.2E-09 lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.3E-10 lb	D
1,3 Butadiene	1.7E-07 lb	D
2-Chloroacetophenone	1.2E-11 lb	D
Chlorobenzene	3.8E-11 lb	D
2,4-Dinitrotoluene	4.8E-13 lb	D
Ethyl Chloride	7.2E-11 lb	D
Ethylbenzene	1.9E-05 lb	D
Ethylene Dibromide	2.1E-12 lb	D
Ethylene Dichloride	6.9E-11 lb	D
Hexane	1.2E-10 lb	D
Isophorone ($C_9H_{14}O$)	1.0E-09 lb	D
Methyl Bromide	2.7E-10 lb	D
Methyl Chloride	9.1E-10 lb	D
Methyl Ethyl Ketone	6.7E-10 lb	D
Methyl Hydrazine	2.9E-10 lb	D
Methyl Methacrylate	3.4E-11 lb	D
Methyl Tert Butyl Ether (MTBE)	6.0E-11 lb	D
Naphthalene	4.6E-07 lb	D
Propylene	1.1E-05 lb	D
Styrene	4.3E-11 lb	D
Toluene	2.5E-04 lb	D
Trichloroethane	1.2E-09 lb	D
Vinyl Acetate	1.3E-11 lb	D
Xylenes	1.5E-04 lb	D
Bromoform	6.7E-11 lb	D
Chloroform	1.0E-10 lb	D
Carbon Disulfide	2.2E-10 lb	D
Dimethyl Sulfate	8.2E-11 lb	D
Cumene	9.1E-12 lb	D
Cyanide	4.3E-09 lb	D
Perchloroethylene	1.9E-07 lb	D
Methylene Chloride	4.6E-06 lb	D
Carbon Tetrachloride	8.1E-08 lb	D
Phenols	2.5E-06 lb	D
Fluorides	2.8E-07 lb	D
Polyaromatic Hydrocarbons (total)	3.2E-05 lb	E
Biphenyl	4.8E-06 lb	E
Acenaphthene	1.6E-09 lb	E
Acenaphthylene	7.9E-10 lb	E
Anthracene	6.6E-10 lb	E
Benzo(a)anthracene	2.5E-10 lb	E
Benzo(a)pyrene	1.2E-10 lb	E
Benzo(b,j,k)fluroanthene	3.5E-10 lb	E

Table A-10a (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF ANTHRACITE COAL

Atmospheric Emissions (cont)			**DQI**
Benzo(g,h,i) perylene	8.5E-11	lb	E
Chrysene	3.2E-10	lb	E
Fluoranthene	2.2E-09	lb	E
Fluorene	2.9E-09	lb	E
Naphthalene	2.5E-05	lb	E
Phenanthrene	1.3E-06	lb	E
Pyrene	1.0E-09	lb	E
5-methyl Chrysene	6.9E-11	lb	E
Dioxins (unspecified)	3.0E-09	lb	D
Furans (unspecified)	1.4E-11	lb	D
CFC12	1.4E-09	lb	D
Radionuclides (unspecified)	2.5E-04	Ci	C
Waterborne Emissions			
Acid (unspecified)	9.0E-06	lb	E
Acid (benzoic)	5.1E-05	lb	E
Acid (hexanoic)	1.1E-05	lb	E
Metal (unspecified)	0.11	lb	E
Dissolved Solids	2.25	lb	E
Suspended Solids	0.38	lb	E
BOD	0.0052	lb	E
COD	0.0049	lb	E
Phenol/Phenolic Compounds	2.5E-05	lb	E
Sulfur	1.3E-04	lb	E
Sulfates	0.0069	lb	E
Sulfides	2.2E-06	lb	E
Oil	0.0011	lb	E
Hydrocarbons	1.0E-05	lb	E
Ammonia	9.0E-04	lb	E
Ammonium	2.0E-06	lb	E
Aluminum	0.0040	lb	E
Antimony	2.5E-06	lb	E
Arsenic	1.4E-05	lb	E
Barium	0.055	lb	E
Beryllium	7.4E-07	lb	E
Cadmium	2.0E-06	lb	E
Chromium (unspecified)	1.1E-04	lb	E
Cobalt	1.1E-06	lb	E
Copper	1.4E-05	lb	E
Iron	0.030	lb	E
Lead	2.8E-05	lb	E
Lithium	0.0080	lb	E
Magnesium	0.032	lb	E
Manganese	0.015	lb	E
Mercury	4.4E-08	lb	E
Molybdenum	1.2E-06	lb	E
Nickel	1.3E-05	lb	E
Selenium	1.2E-06	lb	E
Silver	1.1E-04	lb	E
Sodium	0.51	lb	E

Table A-10a (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF ANTHRACITE COAL

Waterborne Emissions (cont)			**DQI**
Strontium	0.0028	lb	E
Thallium	5.3E-07	lb	E
Tin	1.1E-05	lb	E
Titanium	3.8E-05	lb	E
Vanadium	1.4E-06	lb	E
Yttrium	3.4E-07	lb	E
Zinc	9.4E-05	lb	E
Chlorides (unspecified)	1.82	lb	E
Chlorides (methyl chloride)	2.0E-09	lb	E
Calcium	0.16	lb	E
Fluorine/ Fluorides	3.2E-05	lb	E
Nitrates	4.9E-06	lb	E
Nitrogen (ammonia)	1.7E-06	lb	E
Bromide	0.011	lb	E
Boron	1.6E-04	lb	E
Organic Carbon	3.7E-05	lb	E
Cyanide	3.6E-09	lb	E
Hardness	0.50	lb	E
Total Alkalinity	0.0040	lb	E
Surfactants	4.3E-05	lb	E
Acetone	5.0E-07	lb	E
Alkylated Benzenes	2.2E-06	lb	E
Alkylated Fluorenes	1.3E-07	lb	E
Alkylated Naphthalenes	3.6E-08	lb	E
Alkylated Phenanthrenes	1.5E-08	lb	E
Benzene	8.5E-05	lb	E
Cresols	3.0E-06	lb	E
Cymene	5.0E-09	lb	E
Dibenzofuran	9.6E-09	lb	E
Dibenzothiophene	7.8E-09	lb	E
2,4 dimethylphenol	1.4E-06	lb	E
Ethylbenzene	4.8E-06	lb	E
2-Hexanone	3.3E-07	lb	E
Methyl ethyl Ketone (MEK)	4.1E-09	lb	E
1-methylfluorene	5.7E-09	lb	E
2-methyl naphthalene	8.0E-07	lb	E
4-methyl- 2-pentanone	2.1E-07	lb	E
Naphthalene	9.2E-07	lb	E
Pentamethyl benzene	3.8E-09	lb	E
Phenanthrene	1.3E-08	lb	E
Toluene	8.0E-05	lb	E
Total Biphenyls	1.4E-07	lb	E
total dibenzo- thiophenes	4.4E-10	lb	E
Xylenes	4.2E-05	lb	E
Radionuclides (unspecified)	3.5E-09	Ci	E
Solid Waste	274	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-10b

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF BITUMINOUS COAL

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	11.6	lb	B
Coal - Lignite	1.02	lb	B
Natural gas	58.6	cuft	B
Residual oil	0.37	gal	C
Distillate oil	1.95	gal	C
Gasoline	0.10	gal	C
Liquefied petroleum gas	0.0026	gal	B
Uranium (nuclear power)	2.9E-05	lb	B
Hydropower	5,360	Btu	B
Other renewable energy	2,348	Btu	B
Wood and wood wastes	3,296	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	1.65	lb	D
Particulates (PM10)	0.021	lb	D
Nitrogen Oxides	0.77	lb	C
Hydrocarbons (unspecified)	0.036	lb	D
VOC (unspecified)	0.054	lb	D
TNMOC (unspecified)	7.4E-04	lb	C
Sulfur Dioxide	0.25	lb	C
Sulfur Oxides	0.081	lb	C
Carbon Monoxide	0.43	lb	C
Fossil CO2	92.5	lb	C
Non-Fossil CO2	0.64	lb	D
Aldehydes (Formaldehyde)	4.5E-05	lb	C
Aldehydes (Acetaldehyde)	1.3E-05	lb	D
Aldehydes (Propionaldehyde)	8.3E-08	lb	D
Aldehydes (unspecified)	7.5E-04	lb	D
Organics (unspecified)	3.7E-05	lb	D
Ammonia	3.7E-04	lb	D
Ammonia Chloride	4.5E-06	lb	D
Methane	4.15	lb	C
Kerosene	8.0E-06	lb	D
Chlorine	2.6E-06	lb	D
HCl	0.0084	lb	C
HF	9.4E-04	lb	C
Metals (unspecified)	1.4E-04	lb	D
Mercaptan	4.7E-05	lb	D
Antimony	1.4E-07	lb	C
Arsenic	3.5E-06	lb	C
Beryllium	5.9E-07	lb	C
Cadmium	9.4E-07	lb	C
Chromium (VI)	5.0E-07	lb	D
Chromium	2.4E-06	lb	C
Cobalt	1.9E-06	lb	C
Copper	8.9E-07	lb	D
Lead	5.2E-06	lb	C
Magnesium	7.0E-05	lb	C
Manganese	9.9E-06	lb	C
Mercury	1.3E-06	lb	C

Table A-10b (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF BITUMINOUS COAL

Atmospheric Emissions (cont)			**DQI**
Nickel	2.0E-05	lb	C
Selenium	1.1E-05	lb	C
Zinc	5.9E-07	lb	D
Acetophenone	3.3E-09	lb	D
Acrolein	1.6E-05	lb	D
Nitrous Oxide	0.0018	lb	C
Benzene	3.1E-04	lb	D
Benzyl Chloride	1.5E-07	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-08	lb	D
1,3 Butadiene	5.1E-07	lb	D
2-Chloroacetophenone	1.5E-09	lb	D
Chlorobenzene	4.8E-09	lb	D
2,4-Dinitrotoluene	6.1E-11	lb	D
Ethyl Chloride	9.2E-09	lb	D
Ethylbenzene	3.1E-05	lb	D
Ethylene Dibromide	2.6E-10	lb	D
Ethylene Dichloride	8.7E-09	lb	D
Hexane	1.5E-08	lb	D
Isophorone ($C_9H_{14}O$)	1.3E-07	lb	D
Methyl Bromide	3.5E-08	lb	D
Methyl Chloride	1.2E-07	lb	D
Methyl Ethyl Ketone	8.5E-08	lb	D
Methyl Hydrazine	3.7E-08	lb	D
Methyl Methacrylate	4.4E-09	lb	D
Methyl Tert Butyl Ether (MTBE)	7.6E-09	lb	D
Naphthalene	6.0E-07	lb	D
Propylene	3.3E-05	lb	D
Styrene	5.5E-09	lb	D
Toluene	4.1E-04	lb	D
Trichloroethane	6.1E-09	lb	D
Vinyl Acetate	1.7E-09	lb	D
Xylenes	2.4E-04	lb	D
Bromoform	8.5E-09	lb	D
Chloroform	1.3E-08	lb	D
Carbon Disulfide	2.8E-08	lb	D
Dimethyl Sulfate	1.0E-08	lb	D
Cumene	1.2E-09	lb	D
Cyanide	5.5E-07	lb	D
Perchloroethylene	3.7E-07	lb	D
Methylene Chloride	8.6E-06	lb	D
Carbon Tetrachloride	1.5E-07	lb	D
Phenols	4.6E-06	lb	D
Fluorides	1.0E-05	lb	D
Polyaromatic Hydrocarbons (total)	2.3E-06	lb	E
Biphenyl	1.1E-08	lb	E
Acenaphthene	3.2E-09	lb	E
Acenaphthylene	1.6E-09	lb	E
Anthracene	1.3E-09	lb	E
Nickel	2.0E-05	lb	E

Table A-10b (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF BITUMINOUS COAL

Atmospheric Emissions (cont)		**DQI**
Benzo(a)anthracene	5.1E-10 lb	E
Benzo(a)pyrene	2.4E-10 lb	E
Benzo(b,j,k)fluroanthene	7.0E-10 lb	E
Benzo(g,h,i) perylene	1.7E-10 lb	E
Chrysene	6.3E-10 lb	E
Fluoranthene	4.5E-09 lb	E
Fluorene	5.8E-09 lb	E
Indeno(1,2,3-cd)pyrene	3.9E-10 lb	E
Naphthalene	8.2E-08 lb	E
Phenanthrene	1.7E-08 lb	E
Pyrene	2.1E-09 lb	E
5-methyl Chrysene	1.4E-10 lb	E
Dioxins (unspecified)	5.5E-09 lb	D
Furans (unspecified)	2.8E-11 lb	D
CFC12	2.0E-09 lb	D
Radionuclides (unspecified)	4.5E-04 Ci	C
Waterborne Emissions		
Acid (unspecified)	1.5E-05 lb	E
Acid (benzoic)	7.8E-05 lb	E
Acid (hexanoic)	1.6E-05 lb	E
Metal (unspecified)	0.18 lb	E
Dissolved Solids	3.42 lb	E
Suspended Solids	0.29 lb	E
BOD	0.0091 lb	E
COD	0.0075 lb	E
Phenol/Phenolic Compounds	3.8E-05 lb	E
Sulfur	2.0E-04 lb	E
Sulfates	0.011 lb	E
Sulfides	3.3E-06 lb	E
Oil	0.0017 lb	E
Hydrocarbons	1.5E-05 lb	E
Ammonia	0.0014 lb	E
Ammonium	3.6E-06 lb	E
Aluminum	0.0061 lb	E
Antimony	3.8E-06 lb	E
Arsenic	2.1E-05 lb	E
Barium	0.083 lb	E
Beryllium	1.1E-06 lb	E
Cadmium	3.1E-06 lb	E
Chromium (unspecified)	1.7E-04 lb	E
Cobalt	1.7E-06 lb	E
Copper	2.2E-05 lb	E
Iron	0.021 lb	E
Lead	4.2E-05 lb	E
Lithium	0.013 lb	E
Magnesium	0.048 lb	E
Manganese	0.0059 lb	E
Mercury	6.7E-08 lb	E
Molybdenum	1.8E-06 lb	E

Table A-10b (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF BITUMINOUS COAL

Waterborne Emissions (cont)			**DQI**
Selenium	2.0E-06	lb	E
Silver	1.6E-04	lb	E
Sodium	0.78	lb	E
Strontium	0.0042	lb	E
Thallium	7.9E-07	lb	E
Tin	1.6E-05	lb	E
Titanium	5.8E-05	lb	E
Vanadium	2.1E-06	lb	E
Yttrium	5.2E-07	lb	E
Zinc	1.4E-04	lb	E
Chlorides (unspecified)	2.77	lb	E
Chlorides (methyl chloride)	3.1E-09	lb	E
Calcium	0.25	lb	E
Fluorine/ Fluorides	5.8E-05	lb	E
Nitrates	8.9E-06	lb	E
Nitrogen (ammonia)	3.1E-06	lb	E
Bromide	0.016	lb	E
Boron	2.4E-04	lb	E
Organic Carbon	6.0E-05	lb	E
Cyanide	5.5E-09	lb	E
Hardness	0.76	lb	E
Total Alkalinity	0.0061	lb	E
Surfactants	6.6E-05	lb	E
Acetone	7.7E-07	lb	E
Alkylated Benzenes	3.3E-06	lb	E
Alkylated Fluorenes	1.9E-07	lb	E
Alkylated Naphthalenes	5.4E-08	lb	E
Alkylated Phenanthrenes	2.2E-08	lb	E
Benzene	1.3E-04	lb	E
Cresols	4.5E-06	lb	E
Cymene	7.7E-09	lb	E
Dibenzofuran	1.5E-08	lb	E
Dibenzothiophene	1.2E-08	lb	E
2,4-dimethylphenol	2.2E-06	lb	E
Ethylbenzene	7.2E-06	lb	E
2-Hexanone	5.0E-07	lb	E
Methyl ethyl Ketone (MEK)	6.2E-09	lb	E
1-methylfluorene	8.7E-09	lb	E
2-methyl naphthalene	1.2E-06	lb	E
4-methyl-2-pentanone	3.2E-07	lb	E
Naphthalene	1.4E-06	lb	E
Pentamethyl benzene	5.8E-09	lb	E
Phenanthrene	2.0E-08	lb	E
Toluene	1.2E-04	lb	E
Total Biphenyls	2.1E-07	lb	E
Total dibenzo-thiophenes	6.6E-10	lb	E
Xylenes	6.5E-05	lb	E
Radionuclides (unspecified)	6.3E-09	Ci	E
Solid Waste	240	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-10c

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF LIGNITE COAL

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	14.0	lb	B
Coal - Lignite	1.66	lb	B
Natural gas	73.5	cuft	B
Residual oil	1.98	gal	C
Distillate oil	0.25	gal	C
Gasoline	0.17	gal	C
Liquefied petroleum gas	0.0028	gal	B
Uranium (nuclear power)	3.8E-05	lb	B
Hydropower	7,068	Btu	B
Other renewable energy	3,097	Btu	B
Wood and wood wastes	4,346	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	0.13	lb	D
Particulates (PM10)	0.010	lb	D
Nitrogen Oxides	0.33	lb	C
Hydrocarbons (unspecified)	0.038	lb	D
VOC (unspecified)	0.010	lb	D
TNMOC (unspecified)	8.5E-04	lb	C
Sulfur Dioxide	0.31	lb	C
Sulfur Oxides	0.14	lb	C
Carbon Monoxide	0.47	lb	C
Fossil CO2	106	lb	C
Non-Fossil CO2	0.85	lb	D
Aldehydes (Formaldehyde)	1.2E-04	lb	C
Aldehydes (Acetaldehyde)	2.0E-05	lb	D
Aldehydes (Propionaldehyde)	7.0E-08	lb	D
Aldehydes (unspecified)	7.8E-04	lb	D
Organics (unspecified)	4.7E-05	lb	D
Ammonia	3.9E-04	lb	D
Ammonia Chloride	5.9E-06	lb	D
Methane	1.30	lb	C
Kerosene	1.1E-05	lb	D
Chlorine	3.4E-06	lb	D
HCl	0.011	lb	C
HF	0.0012	lb	C
Metals (unspecified)	1.9E-04	lb	D
Mercaptan	8.2E-07	lb	D
Antimony	1.8E-07	lb	C
Arsenic	5.9E-06	lb	C
Beryllium	3.0E-07	lb	C
Cadmium	1.3E-06	lb	C
Chromium (VI)	6.2E-07	lb	D
Chromium	3.9E-06	lb	C
Cobalt	1.2E-05	lb	C
Copper	1.6E-07	lb	D
Lead	3.1E-05	lb	C
Magnesium	8.6E-05	lb	C
Manganese	1.7E-05	lb	C

Table A-10c (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF LIGNITE COAL

Atmospheric Emissions (cont)			**DQI**
Mercury	1.2E-06	lb	C
Nickel	1.6E-04	lb	C
Selenium	1.2E-05	lb	C
Zinc	1.1E-07	lb	D
Acetophenone	2.8E-09	lb	D
Acrolein	2.2E-05	lb	D
Nitrous Oxide	0.0014	lb	C
Benzene	3.9E-04	lb	D
Benzyl Chloride	1.3E-07	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.3E-08	lb	D
1,3 Butadiene	8.5E-07	lb	D
2-Chloroacetophenone	1.3E-09	lb	D
Chlorobenzene	4.0E-09	lb	D
2,4-Dinitrotoluene	5.2E-11	lb	D
Ethyl Chloride	7.7E-09	lb	D
Ethylbenzene	3.9E-05	lb	D
Ethylene Dibromide	2.2E-10	lb	D
Ethylene Dichloride	7.4E-09	lb	D
Hexane	1.2E-08	lb	D
Isophorone ($C_9H_{14}O$)	1.1E-07	lb	D
Methyl Bromide	2.9E-08	lb	D
Methyl Chloride	9.8E-08	lb	D
Methyl Ethyl Ketone	7.2E-08	lb	D
Methyl Hydrazine	3.1E-08	lb	D
Methyl Methacrylate	3.7E-09	lb	D
Methyl Tert Butyl Ether (MTBE)	6.4E-09	lb	D
Naphthalene	2.6E-06	lb	D
Propylene	5.6E-05	lb	D
Styrene	4.6E-09	lb	D
Toluene	5.1E-04	lb	D
Trichloroethane	5.5E-09	lb	D
Vinyl Acetate	1.4E-09	lb	D
Xylenes	3.0E-04	lb	D
Bromoform	7.2E-09	lb	D
Chloroform	1.1E-08	lb	D
Carbon Disulfide	2.4E-08	lb	D
Dimethyl Sulfate	8.8E-09	lb	D
Cumene	9.8E-10	lb	D
Cyanide	4.6E-07	lb	D
Perchloroethylene	4.9E-07	lb	D
Methylene Chloride	1.4E-05	lb	D
Carbon Tetrachloride	2.0E-07	lb	D
Phenols	8.0E-06	lb	D
Fluorides	6.6E-07	lb	D
Polyaromatic Hydrocarbons (total)	3.8E-06	lb	E
Biphenyl	1.3E-08	lb	E
Acenaphthene	4.0E-09	lb	E
Acenaphthylene	2.0E-09	lb	E
Anthracene	1.6E-09	lb	E
Benzo(a)anthracene	6.3E-10	lb	E
Benzo(a)pyrene	3.0E-10	lb	E

Table A-10c (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF LIGNITE COAL

Atmospheric Emissions (cont)		**DQI**
Benzo(b,j,k)fluroanthene	8.6E-10 lb	E
Benzo(g,h,i) perylene	2.1E-10 lb	E
Chrysene	7.8E-10 lb	E
Fluoranthene	5.5E-09 lb	E
Fluorene	7.1E-09 lb	E
Indeno(1,2,3-cd)pyrene	4.8E-10 lb	E
Naphthalene	1.0E-07 lb	E
Phenanthrene	2.1E-08 lb	E
Pyrene	2.6E-09 lb	E
5-methyl Chrysene	1.7E-10 lb	E
Dioxins (unspecified)	7.3E-09 lb	D
Furans (unspecified)	3.5E-11 lb	D
CFC12	2.1E-09 lb	D
Radionuclides (unspecified)	6.0E-04 Ci	C
Waterborne Emissions		
Acid (unspecified)	1.8E-05 lb	E
Acid (benzoic)	8.4E-05 lb	E
Acid (hexanoic)	1.7E-05 lb	E
Metal (unspecified)	0.23 lb	E
Dissolved Solids	3.69 lb	E
Suspended Solids	0.20 lb	E
BOD	0.012 lb	E
COD	0.0086 lb	E
Phenol/Phenolic Compounds	4.1E-05 lb	E
Sulfur	2.2E-04 lb	E
Sulfates	0.014 lb	E
Sulfides	3.4E-06 lb	E
Oil	0.0019 lb	E
Hydrocarbons	1.7E-05 lb	E
Ammonia	0.0015 lb	E
Ammonium	4.7E-06 lb	E
Aluminum	0.0064 lb	E
Antimony	4.0E-06 lb	E
Arsenic	2.2E-05 lb	E
Barium	0.088 lb	E
Beryllium	1.2E-06 lb	E
Cadmium	3.3E-06 lb	E
Chromium (unspecified)	1.8E-04 lb	E
Cobalt	1.8E-06 lb	E
Copper	2.4E-05 lb	E
Iron	0.013 lb	E
Lead	4.5E-05 lb	E
Lithium	0.016 lb	E
Magnesium	0.052 lb	E
Manganese	3.6E-04 lb	E
Mercury	7.1E-08 lb	E
Molybdenum	1.9E-06 lb	E
Nickel	2.1E-05 lb	E
Selenium	2.4E-06 lb	E
Silver	1.7E-04 lb	E

Table A-10c (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF LIGNITE COAL

Waterborne Emissions (cont)			**DQI**
Sodium	0.84	lb	E
Strontium	0.0045	lb	E
Thallium	8.4E-07	lb	E
Tin	1.7E-05	lb	E
Titanium	6.1E-05	lb	E
Vanadium	2.3E-06	lb	E
Yttrium	5.6E-07	lb	E
Zinc	1.5E-04	lb	E
Chlorides (unspecified)	2.99	lb	E
Chlorides (methyl chloride)	3.3E-09	lb	E
Calcium	0.27	lb	E
Fluorine/ Fluorides	7.7E-05	lb	E
Nitrates	1.2E-05	lb	E
Nitrogen (ammonia)	4.1E-06	lb	E
Bromide	0.018	lb	E
Boron	2.6E-04	lb	E
Organic Carbon	7.6E-05	lb	E
Cyanide	6.0E-09	lb	E
Hardness	0.82	lb	E
Total Alkalinity	0.0066	lb	E
Surfactants	7.1E-05	lb	E
Acetone	8.3E-07	lb	E
Alkylated Benzenes	3.5E-06	lb	E
Alkylated Fluorenes	2.0E-07	lb	E
Alkylated Naphthalenes	5.7E-08	lb	E
Alkylated Phenanthrenes	2.4E-08	lb	E
Benzene	1.4E-04	lb	E
Cresols	4.9E-06	lb	E
Cymene	8.3E-09	lb	E
Dibenzofuran	1.6E-08	lb	E
Dibenzothiophene	1.3E-08	lb	E
2,4 dimethylphenol	2.3E-06	lb	E
Ethylbenzene	7.8E-06	lb	E
2-Hexanone	5.4E-07	lb	E
Methyl ethyl Ketone (MEK)	6.7E-09	lb	E
1-methylfluorene	9.4E-09	lb	E
2-methyl naphthalene	1.3E-06	lb	E
4-methyl-2-pentanone	3.5E-07	lb	E
Naphthalene	1.5E-06	lb	E
Pentamethyl benzene	6.2E-09	lb	E
Phenanthrene	2.1E-08	lb	E
Toluene	1.3E-04	lb	E
Total Biphenyls	2.3E-07	lb	E
total dibenzo- thiophenes	7.0E-10	lb	E
Xylenes	7.0E-05	lb	E
Radionuclides (unspecified)	8.4E-09	Ci	E
Solid Waste	5.77	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-11

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 CUBIC FEET OF NATURAL GAS

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	0.76	lb	B
Coal - Lignite	0.070	lb	B
Natural gas	74.3	cuft	B
Residual oil	0.010	gal	B
Distillate oil	0.013	gal	B
Gasoline	0.0046	gal	B
Liquefied petroleum gas	3.5E-05	gal	B
Uranium (nuclear power)	2.1E-06	lb	B
Hydropower	380	Btu	B
Other renewable energy	167	Btu	B
Wood and wood wastes	234	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	0.0014	lb	C
Particulates (PM10)	8.2E-04	lb	D
Nitrogen Oxides	0.016	lb	C
Hydrocarbons (unspecified)	4.2E-04	lb	D
VOC (unspecified)	0.039	lb	D
TNMOC (unspecified)	4.6E-05	lb	C
Sulfur Dioxide	1.21	lb	C
Sulfur Oxides	0.0015	lb	C
Carbon Monoxide	0.014	lb	C
Fossil CO2	11.5	lb	C
Non-Fossil CO2	0.046	lb	D
Aldehydes (Formaldehyde)	1.9E-05	lb	C
Aldehydes (Acetaldehyde)	1.3E-06	lb	D
Aldehydes (Propionaldehyde)	8.4E-11	lb	D
Aldehydes (unspecified)	9.0E-06	lb	C
Organics (unspecified)	2.5E-06	lb	D
Ammonia	4.4E-06	lb	D
Ammonia Chloride	3.2E-07	lb	D
Methane	0.70	lb	C
Kerosene	5.7E-07	lb	D
Chlorine	1.8E-07	lb	D
HCl	5.1E-04	lb	C
HF	6.2E-05	lb	C
Metals (unspecified)	1.0E-05	lb	D
Mercaptan	4.5E-08	lb	D
Antimony	9.3E-09	lb	C
Arsenic	2.0E-07	lb	C
Beryllium	1.4E-08	lb	C
Cadmium	9.2E-08	lb	C
Chromium (VI)	3.3E-08	lb	C
Chromium	2.0E-07	lb	D
Cobalt	1.0E-07	lb	C
Copper	7.6E-09	lb	D
Lead	2.4E-07	lb	C
Magnesium	4.5E-06	lb	C
Manganese	6.3E-07	lb	C

Table A-11 (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 CUBIC FEET OF NATURAL GAS

Atmospheric Emissions (cont)			**DQI**
Mercury	5.5E-08	lb	C
Nickel	1.0E-06	lb	C
Selenium	5.6E-07	lb	C
Zinc	5.1E-09	lb	D
Acetophenone	3.3E-12	lb	D
Acrolein	1.2E-06	lb	D
Nitrous Oxide	2.4E-04	lb	C
Benzene	0.0048	lb	D
Benzyl Chloride	1.5E-10	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-11	lb	D
1,3 Butadiene	3.0E-08	lb	D
2-Chloroacetophenone	1.5E-12	lb	D
Chlorobenzene	4.9E-12	lb	D
2,4-Dinitrotoluene	6.2E-14	lb	D
Ethyl Chloride	9.3E-12	lb	D
Ethylbenzene	5.7E-04	lb	D
Ethylene Dibromide	2.7E-13	lb	D
Ethylene Dichloride	8.8E-12	lb	D
Hexane	1.5E-11	lb	D
Isophorone ($C_9H_{14}O$)	1.3E-10	lb	D
Methyl Bromide	3.5E-11	lb	D
Methyl Chloride	1.2E-10	lb	D
Methyl Ethyl Ketone	8.6E-11	lb	D
Methyl Hydrazine	3.8E-11	lb	D
Methyl Methacrylate	4.4E-12	lb	D
Methyl Tert Butyl Ether (MTBE)	7.7E-12	lb	D
Naphthalene	9.1E-08	lb	D
Propylene	2.0E-06	lb	D
Styrene	5.5E-12	lb	D
Toluene	0.0074	lb	D
Trichloroethane	2.4E-11	lb	D
Vinyl Acetate	1.7E-12	lb	D
Xylenes	0.0043	lb	D
Bromoform	8.6E-12	lb	D
Chloroform	1.3E-11	lb	D
Carbon Disulfide	2.9E-11	lb	D
Dimethyl Sulfate	1.1E-11	lb	D
Cumene	1.2E-12	lb	D
Cyanide	5.5E-10	lb	D
Perchloroethylene	1.9E-08	lb	D
Methylene Chloride	2.8E-07	lb	D
Carbon Tetrachloride	1.1E-08	lb	D
Phenols	8.3E-08	lb	D
Fluorides	3.6E-08	lb	D
Polyaromatic Hydrocarbons (total)	1.4E-07	lb	E
Biphenyl	7.0E-10	lb	E
Acenaphthene	2.1E-10	lb	E
Acenaphthylene	1.0E-10	lb	E
Anthracene	8.7E-11	lb	E
Benzo(a)anthracene	3.3E-11	lb	E
Benzo(a)pyrene	1.6E-11	lb	E

Table A-11 (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 CUBIC FEET OF NATURAL GAS

Atmospheric Emissions (cont)		**DQI**
Benzo(b,j,k)fluroanthene	4.5E-11 lb	E
Benzo(g,h,i) perylene	1.1E-11 lb	E
Chrysene	4.1E-11 lb	E
Fluoranthene	2.9E-10 lb	E
Fluorene	3.8E-10 lb	E
Indeno(1,2,3-cd)pyrene	2.5E-11 lb	E
Naphthalene	5.4E-09 lb	E
Phenanthrene	1.1E-09 lb	E
Pyrene	1.4E-10 lb	E
5-methyl Chrysene	9.1E-12 lb	E
Dioxins (unspecified)	3.9E-10 lb	D
Furans (unspecified)	1.9E-12 lb	D
CFC12	2.4E-11 lb	D
Radionuclides (unspecified)	3.2E-05 Ci	C
Waterborne Emissions		
Acid (unspecified)	2.7E-04 lb	E
Acid (benzoic)	2.2E-04 lb	E
Acid (hexanoic)	4.6E-05 lb	E
Metal (unspecified)	3.39 lb	E
Dissolved Solids	9.76 lb	E
Suspended Solids	0.14 lb	E
BOD	0.038 lb	E
COD	0.063 lb	E
Phenol/Phenolic Compounds	9.8E-05 lb	E
Sulfur	5.8E-04 lb	E
Sulfates	0.017 lb	E
Sulfides	3.8E-08 lb	E
Oil	0.0042 lb	E
Hydrocarbons	4.4E-05 lb	E
Ammonia	0.0033 lb	E
Ammonium	2.5E-07 lb	E
Aluminum	0.0041 lb	E
Antimony	2.5E-06 lb	E
Arsenic	4.8E-05 lb	E
Barium	0.063 lb	E
Beryllium	2.2E-06 lb	E
Cadmium	7.1E-06 lb	E
Chromium (unspecified)	1.1E-04 lb	E
Cobalt	4.9E-06 lb	E
Copper	3.1E-05 lb	E
Iron	0.013 lb	E
Lead	7.0E-05 lb	E
Lithium	0.23 lb	E
Magnesium	0.14 lb	E
Manganese	2.3E-04 lb	E
Mercury	4.4E-08 lb	E
Molybdenum	5.0E-06 lb	E
Nickel	3.8E-05 lb	E
Selenium	5.8E-07 lb	E
Silver	4.6E-04 lb	E

Table A-11 (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 CUBIC FEET OF NATURAL GAS

Waterborne Emissions (cont)			**DQI**
Sodium	2.23	lb	E
Strontium	0.012	lb	E
Thallium	5.3E-07	lb	E
Tin	2.4E-05	lb	E
Titanium	3.8E-05	lb	E
Vanadium	5.9E-06	lb	E
Yttrium	1.5E-06	lb	E
Zinc	1.1E-04	lb	E
Chlorides (unspecified)	7.91	lb	E
Chlorides (methyl chloride)	8.8E-09	lb	E
Calcium	0.70	lb	E
Fluorine/ Fluorides	4.2E-06	lb	E
Nitrates	6.3E-07	lb	E
Nitrogen (ammonia)	2.2E-07	lb	E
Bromide	0.047	lb	E
Boron	6.9E-04	lb	E
Organic Carbon	0.0011	lb	E
Cyanide	1.6E-08	lb	E
Hardness	2.17	lb	E
Total Alkalinity	0.018	lb	E
Surfactants	2.2E-04	lb	E
Acetone	2.2E-06	lb	E
Alkylated Benzenes	2.2E-06	lb	E
Alkylated Fluorenes	1.3E-07	lb	E
Alkylated Naphthalenes	3.6E-08	lb	E
Alkylated Phenanthrenes	1.5E-08	lb	E
Benzene	3.7E-04	lb	E
Cresols	1.3E-05	lb	E
Cymene	2.2E-08	lb	E
Dibenzofuran	4.2E-08	lb	E
Dibenzothiophene	3.4E-08	lb	E
2,4-dimethylphenol	6.1E-06	lb	E
Ethylbenzene	2.1E-05	lb	E
2-Hexanone	1.4E-06	lb	E
Methyl ethyl Ketone (MEK)	1.8E-08	lb	E
1-methylfluorene	2.5E-08	lb	E
2-methyl naphthalene	3.5E-06	lb	E
4-methyl-2-pentanone	9.2E-07	lb	E
Naphthalene	4.0E-06	lb	E
Pentamethyl benzene	1.6E-08	lb	E
Phenanthrene	2.8E-08	lb	E
Toluene	3.5E-04	lb	E
Total Biphenyls	1.4E-07	lb	E
Total dibenzo-thiophenes	4.4E-10	lb	E
Xylenes	1.8E-04	lb	E
Radionuclides (unspecified)	4.6E-10	Ci	E
Solid Waste	1.60	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-12a

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	382	lb	B
Coal - Lignite	35.5	lb	B
Natural gas	8,093	cuft	B
Residual oil	53.5	gal	B
Distillate oil	6.66	gal	B
Gasoline	0.80	gal	B
Liquefied petroleum gas	1.16	gal	B
Uranium (nuclear power)	0.0011	lb	B
Hydropower	207,514	Btu	B
Other renewable energy	90,917	Btu	B
Wood and wood wastes	127,594	Btu	B
Precombustion Emissions			
Atmospheric Emissions			**DQI**
Particulates (unspecified)	2.71	lb	C
Particulates (PM10)	0.70	lb	D
Nitrogen Oxides	27.3	lb	C
Hydrocarbons (unspecified)	17.0	lb	D
VOC (unspecified)	1.08	lb	D
TNMOC (unspecified)	0.023	lb	C
Sulfur Dioxide	15.2	lb	C
Sulfur Oxides	23.4	lb	C
Carbon Monoxide	115	lb	C
Fossil CO2	3,548	lb	C
Non-Fossil CO2	24.9	lb	D
Aldehydes (Formaldehyde)	0.0024	lb	C
Aldehydes (Acetaldehyde)	1.9E-04	lb	D
Aldehydes (Propionaldehyde)	4.2E-08	lb	D
Aldehydes (unspecified)	0.35	lb	C
Organics (unspecified)	0.0013	lb	D
Ammonia	0.18	lb	D
Ammonia Chloride	1.7E-04	lb	D
Methane	38.1	lb	C
Kerosene	3.1E-04	lb	D
Chlorine	1.0E-04	lb	D
HCl	0.28	lb	C
HF	0.031	lb	C
Metals (unspecified)	0.0055	lb	D
Mercaptan	2.3E-05	lb	D
Antimony	4.8E-06	lb	C
Arsenic	1.3E-04	lb	C
Beryllium	6.2E-06	lb	C
Cadmium	3.3E-05	lb	C
Chromium (VI)	1.7E-05	lb	C
Chromium	9.4E-05	lb	D
Cobalt	2.0E-04	lb	C
Copper	1.5E-06	lb	D
Lead	1.5E-04	lb	C
Magnesium	0.0023	lb	C
Manganese	4.0E-04	lb	C

Table A-12a (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Atmospheric Emissions (cont)			DQI
Mercury	2.4E-05	lb	C
Nickel	0.0026	lb	C
Selenium	3.0E-04	lb	C
Zinc	1.0E-06	lb	D
Acetophenone	1.7E-09	lb	D
Acrolein	5.8E-04	lb	D
Nitrous Oxide	0.066	lb	C
Benzene	0.037	lb	D
Benzyl Chloride	7.8E-08	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.2E-09	lb	D
1,3 Butadiene	4.0E-06	lb	D
2-Chloroacetophenone	7.8E-10	lb	D
Chlorobenzene	2.5E-09	lb	D
2,4-Dinitrotoluene	3.1E-11	lb	D
Ethyl Chloride	4.7E-09	lb	D
Ethylbenzene	0.0043	lb	D
Ethylene Dibromide	1.3E-10	lb	D
Ethylene Dichloride	4.5E-09	lb	D
Hexane	7.5E-09	lb	D
Isophorone ($C_9H_{14}O$)	6.5E-08	lb	D
Methyl Bromide	1.8E-08	lb	D
Methyl Chloride	5.9E-08	lb	D
Methyl Ethyl Ketone	4.4E-08	lb	D
Methyl Hydrazine	1.9E-08	lb	D
Methyl Methacrylate	2.2E-09	lb	D
Methyl Tert Butyl Ether (MTBE)	3.9E-09	lb	D
Naphthalene	5.1E-05	lb	D
Propylene	2.6E-04	lb	D
Styrene	2.8E-09	lb	D
Toluene	0.055	lb	D
Trichloroethane	8.1E-07	lb	D
Vinyl Acetate	8.5E-10	lb	D
Xylenes	0.032	lb	D
Bromoform	4.4E-09	lb	D
Chloroform	6.6E-09	lb	D
Carbon Disulfide	1.5E-08	lb	D
Dimethyl Sulfate	5.4E-09	lb	D
Cumene	5.9E-10	lb	D
Cyanide	2.8E-07	lb	D
Perchloroethylene	1.1E-05	lb	D
Methylene Chloride	2.5E-04	lb	D
Carbon Tetrachloride	5.8E-06	lb	D
Phenols	1.3E-04	lb	D
Fluorides	1.9E-05	lb	D
Polyaromatic Hydrocarbons (total)	2.1E-05	lb	E
Biphenyl	3.6E-07	lb	E
Acenaphthene	1.1E-07	lb	E
Acenaphthylene	5.2E-08	lb	E
Anthracene	4.4E-08	lb	E
Benzo(a)anthracene	1.7E-08	lb	E
Benzo(a)pyrene	7.9E-09	lb	E

Table A-12a (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Atmospheric Emissions (cont)			**DQI**
Benzo(b,j,k)fluroanthene	2.3E-08	lb	E
Benzo(g,h,i) perylene	5.6E-09	lb	E
Chrysene	2.1E-08	lb	E
Fluoranthene	1.5E-07	lb	E
Fluorene	1.9E-07	lb	E
Indeno(1,2,3-cd)pyrene	1.3E-08	lb	E
Naphthalene	2.7E-06	lb	E
Phenanthrene	5.6E-07	lb	E
Pyrene	6.9E-08	lb	E
5-methyl Chrysene	4.6E-09	lb	E
Dioxins (unspecified)	2.1E-07	lb	D
Furans (unspecified)	9.5E-10	lb	D
CFC12	9.6E-07	lb	D
Radionuclides (unspecified)	0.018	Ci	C
Waterborne Emissions			
Acid (unspecified)	0.0020	lb	E
Acid (benzoic)	0.033	lb	E
Acid (hexanoic)	0.0068	lb	E
Metal (unspecified)	25.5	lb	E
Dissolved Solids	1,443	lb	E
Suspended Solids	85.8	lb	E
BOD	0.82	lb	E
COD	2.42	lb	E
Phenol/Phenolic Compounds	0.016	lb	E
Sulfur	0.086	lb	E
Sulfates	2.58	lb	E
Sulfides	0.0016	lb	E
Oil	0.74	lb	E
Hydrocarbons	0.0065	lb	E
Ammonia	0.59	lb	E
Ammonium	1.4E-04	lb	E
Aluminum	2.79	lb	E
Antimony	0.0017	lb	E
Arsenic	0.0089	lb	E
Barium	38.2	lb	E
Beryllium	4.9E-04	lb	E
Cadmium	0.0013	lb	E
Chromium (unspecified)	0.079	lb	E
Cobalt	7.2E-04	lb	E
Copper	0.0091	lb	E
Iron	5.56	lb	E
Lead	0.019	lb	E
Lithium	1.80	lb	E
Magnesium	20.3	lb	E
Manganese	0.035	lb	E
Mercury	3.1E-05	lb	E
Molybdenum	7.4E-04	lb	E
Nickel	0.0087	lb	E
Selenium	3.9E-04	lb	E
Silver	0.068	lb	E

Table A-12a (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Waterborne Emissions (cont)			**DQI**
Sodium	330	lb	E
Strontium	1.77	lb	E
Thallium	3.7E-04	lb	E
Tin	0.0071	lb	E
Titanium	0.027	lb	E
Vanadium	8.8E-04	lb	E
Yttrium	2.2E-04	lb	E
Zinc	0.064	lb	E
Chlorides (unspecified)	1,170	lb	E
Chlorides (methyl chloride)	1.3E-06	lb	E
Calcium	104	lb	E
Fluorine/ Fluorides	0.0023	lb	E
Nitrates	3.5E-04	lb	E
Nitrogen (ammonia)	1.2E-04	lb	E
Bromide	6.94	lb	E
Boron	0.10	lb	E
Organic Carbon	0.0083	lb	E
Cyanide	2.3E-06	lb	E
Hardness	321	lb	E
Total Alkalinity	2.55	lb	E
Surfactants	0.027	lb	E
Acetone	3.2E-04	lb	E
Alkylated Benzenes	0.0015	lb	E
Alkylated Fluorenes	8.9E-05	lb	E
Alkylated Naphthalenes	2.5E-05	lb	E
Alkylated Phenanthrenes	1.0E-05	lb	E
Benzene	0.054	lb	E
Cresols	0.0019	lb	E
Cymene	3.2E-06	lb	E
Dibenzofuran	6.2E-06	lb	E
Dibenzothiophene	5.0E-06	lb	E
2,4 dimethylphenol	9.1E-04	lb	E
Ethylbenzene	0.0031	lb	E
2-Hexanone	2.1E-04	lb	E
Methyl ethyl Ketone (MEK)	2.6E-06	lb	E
1-methylfluorene	3.7E-06	lb	E
2-methyl naphthalene	5.1E-04	lb	E
4-methyl-2-pentanone	1.4E-04	lb	E
Naphthalene	5.9E-04	lb	E
Pentamethyl benzene	2.4E-06	lb	E
Phenanthrene	9.0E-06	lb	E
Toluene	0.051	lb	E
Total Biphenyls	9.9E-05	lb	E
Total dibenzo-thiophenes	3.1E-07	lb	E
Xylenes	0.027	lb	E
Radionuclides (unspecified)	2.5E-07	Ci	E
Solid Waste	421	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-12b

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF DISTILLATE FUEL OIL

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	351	lb	B
Coal - Lignite	32.6	lb	B
Natural gas	7,431	cuft	B
Residual oil	49.2	gal	B
Distillate oil	6.11	gal	B
Gasoline	0.73	gal	B
Liquefied petroleum gas	1.06	gal	B
Uranium (nuclear power)	0.0010	lb	B
Hydropower	190,533	Btu	B
Other renewable energy	83,477	Btu	B
Wood and wood wastes	117,152	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	2.49	lb	C
Particulates (PM10)	0.64	lb	D
Nitrogen Oxides	25.0	lb	C
Hydrocarbons (unspecified)	15.6	lb	D
VOC (unspecified)	0.99	lb	D
TNMOC (unspecified)	0.021	lb	C
Sulfur Dioxide	14.0	lb	C
Sulfur Oxides	21.5	lb	C
Carbon Monoxide	106	lb	C
Fossil CO2	3,258	lb	C
Non-Fossil CO2	22.8	lb	D
Aldehydes (Formaldehyde)	0.0022	lb	C
Aldehydes (Acetaldehyde)	1.7E-04	lb	D
Aldehydes (Propionaldehyde)	3.9E-08	lb	D
Aldehydes (unspecified)	0.32	lb	C
Organics (unspecified)	0.0012	lb	D
Ammonia	0.16	lb	D
Ammonia Chloride	1.6E-04	lb	D
Methane	34.9	lb	C
Kerosene	2.9E-04	lb	D
Chlorine	9.3E-05	lb	D
HCl	0.25	lb	C
HF	0.029	lb	C
Metals (unspecified)	0.0050	lb	D
Mercaptan	2.1E-05	lb	D
Antimony	4.4E-06	lb	C
Arsenic	1.2E-04	lb	C
Beryllium	5.7E-06	lb	C
Cadmium	3.0E-05	lb	C
Chromium (VI)	1.5E-05	lb	C
Chromium	8.7E-05	lb	D
Cobalt	1.9E-04	lb	C
Copper	1.4E-06	lb	D
Lead	1.3E-04	lb	C
Magnesium	0.0021	lb	C
Manganese	3.7E-04	lb	C

Table A-12b (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF DISTILLATE FUEL OIL

Atmospheric Emissions (cont)			**DQI**
Mercury	2.2E-05	lb	C
Nickel	0.0024	lb	C
Selenium	2.7E-04	lb	C
Zinc	9.3E-07	lb	D
Acetophenone	1.5E-09	lb	D
Acrolein	5.3E-04	lb	D
Nitrous Oxide	0.060	lb	C
Benzene	0.034	lb	D
Benzyl Chloride	7.2E-08	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09	lb	D
1,3 Butadiene	3.7E-06	lb	D
2-Chloroacetophenone	7.2E-10	lb	D
Chlorobenzene	2.3E-09	lb	D
2,4-Dinitrotoluene	2.9E-11	lb	D
Ethyl Chloride	4.3E-09	lb	D
Ethylbenzene	0.0039	lb	D
Ethylene Dibromide	1.2E-10	lb	D
Ethylene Dichloride	4.1E-09	lb	D
Hexane	6.9E-09	lb	D
Isophorone ($C_9H_{14}O$)	5.9E-08	lb	D
Methyl Bromide	1.6E-08	lb	D
Methyl Chloride	5.4E-08	lb	D
Methyl Ethyl Ketone	4.0E-08	lb	D
Methyl Hydrazine	1.7E-08	lb	D
Methyl Methacrylate	2.1E-09	lb	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09	lb	D
Naphthalene	4.7E-05	lb	D
Propylene	2.4E-04	lb	D
Styrene	2.6E-09	lb	D
Toluene	0.051	lb	D
Trichloroethane	7.5E-07	lb	D
Vinyl Acetate	7.8E-10	lb	D
Xylenes	0.030	lb	D
Bromoform	4.0E-09	lb	D
Chloroform	6.1E-09	lb	D
Carbon Disulfide	1.3E-08	lb	D
Dimethyl Sulfate	4.9E-09	lb	D
Cumene	5.4E-10	lb	D
Cyanide	2.6E-07	lb	D
Perchloroethylene	1.0E-05	lb	D
Methylene Chloride	2.3E-04	lb	D
Carbon Tetrachloride	5.4E-06	lb	D
Phenols	1.2E-04	lb	D
Fluorides	1.8E-05	lb	D
Polyaromatic Hydrocarbons (total)	2.0E-05	lb	E
Biphenyl	3.3E-07	lb	E
Acenaphthene	9.8E-08	lb	E
Acenaphthylene	4.8E-08	lb	E
Anthracene	4.0E-08	lb	E
Benzo(a)anthracene	1.5E-08	lb	E
Benzo(a)pyrene	7.3E-09	lb	E

Table A-12b (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF DISTILLATE FUEL OIL

Atmospheric Emissions (cont)			**DQI**
Benzo(b,j,k)fluroanthene	2.1E-08	lb	E
Benzo(g,h,i) perylene	5.2E-09	lb	E
Chrysene	1.9E-08	lb	E
Fluoranthene	1.4E-07	lb	E
Fluorene	1.7E-07	lb	E
Naphthalene	2.5E-06	lb	E
Phenanthrene	5.2E-07	lb	E
Pyrene	6.3E-08	lb	E
5-methyl Chrysene	4.2E-09	lb	E
Dioxins (unspecified)	2.0E-07	lb	D
Furans (unspecified)	8.7E-10	lb	D
CFC12	8.9E-07	lb	D
Radionuclides (unspecified)	0.016	Ci	C
Waterborne Emissions			
Acid (unspecified)	0.0018	lb	E
Acid (benzoic)	0.030	lb	E
Acid (hexanoic)	0.0062	lb	E
Metal (unspecified)	23.4	lb	E
Dissolved Solids	1,325	lb	E
Suspended Solids	78.8	lb	E
BOD	0.75	lb	E
COD	2.22	lb	E
Phenol/Phenolic Compounds	0.015	lb	E
Sulfur	0.079	lb	E
Sulfates	2.37	lb	E
Sulfides	0.0014	lb	E
Oil	0.68	lb	E
Hydrocarbons	0.0059	lb	E
Ammonia	0.54	lb	E
Ammonium	1.3E-04	lb	E
Aluminum	2.56	lb	E
Antimony	0.0016	lb	E
Arsenic	0.0081	lb	E
Barium	35.1	lb	E
Beryllium	4.5E-04	lb	E
Cadmium	0.0012	lb	E
Chromium (unspecified)	0.073	lb	E
Cobalt	6.6E-04	lb	E
Copper	0.0084	lb	E
Iron	5.11	lb	E
Lead	0.017	lb	E
Lithium	1.65	lb	E
Magnesium	18.7	lb	E
Manganese	0.032	lb	E
Mercury	2.8E-05	lb	E
Molybdenum	6.8E-04	lb	E
Nickel	0.0080	lb	E
Selenium	3.5E-04	lb	E
Silver	0.062	lb	E
Sodium	303	lb	E

Table A-12b (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF DISTILLATE FUEL OIL

Waterborne Emissions (cont)			**DQI**
Strontium	1.62	lb	E
Thallium	3.4E-04	lb	E
Tin	0.0065	lb	E
Titanium	0.025	lb	E
Vanadium	8.1E-04	lb	E
Yttrium	2.0E-04	lb	E
Zinc	0.059	lb	E
Chlorides (unspecified)	1,074	lb	E
Chlorides (methyl chloride)	1.2E-06	lb	E
Calcium	95.5	lb	E
Fluorine/ Fluorides	0.0021	lb	E
Nitrates	3.2E-04	lb	E
Nitrogen (ammonia)	1.1E-04	lb	E
Bromide	6.37	lb	E
Boron	0.093	lb	E
Organic Carbon	0.0076	lb	E
Cyanide	2.1E-06	lb	E
Hardness	294	lb	E
Total Alkalinity	2.34	lb	E
Surfactants	0.025	lb	E
Acetone	3.0E-04	lb	E
Alkylated Benzenes	0.0014	lb	E
Alkylated Fluorenes	8.1E-05	lb	E
Alkylated Naphthalenes	2.3E-05	lb	E
Alkylated Phenanthrenes	9.5E-06	lb	E
Benzene	0.050	lb	E
Cresols	0.0018	lb	E
Cymene	3.0E-06	lb	E
Dibenzofuran	5.7E-06	lb	E
Dibenzothiophene	4.6E-06	lb	E
2,4 dimethylphenol	8.3E-04	lb	E
Ethylbenzene	0.0028	lb	E
2-Hexanone	1.9E-04	lb	E
Methyl ethyl Ketone (MEK)	2.4E-06	lb	E
1-methylfluorene	3.4E-06	lb	E
2-methyl naphthalene	4.7E-04	lb	E
4-methyl-2-pentanone	1.2E-04	lb	E
Naphthalene	5.4E-04	lb	E
Pentamethyl benzene	2.2E-06	lb	E
Phenanthrene	8.2E-06	lb	E
Toluene	0.047	lb	E
Total Biphenyls	9.1E-05	lb	E
total dibenzo- thiophenes	2.8E-07	lb	E
Xylenes	0.025	lb	E
Radionuclides (unspecified)	2.3E-07	Ci	E
Solid Waste	387	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-12c

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF GASOLINE

Total Precombustion Fuel Use and Process Energy			**DQI**
	United States		
Coal - Bituminous	299	lb	B
Coal - Lignite	27.8	lb	B
Natural gas	6,332	cuft	B
Residual oil	41.9	gal	B
Distillate oil	5.21	gal	B
Gasoline	0.63	gal	B
Liquefied petroleum gas	0.91	gal	B
Uranium (nuclear power)	8.8E-04	lb	B
Hydropower	162,363	Btu	B
Other renewable energy	71,135	Btu	B
Wood and wood wastes	99,831	Btu	B
Precombustion Emissions			
Atmospheric Emissions			**DQI**
Particulates (unspecified)	2.12	lb	C
Particulates (PM10)	0.55	lb	D
Nitrogen Oxides	21.3	lb	C
Hydrocarbons (unspecified)	13.3	lb	D
VOC (unspecified)	0.85	lb	D
TNMOC (unspecified)	0.018	lb	C
Sulfur Dioxide	11.9	lb	C
Sulfur Oxides	18.3	lb	C
Carbon Monoxide	90.0	lb	C
Fossil CO2	2,776	lb	C
Non-Fossil CO2	19.5	lb	D
Aldehydes (Formaldehyde)	0.0019	lb	C
Aldehydes (Acetaldehyde)	1.5E-04	lb	D
Aldehydes (Propionaldehyde)	3.3E-08	lb	D
Aldehydes (unspecified)	0.28	lb	C
Organics (unspecified)	0.0010	lb	D
Ammonia	0.14	lb	D
Ammonia Chloride	1.4E-04	lb	D
Methane	29.8	lb	C
Kerosene	2.4E-04	lb	D
Chlorine	7.9E-05	lb	D
HCl	0.22	lb	C
HF	0.025	lb	C
Metals (unspecified)	0.0043	lb	D
Mercaptan	1.8E-05	lb	D
Antimony	3.7E-06	lb	C
Arsenic	1.0E-04	lb	C
Beryllium	4.9E-06	lb	C
Cadmium	2.6E-05	lb	C
Chromium (VI)	1.3E-05	lb	C
Chromium	7.4E-05	lb	D
Cobalt	1.6E-04	lb	C
Copper	1.2E-06	lb	D
Lead	1.1E-04	lb	C
Magnesium	0.0018	lb	C
Manganese	3.1E-04	lb	C

Table A-12c (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF GASOLINE

Atmospheric Emissions (cont)			**DQI**
Mercury	1.9E-05	lb	C
Nickel	0.0021	lb	C
Selenium	2.3E-04	lb	C
Zinc	7.9E-07	lb	D
Acetophenone	1.3E-09	lb	D
Acrolein	4.5E-04	lb	D
Nitrous Oxide	0.051	lb	C
Benzene	0.029	lb	D
Benzyl Chloride	6.1E-08	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	6.4E-09	lb	D
1,3 Butadiene	3.1E-06	lb	D
2-Chloroacetophenone	6.1E-10	lb	D
Chlorobenzene	1.9E-09	lb	D
2,4-Dinitrotoluene	2.4E-11	lb	D
Ethyl Chloride	3.7E-09	lb	D
Ethylbenzene	0.0034	lb	D
Ethylene Dibromide	1.0E-10	lb	D
Ethylene Dichloride	3.5E-09	lb	D
Hexane	5.9E-09	lb	D
Isophorone ($C_9H_{14}O$)	5.1E-08	lb	D
Methyl Bromide	1.4E-08	lb	D
Methyl Chloride	4.6E-08	lb	D
Methyl Ethyl Ketone	3.4E-08	lb	D
Methyl Hydrazine	1.5E-08	lb	D
Methyl Methacrylate	1.7E-09	lb	D
Methyl Tert Butyl Ether (MTBE)	3.1E-09	lb	D
Naphthalene	4.0E-05	lb	D
Propylene	2.1E-04	lb	D
Styrene	2.2E-09	lb	D
Toluene	0.043	lb	D
Trichloroethane	6.4E-07	lb	D
Vinyl Acetate	6.6E-10	lb	D
Xylenes	0.025	lb	D
Bromoform	3.4E-09	lb	D
Chloroform	5.2E-09	lb	D
Carbon Disulfide	1.1E-08	lb	D
Dimethyl Sulfate	4.2E-09	lb	D
Cumene	4.6E-10	lb	D
Cyanide	2.2E-07	lb	D
Perchloroethylene	8.8E-06	lb	D
Methylene Chloride	2.0E-04	lb	D
Carbon Tetrachloride	4.6E-06	lb	D
Phenols	9.8E-05	lb	D
Fluorides	1.5E-05	lb	D
Polyaromatic Hydrocarbons (total)	1.7E-05	lb	E
Biphenyl	2.8E-07	lb	E
Acenaphthene	8.3E-08	lb	E
Acenaphthylene	4.1E-08	lb	E
Anthracene	3.4E-08	lb	E
Benzo(a)anthracene	1.3E-08	lb	E
Benzo(a)pyrene	6.2E-09	lb	E

Table A-12c (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF GASOLINE

			DQI
Atmospheric Emissions (cont)			
Benzo(b,j,k)fluroanthene	1.8E-08	lb	E
Benzo(g,h,i) perylene	4.4E-09	lb	E
Chrysene	1.6E-08	lb	E
Fluoranthene	1.2E-07	lb	E
Fluorene	1.5E-07	lb	E
Indeno(1,2,3-cd)pyrene	1.0E-08	lb	E
Naphthalene	2.1E-06	lb	E
Phenanthrene	4.4E-07	lb	E
Pyrene	5.4E-08	lb	E
5-methyl Chrysene	3.6E-09	lb	E
Dioxins (unspecified)	1.7E-07	lb	D
Furans (unspecified)	7.4E-10	lb	D
CFC12	7.5E-07	lb	D
Radionuclides (unspecified)	0.014	Ci	C
Waterborne Emissions			
Acid (unspecified)	0.0016	lb	E
Acid (benzoic)	0.026	lb	E
Acid (hexanoic)	0.0053	lb	E
Metal (unspecified)	20.0	lb	E
Dissolved Solids	1,129	lb	E
Suspended Solids	67.1	lb	E
BOD	0.64	lb	E
COD	1.89	lb	E
Phenol/Phenolic Compounds	0.013	lb	E
Sulfur	0.067	lb	E
Sulfates	2.02	lb	E
Sulfides	0.0012	lb	E
Oil	0.58	lb	E
Hydrocarbons	0.0051	lb	E
Ammonia	0.46	lb	E
Ammonium	1.1E-04	lb	E
Aluminum	2.18	lb	E
Antimony	0.0014	lb	E
Arsenic	0.0069	lb	E
Barium	29.9	lb	E
Beryllium	3.9E-04	lb	E
Cadmium	0.0010	lb	E
Chromium (unspecified)	0.062	lb	E
Cobalt	5.6E-04	lb	E
Copper	0.0071	lb	E
Iron	4.35	lb	E
Lead	0.015	lb	E
Lithium	1.41	lb	E
Magnesium	15.9	lb	E
Manganese	0.028	lb	E
Mercury	2.4E-05	lb	E
Molybdenum	5.8E-04	lb	E
Nickel	0.0068	lb	E
Selenium	3.0E-04	lb	E
Silver	0.053	lb	E

Table A-12c (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF GASOLINE

Waterborne Emissions (cont)			**DQI**
Sodium	258	lb	E
Strontium	1.38	lb	E
Thallium	2.9E-04	lb	E
Tin	0.0055	lb	E
Titanium	0.021	lb	E
Vanadium	6.9E-04	lb	E
Yttrium	1.7E-04	lb	E
Zinc	0.050	lb	E
Chlorides (unspecified)	915	lb	E
Chlorides (methyl chloride)	1.0E-06	lb	E
Calcium	81.4	lb	E
Fluorine/ Fluorides	0.0018	lb	E
Nitrates	2.7E-04	lb	E
Nitrogen (ammonia)	9.5E-05	lb	E
Bromide	5.43	lb	E
Boron	0.080	lb	E
Organic Carbon	0.0065	lb	E
Cyanide	1.8E-06	lb	E
Hardness	251	lb	E
Total Alkalinity	2.00	lb	E
Surfactants	0.021	lb	E
Acetone	2.5E-04	lb	E
Alkylated Benzenes	0.0012	lb	E
Alkylated Fluorenes	6.9E-05	lb	E
Alkylated Naphthalenes	2.0E-05	lb	E
Alkylated Phenanthrenes	8.1E-06	lb	E
Benzene	0.043	lb	E
Cresols	0.0015	lb	E
Cymene	2.5E-06	lb	E
Dibenzofuran	4.8E-06	lb	E
Dibenzothiophene	3.9E-06	lb	E
2,4-dimethylphenol	7.1E-04	lb	E
Ethylbenzene	0.0024	lb	E
2-Hexanone	1.7E-04	lb	E
Methyl ethyl Ketone (MEK)	2.0E-06	lb	E
1-methylfluorene	2.9E-06	lb	E
2-methyl naphthalene	4.0E-04	lb	E
4-methyl-2-pentanone	1.1E-04	lb	E
Naphthalene	4.6E-04	lb	E
Pentamethyl benzene	1.9E-06	lb	E
Phenanthrene	7.0E-06	lb	E
Toluene	0.040	lb	E
Total Biphenyls	7.7E-05	lb	E
Total dibenzo-thiophenes	2.4E-07	lb	E
Xylenes	0.021	lb	E
Radionuclides (unspecified)	1.9E-07	Ci	E
Solid Waste	330	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-12d

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	219	lb	B
Coal - Lignite	20.4	lb	B
Natural gas	4,645	cuft	B
Residual oil	30.7	gal	B
Distillate oil	3.82	gal	B
Gasoline	0.46	gal	B
Liquefied petroleum gas	0.66	gal	B
Uranium (nuclear power)	6.5E-04	lb	B
Hydropower	119,106	Btu	B
Other renewable energy	52,183	Btu	B
Wood and wood wastes	73,234	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	1.56	lb	C
Particulates (PM10)	0.40	lb	D
Nitrogen Oxides	15.7	lb	C
Hydrocarbons (unspecified)	9.76	lb	D
VOC (unspecified)	0.62	lb	D
TNMOC (unspecified)	0.013	lb	C
Sulfur Dioxide	8.74	lb	C
Sulfur Oxides	13.4	lb	C
Carbon Monoxide	66.1	lb	C
Fossil CO2	2,037	lb	C
Non-Fossil CO2	14.3	lb	D
Aldehydes (Formaldehyde)	0.0014	lb	C
Aldehydes (Acetaldehyde)	1.1E-04	lb	D
Aldehydes (Propionaldehyde)	2.4E-08	lb	D
Aldehydes (unspecified)	0.20	lb	C
Organics (unspecified)	7.3E-04	lb	D
Ammonia	0.10	lb	D
Ammonia Chloride	9.9E-05	lb	D
Methane	21.8	lb	C
Kerosene	1.8E-04	lb	D
Chlorine	5.8E-05	lb	D
HCl	0.16	lb	C
HF	0.018	lb	C
Metals (unspecified)	0.0031	lb	D
Mercaptan	1.3E-05	lb	D
Antimony	2.7E-06	lb	C
Arsenic	7.5E-05	lb	C
Beryllium	3.6E-06	lb	C
Cadmium	1.9E-05	lb	C
Chromium (VI)	9.5E-06	lb	C
Chromium	5.4E-05	lb	D
Cobalt	1.2E-04	lb	C
Copper	8.7E-07	lb	D
Lead	8.4E-05	lb	C
Magnesium	0.0013	lb	C
Manganese	2.3E-04	lb	C

Table A-12d (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Atmospheric Emissions (cont)		**DQI**
Mercury	1.4E-05 lb	C
Nickel	0.0015 lb	C
Selenium	1.7E-04 lb	C
Zinc	5.8E-07 lb	D
Acetophenone	9.6E-10 lb	D
Acrolein	3.3E-04 lb	D
Nitrous Oxide	0.038 lb	C
Benzene	0.021 lb	D
Benzyl Chloride	4.5E-08 lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	4.7E-09 lb	D
1,3 Butadiene	2.3E-06 lb	D
2-Chloroacetophenone	4.5E-10 lb	D
Chlorobenzene	1.4E-09 lb	D
2,4-Dinitrotoluene	1.8E-11 lb	D
Ethyl Chloride	2.7E-09 lb	D
Ethylbenzene	0.0025 lb	D
Ethylene Dibromide	7.7E-11 lb	D
Ethylene Dichloride	2.6E-09 lb	D
Hexane	4.3E-09 lb	D
Isophorone ($C_9H_{14}O$)	3.7E-08 lb	D
Methyl Bromide	1.0E-08 lb	D
Methyl Chloride	3.4E-08 lb	D
Methyl Ethyl Ketone	2.5E-08 lb	D
Methyl Hydrazine	1.1E-08 lb	D
Methyl Methacrylate	1.3E-09 lb	D
Methyl Tert Butyl Ether (MTBE)	2.2E-09 lb	D
Naphthalene	3.0E-05 lb	D
Propylene	1.5E-04 lb	D
Styrene	1.6E-09 lb	D
Toluene	0.032 lb	D
Trichloroethane	4.7E-07 lb	D
Vinyl Acetate	4.9E-10 lb	D
Xylenes	0.019 lb	D
Bromoform	2.5E-09 lb	D
Chloroform	3.8E-09 lb	D
Carbon Disulfide	8.3E-09 lb	D
Dimethyl Sulfate	3.1E-09 lb	D
Cumene	3.4E-10 lb	D
Cyanide	1.6E-07 lb	D
Perchloroethylene	6.5E-06 lb	D
Methylene Chloride	1.5E-04 lb	D
Carbon Tetrachloride	3.4E-06 lb	D
Phenols	7.2E-05 lb	D
Fluorides	1.1E-05 lb	D
Polyaromatic Hydrocarbons (total)	1.2E-05 lb	E
Biphenyl	2.0E-07 lb	E
Acenaphthene	6.1E-08 lb	E
Acenaphthylene	3.0E-08 lb	E
Anthracene	2.5E-08 lb	E
Benzo(a)anthracene	9.6E-09 lb	E
Benzo(a)pyrene	4.6E-09 lb	E

Table A-12d (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Atmospheric Emissions (cont)			**DQI**
Benzo(b,j,k)fluroanthene	1.3E-08	lb	E
Benzo(g,h,i) perylene	3.2E-09	lb	E
Chrysene	1.2E-08	lb	E
Fluoranthene	8.5E-08	lb	E
Fluorene	1.1E-07	lb	E
Indeno(1,2,3-cd)pyrene	7.3E-09	lb	E
Naphthalene	1.6E-06	lb	E
Phenanthrene	3.2E-07	lb	E
Pyrene	4.0E-08	lb	E
5-methyl Chrysene	2.6E-09	lb	E
Dioxins (unspecified)	1.2E-07	lb	D
Furans (unspecified)	5.5E-10	lb	D
CFC12	5.5E-07	lb	D
Radionuclides (unspecified)	0.010	Ci	C
Waterborne Emissions			
Acid (unspecified)	0.0012	lb	E
Acid (benzoic)	0.019	lb	E
Acid (hexanoic)	0.0039	lb	E
Metal (unspecified)	14.6	lb	E
Dissolved Solids	828	lb	E
Suspended Solids	49.2	lb	E
BOD	0.47	lb	E
COD	1.39	lb	E
Phenol/Phenolic Compounds	0.0094	lb	E
Sulfur	0.049	lb	E
Sulfates	1.48	lb	E
Sulfides	8.9E-04	lb	E
Oil	0.43	lb	E
Hydrocarbons	0.0037	lb	E
Ammonia	0.34	lb	E
Ammonium	8.0E-05	lb	E
Aluminum	1.60	lb	E
Antimony	0.0010	lb	E
Arsenic	0.0051	lb	E
Barium	21.9	lb	E
Beryllium	2.8E-04	lb	E
Cadmium	7.5E-04	lb	E
Chromium (unspecified)	0.045	lb	E
Cobalt	4.1E-04	lb	E
Copper	0.0052	lb	E
Iron	3.19	lb	E
Lead	0.011	lb	E
Lithium	1.03	lb	E
Magnesium	11.7	lb	E
Manganese	0.020	lb	E
Mercury	1.8E-05	lb	E
Molybdenum	4.3E-04	lb	E
Nickel	0.0050	lb	E
Selenium	2.2E-04	lb	E
Silver	0.039	lb	E

Table A-12d (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Waterborne Emissions (cont)			**DQI**
Sodium	189	lb	E
Strontium	1.01	lb	E
Thallium	2.1E-04	lb	E
Tin	0.0041	lb	E
Titanium	0.015	lb	E
Vanadium	5.0E-04	lb	E
Yttrium	1.3E-04	lb	E
Zinc	0.037	lb	E
Chlorides (unspecified)	671	lb	E
Chlorides (methyl chloride)	7.5E-07	lb	E
Calcium	59.7	lb	E
Fluorine/ Fluorides	0.0013	lb	E
Nitrates	2.0E-04	lb	E
Nitrogen (ammonia)	6.9E-05	lb	E
Bromide	3.98	lb	E
Boron	0.058	lb	E
Organic Carbon	0.0048	lb	E
Cyanide	1.3E-06	lb	E
Hardness	184	lb	E
Total Alkalinity	1.47	lb	E
Surfactants	0.016	lb	E
Acetone	1.9E-04	lb	E
Alkylated Benzenes	8.8E-04	lb	E
Alkylated Fluorenes	5.1E-05	lb	E
Alkylated Naphthalenes	1.4E-05	lb	E
Alkylated Phenanthrenes	6.0E-06	lb	E
Benzene	0.031	lb	E
Cresols	0.0011	lb	E
Cymene	1.9E-06	lb	E
Dibenzofuran	3.5E-06	lb	E
Dibenzothiophene	2.9E-06	lb	E
2,4 dimethylphenol	5.2E-04	lb	E
Ethylbenzene	0.0018	lb	E
2-Hexanone	1.2E-04	lb	E
Methyl ethyl Ketone (MEK)	1.5E-06	lb	E
1-methylfluorene	2.1E-06	lb	E
2-methyl naphthalene	2.9E-04	lb	E
4-methyl-2-pentanone	7.8E-05	lb	E
Naphthalene	3.4E-04	lb	E
Pentamethyl benzene	1.4E-06	lb	E
Phenanthrene	5.2E-06	lb	E
Toluene	0.029	lb	E
Total Biphenyls	5.7E-05	lb	E
total dibenzo- thiophenes	1.8E-07	lb	E
Xylenes	0.016	lb	E
Radionuclides (unspecified)	1.4E-07	Ci	E
Solid Waste	242	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-12e

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED KEROSENE

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	327	lb	B
Coal - Lignite	30.4	lb	B
Natural gas	6,932	cuft	B
Residual oil	45.9	gal	B
Distillate oil	5.70	gal	B
Gasoline	0.69	gal	B
Liquefied petroleum gas	0.99	gal	B
Uranium (nuclear power)	9.6E-04	lb	B
Hydropower	177,738	Btu	B
Other renewable energy	77,871	Btu	B
Wood and wood wastes	109,285	Btu	B

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	2.32	lb	C
Particulates (PM10)	0.60	lb	D
Nitrogen Oxides	23.4	lb	C
Hydrocarbons (unspecified)	14.6	lb	D
VOC (unspecified)	0.93	lb	D
TNMOC (unspecified)	0.020	lb	C
Sulfur Dioxide	13.0	lb	C
Sulfur Oxides	20.0	lb	C
Carbon Monoxide	98.6	lb	C
Fossil CO2	3,039	lb	C
Non-Fossil CO2	21.3	lb	D
Aldehydes (Formaldehyde)	0.0021	lb	C
Aldehydes (Acetaldehyde)	1.6E-04	lb	D
Aldehydes (Propionaldehyde)	3.6E-08	lb	D
Aldehydes (unspecified)	0.30	lb	C
Organics (unspecified)	0.0011	lb	D
Ammonia	0.15	lb	D
Ammonia Chloride	1.5E-04	lb	D
Methane	32.6	lb	C
Kerosene	2.7E-04	lb	D
Chlorine	8.6E-05	lb	D
HCl	0.24	lb	C
HF	0.027	lb	C
Metals (unspecified)	0.0047	lb	D
Mercaptan	1.9E-05	lb	D
Antimony	4.1E-06	lb	C
Arsenic	1.1E-04	lb	C
Beryllium	5.3E-06	lb	C
Cadmium	2.8E-05	lb	C
Chromium (VI)	1.4E-05	lb	C
Chromium	8.1E-05	lb	D
Cobalt	1.7E-04	lb	C
Copper	1.3E-06	lb	D
Lead	1.3E-04	lb	C
Magnesium	0.0020	lb	C
Manganese	3.4E-04	lb	C

Table A-12e (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED KEROSENE

Atmospheric Emissions (cont)		**DQI**
Mercury	2.1E-05 lb	C
Nickel	0.0022 lb	C
Selenium	2.5E-04 lb	C
Zinc	8.7E-07 lb	D
Acetophenone	1.4E-09 lb	D
Acrolein	5.0E-04 lb	D
Nitrous Oxide	0.056 lb	C
Benzene	0.032 lb	D
Benzyl Chloride	6.7E-08 lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.0E-09 lb	D
1,3 Butadiene	3.4E-06 lb	D
2-Chloroacetophenone	6.7E-10 lb	D
Chlorobenzene	2.1E-09 lb	D
2,4-Dinitrotoluene	2.7E-11 lb	D
Ethyl Chloride	4.0E-09 lb	D
Ethylbenzene	0.0037 lb	D
Ethylene Dibromide	1.1E-10 lb	D
Ethylene Dichloride	3.8E-09 lb	D
Hexane	6.4E-09 lb	D
Isophorone ($C_9H_{14}O$)	5.5E-08 lb	D
Methyl Bromide	1.5E-08 lb	D
Methyl Chloride	5.1E-08 lb	D
Methyl Ethyl Ketone	3.7E-08 lb	D
Methyl Hydrazine	1.6E-08 lb	D
Methyl Methacrylate	1.9E-09 lb	D
Methyl Tert Butyl Ether (MTBE)	3.3E-09 lb	D
Naphthalene	4.4E-05 lb	D
Propylene	2.2E-04 lb	D
Styrene	2.4E-09 lb	D
Toluene	0.048 lb	D
Trichloroethane	7.0E-07 lb	D
Vinyl Acetate	7.3E-10 lb	D
Xylenes	0.028 lb	D
Bromoform	3.7E-09 lb	D
Chloroform	5.6E-09 lb	D
Carbon Disulfide	1.2E-08 lb	D
Dimethyl Sulfate	4.6E-09 lb	D
Cumene	5.1E-10 lb	D
Cyanide	2.4E-07 lb	D
Perchloroethylene	9.6E-06 lb	D
Methylene Chloride	2.2E-04 lb	D
Carbon Tetrachloride	5.0E-06 lb	D
Phenols	1.1E-04 lb	D
Fluorides	1.7E-05 lb	D
Polyaromatic Hydrocarbons (total)	1.8E-05 lb	E
Biphenyl	3.0E-07 lb	E
Acenaphthene	9.1E-08 lb	E
Acenaphthylene	4.5E-08 lb	E
Anthracene	3.8E-08 lb	E
Benzo(a)anthracene	1.4E-08 lb	E
Benzo(a)pyrene	6.8E-09 lb	E

Table A-12e (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED KEROSENE

			DQI
Atmospheric Emissions (cont)			
Benzo(b,j,k)fluroanthene	2.0E-08	lb	E
Benzo(g,h,i) perylene	4.8E-09	lb	E
Chrysene	1.8E-08	lb	E
Fluoranthene	1.3E-07	lb	E
Fluorene	1.6E-07	lb	E
Indeno(1,2,3-cd)pyrene	1.1E-08	lb	E
Naphthalene	2.3E-06	lb	E
Phenanthrene	4.8E-07	lb	E
Pyrene	5.9E-08	lb	E
5-methyl Chrysene	3.9E-09	lb	E
Dioxins (unspecified)	1.8E-07	lb	D
Furans (unspecified)	8.2E-10	lb	D
CFC12	8.3E-07	lb	D
Radionuclides (unspecified)	0.015	Ci	C
Waterborne Emissions			
Acid (unspecified)	0.0017	lb	E
Acid (benzoic)	0.028	lb	E
Acid (hexanoic)	0.0058	lb	E
Metal (unspecified)	21.9	lb	E
Dissolved Solids	1,236	lb	E
Suspended Solids	73.5	lb	E
BOD	0.70	lb	E
COD	2.07	lb	E
Phenol/Phenolic Compounds	0.014	lb	E
Sulfur	0.073	lb	E
Sulfates	2.21	lb	E
Sulfides	0.0013	lb	E
Oil	0.64	lb	E
Hydrocarbons	0.0055	lb	E
Ammonia	0.51	lb	E
Ammonium	1.2E-04	lb	E
Aluminum	2.39	lb	E
Antimony	0.0015	lb	E
Arsenic	0.0076	lb	E
Barium	32.7	lb	E
Beryllium	4.2E-04	lb	E
Cadmium	0.0011	lb	E
Chromium (unspecified)	0.068	lb	E
Cobalt	6.1E-04	lb	E
Copper	0.0078	lb	E
Iron	4.77	lb	E
Lead	0.016	lb	E
Lithium	1.54	lb	E
Magnesium	17.4	lb	E
Manganese	0.030	lb	E
Mercury	2.6E-05	lb	E
Molybdenum	6.4E-04	lb	E
Nickel	0.0075	lb	E
Selenium	3.3E-04	lb	E
Silver	0.058	lb	E

Table A-12e (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED KEROSENE

Waterborne Emissions (cont)			**DQI**
Sodium	282	lb	E
Strontium	1.51	lb	E
Thallium	3.1E-04	lb	E
Tin	0.0061	lb	E
Titanium	0.023	lb	E
Vanadium	7.5E-04	lb	E
Yttrium	1.9E-04	lb	E
Zinc	0.055	lb	E
Chlorides (unspecified)	1,002	lb	E
Chlorides (methyl chloride)	1.1E-06	lb	E
Calcium	89.1	lb	E
Fluorine/ Fluorides	0.0020	lb	E
Nitrates	3.0E-04	lb	E
Nitrogen (ammonia)	1.0E-04	lb	E
Bromide	5.94	lb	E
Boron	0.087	lb	E
Organic Carbon	0.0071	lb	E
Cyanide	2.0E-06	lb	E
Hardness	275	lb	E
Total Alkalinity	2.19	lb	E
Surfactants	0.023	lb	E
Acetone	2.8E-04	lb	E
Alkylated Benzenes	0.0013	lb	E
Alkylated Fluorenes	7.6E-05	lb	E
Alkylated Naphthalenes	2.1E-05	lb	E
Alkylated Phenanthrenes	8.9E-06	lb	E
Benzene	0.047	lb	E
Cresols	0.0016	lb	E
Cymene	2.8E-06	lb	E
Dibenzofuran	5.3E-06	lb	E
Dibenzothiophene	4.3E-06	lb	E
2,4 dimethylphenol	7.8E-04	lb	E
Ethylbenzene	0.0026	lb	E
2-Hexanone	1.8E-04	lb	E
Methyl ethyl Ketone (MEK)	2.2E-06	lb	E
1-methylfluorene	3.2E-06	lb	E
2-methyl naphthalene	4.4E-04	lb	E
4-methyl- 2-pentanone	1.2E-04	lb	E
Naphthalene	5.1E-04	lb	E
Pentamethyl benzene	2.1E-06	lb	E
Phenanthrene	7.7E-06	lb	E
Toluene	0.044	lb	E
Total Biphenyls	8.5E-05	lb	E
total dibenzo- thiophenes	2.6E-07	lb	E
Xylenes	0.023	lb	E
Radionuclides (unspecified)	2.1E-07	Ci	E
Solid Waste	361	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Table A-13

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIIONS FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL-GRADE URANIUM

Total Precombustion Fuel Use and Process Energy	**United States**		**DQI**
Coal - Bituminous	1,027,059	lb	C
Coal - Lignite	93,320	lb	C
Natural gas	6,978,489	cuft	C
Residual oil	5,214	gal	C
Distillate oil	4,758	gal	C
Gasoline	163	gal	C
Liquefied petroleum gas	14.5	gal	C
Uranium (nuclear power)	2.74	lb	C
Hydropower	505,588	thousand Btu	C
Other renewable energy	221,511	thousand Btu	C
Wood and wood wastes	310,869	thousand Btu	C

Precombustion Emissions

Atmospheric Emissions			**DQI**
Particulates (unspecified)	18,786	lb	D
Particulates (PM10)	384	lb	D
Nitrogen Oxides	21,925	lb	C
Hydrocarbons (unspecified)	3,501	lb	D
VOC (unspecified)	352	lb	D
TNMOC (unspecified)	63.8	lb	C
Sulfur Dioxide	74,096	lb	C
Sulfur Oxides	984	lb	C
Carbon Monoxide	2,896	lb	C
Fossil CO2	3,568,987	lb	C
Non-Fossil CO2	60,620	lb	D
Aldehydes (Formaldehyde)	2.36	lb	C
Aldehydes (Acetaldehyde)	0.29	lb	D
Aldehydes (Propionaldehyde)	0.0044	lb	D
Aldehydes (unspecified)	5.87	lb	D
Organics (unspecified)	5.47	lb	D
Ammonia	46.3	lb	D
Ammonia Chloride	155	lb	D
Methane	9,087	lb	C
Kerosene	278	lb	D
Chlorine	0.25	lb	D
HCl	677	lb	C
HF	83.5	lb	C
Metals (unspecified)	13.3	lb	D
Mercaptan	2.52	lb	D
Antimony	0.013	lb	C
Arsenic	0.25	lb	C
Beryllium	0.014	lb	C
Cadmium	0.041	lb	C
Chromium (VI)	0.044	lb	D
Chromium	0.17	lb	C
Cobalt	0.087	lb	C
Copper	0.0031	lb	D
Lead	0.30	lb	C
Magnesium	6.16	lb	C
Manganese	0.79	lb	C

Table A-13 (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIIONS FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL-GRADE URANIUM

Atmospheric Emissions (cont)			**DQI**
Mercury	0.066	lb	C
Nickel	0.59	lb	C
Selenium	0.74	lb	C
Zinc	0.0020	lb	D
Acetophenone	1.7E-04	lb	D
Acrolein	1.41	lb	D
Nitrous Oxide	88.4	lb	C
Benzene	34.1	lb	D
Benzyl Chloride	0.0081	lb	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.5E-04	lb	D
1,3 Butadiene	8.5E-04	lb	D
2-Chloroacetophenone	8.1E-05	lb	D
Chlorobenzene	2.6E-04	lb	D
2,4-Dinitrotoluene	3.3E-06	lb	D
Ethyl Chloride	4.9E-04	lb	D
Ethylbenzene	3.70	lb	D
Ethylene Dibromide	1.4E-05	lb	D
Ethylene Dichloride	4.7E-04	lb	D
Hexane	7.8E-04	lb	D
Isophorone ($C_9H_{14}O$)	0.0068	lb	D
Methyl Bromide	0.0019	lb	D
Methyl Chloride	0.0062	lb	D
Methyl Ethyl Ketone	0.0045	lb	D
Methyl Hydrazine	0.0020	lb	D
Methyl Methacrylate	2.3E-04	lb	D
Methyl Tert Butyl Ether (MTBE)	4.1E-04	lb	D
Naphthalene	0.040	lb	D
Propylene	0.056	lb	D
Styrene	2.9E-04	lb	D
Toluene	47.8	lb	D
Trichloroethane	2.4E-04	lb	D
Vinyl Acetate	8.8E-05	lb	D
Xylenes	27.9	lb	D
Bromoform	4.5E-04	lb	D
Chloroform	6.9E-04	lb	D
Carbon Disulfide	0.0015	lb	D
Dimethyl Sulfate	5.6E-04	lb	D
Cumene	6.2E-05	lb	D
Cyanide	0.029	lb	D
Perchloroethylene	0.025	lb	D
Methylene Chloride	0.30	lb	D
Carbon Tetrachloride	0.014	lb	D
Phenols	0.055	lb	D
Fluorides	13.5	lb	D
Polyaromatic Hydrocarbons (total)	0.015	lb	E
Biphenyl	9.5E-04	lb	E
Acenaphthene	2.9E-04	lb	E
Acenaphthylene	1.4E-04	lb	E
Anthracene	1.2E-04	lb	E
Benzo(a)anthracene	4.5E-05	lb	E
Benzo(a)pyrene	2.1E-05	lb	E

Table A-13 (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIIONS FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL-GRADE URANIUM

Atmospheric Emissions (cont)			**DQI**
Benzo(b,j,k)fluroanthene	6.2E-05	lb	E
Benzo(g,h,i) perylene	1.5E-05	lb	E
Chrysene	5.6E-05	lb	E
Fluoranthene	4.0E-04	lb	E
Fluorene	5.1E-04	lb	E
Indeno(1,2,3-cd)pyrene	3.4E-05	lb	E
Naphthalene	0.0073	lb	E
Phenanthrene	0.0015	lb	E
Pyrene	1.8E-04	lb	E
5-methyl Chrysene	1.2E-05	lb	E
Dioxins (unspecified)	5.2E-04	lb	D
Furans (unspecified)	2.5E-06	lb	D
CFC12	8.8E-06	lb	D
Radionuclides (unspecified)	15,520	Ci	C
Waterborne Emissions			
Acid (unspecified)	1.74	lb	E
Acid (benzoic)	1.72	lb	E
Acid (hexanoic)	0.36	lb	E
Metal (unspecified)	22,002	lb	E
Dissolved Solids	75,717	lb	E
Suspended Solids	9,455	lb	E
BOD	854	lb	E
COD	426	lb	E
Phenol/Phenolic Compounds	0.78	lb	E
Sulfur	4.50	lb	E
Sulfates	201,256	lb	E
Sulfides	0.014	lb	E
Oil	33.9	lb	E
Hydrocarbons	0.34	lb	E
Ammonia	26.4	lb	E
Ammonium	124	lb	E
Aluminum	1,266	lb	E
Antimony	0.032	lb	E
Arsenic	3.84	lb	E
Barium	749	lb	E
Beryllium	0.019	lb	E
Cadmium	1.96	lb	E
Chromium (unspecified)	1.44	lb	E
Cobalt	0.038	lb	E
Copper	30.7	lb	E
Iron	5,845	lb	E
Lead	4.87	lb	E
Lithium	1,522	lb	E
Magnesium	1,068	lb	E
Manganese	566	lb	E
Mercury	0.043	lb	E
Molybdenum	0.039	lb	E
Nickel	0.33	lb	E
Selenium	43.4	lb	E
Silver	3.56	lb	E

Table A-13 (Cont'd)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIIONS FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL-GRADE URANIUM

Waterborne Emissions (cont)			**DQI**
Sodium	17,670	lb	E
Strontium	92.6	lb	E
Thallium	0.0067	lb	E
Tin	0.22	lb	E
Titanium	0.49	lb	E
Vanadium	0.046	lb	E
Yttrium	0.011	lb	E
Zinc	61.7	lb	E
Chlorides (unspecified)	61,678	lb	E
Chlorides (methyl chloride)	6.8E-05	lb	E
Calcium	5,538	lb	E
Fluorine/ Fluorides	2,007	lb	E
Nitrates	308	lb	E
Nitrogen (ammonia)	108	lb	E
Bromide	364	lb	E
Boron	5.33	lb	E
Organic Carbon	7.17	lb	E
Cyanide	1.2E-04	lb	E
Hardness	16,819	lb	E
Total Alkalinity	136	lb	E
Surfactants	1.65	lb	E
Acetone	0.017	lb	E
Alkylated Benzenes	0.028	lb	E
Alkylated Fluorenes	0.0016	lb	E
Alkylated Naphthalenes	4.6E-04	lb	E
Alkylated Phenanthrenes	1.9E-04	lb	E
Benzene	2.85	lb	E
Cresols	0.10	lb	E
Cymene	1.7E-04	lb	E
Dibenzofuran	3.2E-04	lb	E
Dibenzothiophene	2.6E-04	lb	E
2,4 dimethylphenol	0.048	lb	E
Ethylbenzene	0.16	lb	E
2-Hexanone	0.011	lb	E
Methyl ethyl Ketone (MEK)	1.4E-04	lb	E
1-methylfluorene	1.9E-04	lb	E
2-methyl naphthalene	0.027	lb	E
4-methyl- 2-pentanone	0.0071	lb	E
Naphthalene	0.031	lb	E
Pentamethyl benzene	1.3E-04	lb	E
Phenanthrene	2.6E-04	lb	E
Toluene	2.69	lb	E
Total Biphenyls	0.0018	lb	E
Total dibenzo-thiophenes	5.6E-06	lb	E
Xylenes	1.43	lb	E
Radionuclides (unspecified)	0.22	Ci	E
Solid Waste	5,264,237	lb	C

Note: Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

Source: Franklin Associates, A Division of ERG

Total Environmental Emissions for Process, Utility, and Transportation Fuels

The environmental emissions associated with the consumption of 1,000 units of the various types of fuels by mobile and stationary sources are reported in Tables A-14 through A-33. Precombustion and combustion emissions are shown separately and also totaled. Mobile sources include various modes of transportation such as truck, rail, barge, etc. Stationary sources include industrial and utility boilers, and other types of stationary industrial equipment such as compressors and pumps.

Coal

Utility Boilers.

Anthracite Coal Combustion in Utility Boilers. Anthracite represents a small percentage of utility fuel; bituminous coal is the predominant fuel used in utility boilers (References A-66 and A-70). Anthracite is a high ranking coal with a high heating value and less volatile matter than other coal varieties (Reference A-64). Most anthracite is mined in Pennsylvania, and consumed in Pennsylvania and surrounding states (Reference A-64). Due to its unique composition and limited consumption, the environmental emissions associated with anthracite coal are also unique. The following discussion outlines the calculations and assumptions used for developing an environmental profile for anthracite combustion.

The environmental effects of coal combustion depend on the ash and sulfur content of coal, the type of boiler, and the firing mechanism used. Operational data are not available specifically for boilers that consume anthracite because anthracite is not a primary fuel and is not categorized as a separate group. This appendix assumes a sulfur content of 3 percent and an ash content of 6.5 percent (References A-5 and A-74). Since anthracite is consumed exclusively in Pennsylvania and surrounding states, a boiler profile of Pennsylvania utility boilers was developed in order to estimate the types of boilers used for anthracite combustion (Reference A-70). According to data reported by U.S. utilities (Reference A-70), all utility boilers in Pennsylvania are dry bottom boilers. The majority of these boilers (81.0 percent) use front-firing technologies; tangential-firing (10.2 percent) and opposed-firing (7.7 percent) technologies account for the remainder of anthracite boiler firing technologies (Reference A-75). These above percentages for anthracite composition and boiler properties were used to calculate emissions that are representative of anthracite boilers in U.S. utilities.

Air emissions from utility coal combustion were calculated from EPA sources. EPA's AP-42 database (References A-64 and A-72) includes emission factors for greenhouse gases, particulates, organic compounds, and trace metals. The AP-42 documentation includes emissions that are specific to anthracite coal combustion, but in cases where anthracite data were not available, bituminous coal combustion data were adjusted to represent anthracite combustion. Hazardous air pollutants (HAPs) were estimated from EPA's report to Congress on emissions from utility boilers (Reference A-67).

The emissions of particulates and sulfur oxides depend not only on coal quality and boiler technologies, but also on post-combustion control technologies. Coal-fired power plants commonly employ particulate control devices, which range in efficiency from 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-50). This appendix assumes that an average of 99 percent of the fly ash is collected in particulate control devices. FGD (flue gas desulfurization) controls remove sulfur oxides from post-combustion streams. For utility boilers that burn anthracite coal, the sulfur oxide removal efficiency of FGD controls range from 85 to 99 percent (Reference A-70). However, a majority of anthracite boilers do not employ FGD controls (Reference A-70), and thus the net FGD sulfur oxide removal efficiency for U.S. anthracite utility boilers is approximately 58 percent.

Water emissions represent a small portion of the total environmental emissions from coal-fired utilities (Reference A-67). Water emissions from utility coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) wastes. Some solid waste byproducts from utility coal combustion are now being diverted from the landfill by being incorporated in other useful products, such as cement and concrete products, mineral filler in asphalt, grouting, and wall board (Reference A-73). By finding applications for coal combustion byproducts, utilities are reducing their generation of solid waste.

Bituminous Coal Combustion in Utility Boilers. In this appendix, bituminous coal includes the subbituminous coal rank. The composition of bituminous and subbituminous coals are not exactly the same; subbituminous coal has a lower sulfur content and higher moisture content than bituminous coal. However, bituminous and subbituminous coals are used in similar applications, and emission data for their combustion are usually aggregated.

In 2000 over 90 percent of the coal consumed in the U.S. was used by utilities (Reference A-66).The environmental effects of coal combustion depend on the ash and sulfur content of coal, the type of boiler, the firing mechanism used, and the environmental control technologies employed. In 2000 the average sulfur content of coal received by utilities was 1.04 percent by weight, and the average ash content was 8.81 percent by weight (Reference A-66). These averages represent bituminous and subbituminous coal and are weighted according to the 74/26 split between bituminous and subbituminous coal received by utilities in 2000 (Reference A-66). According to data reported by U.S. utilities (Reference A-62), 95 percent of utility boilers fall under one of the following four categories: dry bottom boilers with tangential firing (42 percent), dry bottom boilers with opposed firing (36 percent), dry bottom boilers with front firing (10 percent), and wet bottom boilers with cyclone firing (7 percent). These percentages were used to calculate emissions that are representative of U.S. coal-fired utilities.

Air emissions from utility coal combustion were calculated from EPA sources. EPA's AP-42 database (Reference A-72) includes emission factors for greenhouse gases, particulates, organic compounds, and trace metals. Greenhouse gas and particulate emissions are also available in EPA's eGRID database (Reference A-62), which includes reported emissions from U.S. utilities. Hazardous air pollutants (HAPs) were estimated from EPA's report to Congress on emissions from utility boilers (Reference A-67).

The emissions of particulates and sulfur oxides depend not only on coal quality and boiler technologies, but also on post-combustion control technologies. Coal-fired power plants commonly employ particulate control devices, ranging in efficiency from 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-50). This appendix assumes that an average of 99 percent of the fly ash is collected in particulate control devices. FGD (flue gas desulfurization) controls are used to remove sulfur oxides from post-combustion streams. The average sulfur oxide removal efficiency of existing FGD controls is 85 percent (Reference A-75). The sulfur oxide emissions were reduced to account for the desulfurization units employed by 33 percent of the coal-fired units (Reference A-75).

Water effluents represent a small portion of the total environmental emissions from coal-fired utilities (Reference A-67). Water effluents from utility coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water effluents do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) sludge. Some solid waste byproducts from utility coal combustion are diverted from the landfill and incorporated in useful products such as cement and concrete, mineral filler in asphalt, grouting, and wall board (Reference A-73). By finding applications for coal combustion byproducts, utilities are reducing their generation of solid waste.

Lignite Coal Combustion in Utility Boilers. Lignite coal represents a small portion of the total coal consumed by utility boilers. It is not cost-effective to transport lignite, and thus lignite is usually consumed close to the mining site. This restricts most lignite consumption to Texas and North Dakota (Reference A-70).

The environmental effects of coal combustion depend on the ash and sulfur content of coal, the type of boiler, and the firing mechanism used. In 2000 the average sulfur content of lignite coal received by utilities was 0.91 percent by weight, and the average ash content was 14.2 percent by weight (Reference A-69). According to data reported by U.S. utilities (Reference A-70), the majority of utility boilers that consume lignite fall under one of the following five categories: dry bottom boilers with tangential firing (43 percent), dry bottom boilers with concentric firing (22 percent), dry bottom boilers with opposed firing (15 percent), wet bottom boilers with cyclone firing (12 percent), and dry bottom boilers with fluidized bed firing (4 percent). The above percentages for lignite composition and boiler properties were used to calculate emissions that are representative of lignite boilers in U.S. utilities.

Air emissions from utility coal combustion were calculated from EPA sources. EPA's AP-42 database (References A-72 and A-76) includes emission factors for greenhouse gases, particulates, organic compounds, and trace metals. Hazardous air pollutants (HAPs) were estimated from EPA's report to Congress on emissions from utility boilers (Reference A-67).

The emission of particulates and sulfur oxides depend not only on coal quality and boiler technology, but also on post-combustion control technologies. Coal-fired power plants commonly employ particulate control devices, ranging in efficiency from 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-50). This appendix assumes that an average of 99 percent of the fly ash is collected in particulate control devices. FGD (flue gas desulfurization) controls are used to remove sulfur oxides from post-combustion streams. For utility boilers that burn lignite coal, the sulfur oxide removal efficiency of FGD controls ranges from 71 to 99 percent (Reference A-70). However, a majority of lignite utility boilers do not employ FGD controls (Reference A-70), and thus the net FGD sulfur oxide removal efficiency for U.S. lignite utility boilers is approximately 7.8 percent.

Water effluents represent a small portion of the total environmental emissions from coal-fired utilities (Reference A-67). Water effluents from utility coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations.

Solid wastes from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) sludge. Some solid waste byproducts from utility coal combustion are diverted from the landfill and incorporated in products such as cement and concrete, mineral filler in asphalt, grouting, and wall board (Reference A-73). By finding applications for coal combustion byproducts, utilities are reducing their generation of solid waste.

Industrial Boilers.

Anthracite Coal Combustion in Industrial Boilers. In 2000, 9.4 percent of the coal consumed in the U.S. was used by industry (Reference A-79). Industrial combustion of coal is treated separately from combustion of coal for utility boilers because pollutants are often different. Industries often do not burn coal in boilers as large as or of the same type as the utility boilers. They also do not always burn the same kinds of coal.

Average ash and sulfur content for anthracite coal used by industry was assumed to be the same as for anthracite coal received by utilities. Statistics on coal quality show little difference in the ash and sulfur content between utility and industrial coal (Reference A-84). However, particulate control is generally less efficient for industrial coal boilers, and sulfur oxide controls are rarely employed. According to a representative of the industrial boiler industry, 70 percent of industrial boilers are stoker boilers, 20 percent are FBC (fluidized bed combustion) boilers, and 10 percent are PC (pulverized coal) boilers (Reference A-80). These percentages were used to estimate boiler emissions that are representative of current industry practice.

Air emissions from industrial coal combustion were calculated from EPA sources. The National Air Pollutant Emission Trends database (Reference A-78) includes data for hazardous air pollutants such as carbon monoxide, volatile organic compounds (VOCs), and heavy metal emissions; the AP-42 database (References A-72 and A-64) includes data for greenhouse gases, organic compounds, and trace metals.

Water emissions from industrial coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations. All available data for waterborne emissions were specific to utility boiler emissions, not industrial boiler emissions. Assumptions on the size and applications of industrial boilers were used to adjust utility boiler data so that it was representative of industrial boilers. In particular, since industrial boilers use steam directly for heating industrial processes (Reference A-80 and A-81), it was assumed that there are fewer cooling water requirements for industrial boilers than for utility boilers. Also, since industrial boilers are smaller than utility boilers and require less cleaning (References A-80 and A-81), it was assumed that cleaning wastes are less for industrial boilers than for utility boilers.

Solid waste emissions from coal combustion result from bottom ash, fly ash, boiler slag, and FGD (flue gas desulfurization) wastes. Data for these solid wastes are available for utility boilers, but limited solid waste data are available for industrial boilers. Based on discussions with industry representatives, assumptions were made to adjust utility solid waste data so that they are representative of industrial boilers. In particular, utility boilers are usually equipped with environmental control equipment and thus produce more solid wastes related to the capture of fly ash and FGD. Since few industrial boilers employ environmental control equipment, it was assumed that industrial boilers produce 10 percent of the fly ash and FGD wastes of utility boilers. The reduced solid wastes from industrial boilers, however, translates to higher uncontrolled air emissions.

Bituminous Coal Combustion in Industrial Boilers. In this appendix, bituminous coal includes the subbituminous coal rank. The composition of bituminous and subbituminous coals are not exactly the same; subbituminous coal has a lower sulfur content and higher moisture content than bituminous coal. However, bituminous and subbituminous coals are used in similar applications and available emission data for their combustion are usually aggregated.

In 2000, 9.4 percent of the coal consumed in the U.S. was used by industry (Reference A-79). Industrial combustion of coal is treated separately from combustion of coal for utility boilers because pollutants are often different. Industries often do not burn coal in boilers as large as or of the same type as the utility boilers. They also do not always burn the same kinds of coal.

Average ash and sulfur content for bituminous coal used by industry was assumed to be the same as for bituminous coal received by utilities. Statistics on coal quality show little difference in the ash and sulfur content between utility and industrial coal (Reference A-84). However, particulate control is generally less efficient for industrial coal boilers, and sulfur oxide controls are rarely employed. According to a representative of the industrial boiler industry, 70 percent of industrial boilers are stoker boilers, 20 percent are FBC (fluidized bed combustion) boilers, and 10 percent are PC (pulverized coal) boilers (Reference A-80). These percentages were used to estimate boiler emissions that are representative of current industry practice.

Air emissions from industrial coal combustion were calculated from EPA sources. The National Air Pollutant Emission Trends database (Reference A-78) includes data for hazardous air pollutants such as carbon monoxide, volatile organic compounds (VOCs), and heavy metal emissions; the AP-42 database (Reference A-72) includes data for greenhouse gases, organic compounds, and trace metals.

Water emissions from industrial coal combustion were calculated from EPA sources and federal effluent limitations (References A-67 and A-68). Water emissions do not result from the combustion side of coal-fired boilers, but they do result from cooling water and boiler cleaning operations. All available data for waterborne emissions were specific to utility boiler emissions, not industrial boiler emissions. Assumptions on the size and applications of industrial boilers were used to adjust utility boiler data so that it was representative of industrial boilers. In particular, since industrial boilers use steam directly for heating industrial processes (References A-80 and A-81), it was assumed that there are fewer cooling water requirements for industrial boilers than for utility boilers. Also, since industrial boilers are smaller than utility boilers and require less cleaning (References A-80 and A-81), it was assumed that cleaning wastes are less for industrial boilers than for utility boilers.

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Table A-14a

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF ANTHRACITE COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of anthracite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.11	0.026	2.14	B
Particulates (PM10)	0.0060		0.0060	D
Nitrogen Oxides	0.25	4.50	4.75	B
Hydrocarbons (unspecified)	0.024		0.024	D
VOC (unspecified)	0.042		0.042	D
TNMOC (unspecified)	3.7E-04	0.15	0.15	B
Sulfur Dioxide	0.15	34.3	34.5	B
Sulfur Oxides	0.051	58.7	58.7	B
Carbon Monoxide	0.24	0.30	0.54	B
Fossil CO2	58.1	2,840	2,898	B
Non-Fossil CO2	0.35		0.35	D
Aldehydes (Formaldehyde)	2.7E-05		2.7E-05	C
Aldehydes (Acetaldehyde)	4.9E-06		4.9E-06	D
Aldehydes (Propionaldehyde)	6.5E-10		6.5E-10	D
Aldehydes (unspecified)	5.0E-04		5.0E-04	C
Organics (unspecified)	1.9E-05		1.9E-05	D
Ammonia	2.5E-04		2.5E-04	D
Ammonia Chloride	2.4E-06		2.4E-06	D
Methane	1.69	0.020	1.71	B
Kerosene	4.4E-06		4.4E-06	D
Chorine	1.4E-06		1.4E-06	D
HCl	0.0043		0.0043	C
HF	6.6E-04		6.6E-04	C
Metals (unspecified)	7.7E-05		7.7E-05	D
Mercaptan	3.5E-07		3.5E-07	D
Antimony	7.1E-08		7.1E-08	C
Arsenic	1.9E-06	9.5E-05	9.7E-05	C
Beryllium	2.9E-07	1.6E-04	1.6E-04	C
Cadmium	5.0E-07	3.6E-05	3.6E-05	C
Chromium (VI)	2.5E-07		2.5E-07	C
Chromium (unspecified)	4.0E-06	0.014	0.014	D
Cobalt	1.7E-06		1.7E-06	C
Copper	3.7E-07		3.7E-07	D
Lead	3.4E-06	0.0045	0.0045	C
Magnesium	3.5E-05		3.5E-05	C
Manganese	5.9E-06	0.0018	0.0018	C
Mercury	7.5E-07	6.5E-05	6.6E-05	C
Nickel	2.3E-05	0.013	0.013	C
Selenium	5.4E-06	6.5E-04	6.6E-04	C
Zinc	2.5E-07		2.5E-07	D
Acetophenone	2.6E-11		2.6E-11	D
Acrolein	8.5E-06		8.5E-06	D
Nitrous Oxide	0.0011	0.018	0.019	C
Benzene	2.1E-04		2.1E-04	D
Benzyl Chloride	1.2E-09		1.2E-09	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.3E-10		1.3E-10	D
1,3 Butadiene	1.7E-07		1.7E-07	D
2-Chloroacetophenone	1.2E-11		1.2E-11	D
Chlorobenzene	3.8E-11		3.8E-11	D
2,4-Dinitrotoluene	4.8E-13		4.8E-13	D
Ethyl Chloride	7.2E-11		7.2E-11	D
Ethylbenzene	1.9E-05		1.9E-05	D
Ethylene Dibromide	2.1E-12		2.1E-12	D
Ethylene Dichloride	6.9E-11		6.9E-11	D
Hexane	1.2E-10		1.2E-10	D
Isophorone (C9H14O)	1.0E-09		1.0E-09	D
Methyl Bromide	2.7E-10		2.7E-10	D
Methyl Chloride	9.1E-10		9.1E-10	D
Methyl Ethyl Ketone	6.7E-10		6.7E-10	D
Methyl Hydrazine	2.9E-10		2.9E-10	D
Methyl Methacrylate	3.4E-11		3.4E-11	D
Methyl Tert Butyl Ether (MTBE)	6.0E-11		6.0E-11	D

Table A-14a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF ANTHRACITE COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of anthracite coal)

	Precombustion (1)		Total	DQI
Atmospheric Emissions				
Naphthalene	4.6E-07		4.6E-07	D
Propylene	1.1E-05		1.1E-05	D
Styrene	4.3E-11		4.3E-11	D
Toluene	2.5E-04		2.5E-04	D
Trichloroethane	1.2E-09		1.2E-09	D
Vinyl Acetate	1.3E-11		1.3E-11	D
Xylenes	1.5E-04		1.5E-04	D
Bromoform	6.7E-11		6.7E-11	D
Chloroform	1.0E-10		1.0E-10	D
Carbon Disulfide	2.2E-10		2.2E-10	D
Dimethyl Sulfate	8.2E-11		8.2E-11	D
Cumene	9.1E-12		9.1E-12	D
Cyanide	4.3E-09		4.3E-09	D
Perchloroethylene	1.9E-07		1.9E-07	D
Methylene Chloride	4.6E-06		4.6E-06	D
Carbon Tetrachloride	8.1E-08		8.1E-08	D
Phenols	2.5E-06		2.5E-06	D
Fluorides	2.8E-07		2.8E-07	D
Polyaromatic Hydrocarbons (total)	3.2E-05	0.0809	0.081	E
Biphenyl	4.8E-06	0.013	0.013	E
Acenaphthene	1.6E-09		1.6E-09	E
Acenaphthylene	7.9E-10		7.9E-10	E
Anthracene	6.6E-10		6.6E-10	E
Benzo(a)anthracene	2.5E-10		2.5E-10	E
Benzo(a)pyrene	1.2E-10		1.2E-10	E
Benzo(b,j,k)fluroanthene	3.5E-10		3.5E-10	E
Benzo(g,h,i) perylene	8.5E-11		8.5E-11	E
Chrysene	3.2E-10		3.2E-10	E
Fluoranthene	2.2E-09		2.2E-09	E
Fluorene	2.9E-09		2.9E-09	E
Indeno(1,2,3-cd)pyrene	1.9E-10		1.9E-10	E
Naphthalene	2.5E-05	0.065	0.065	E
Phenanthrene	1.3E-06	0.0034	0.0034	E
Pyrene	1.0E-09		1.0E-09	E
5-methyl Chrysene	6.9E-11		6.9E-11	E
Dioxins (unspecified)	3.0E-09		3.0E-09	D
Furans (unspecified)	1.4E-11		1.4E-11	D
CFC12	1.4E-09		1.4E-09	D
Radionuclides (unspecified)	2.5E-04	3.5E-04	5.9E-04	C
Waterborne Emissions				
Acid (unspecified)	9.0E-06		9.0E-06	E
Acid (benzoic)	5.1E-05		5.1E-05	E
Acid (hexanoic)	1.1E-05		1.1E-05	E
Metal (unspecified)	0.11		0.11	E
Dissolved Solids	2.25		2.25	E
Suspended Solids	0.38	0.0048	0.39	D
BOD	0.0052		0.0052	E
COD	0.0049		0.0049	E
Phenol/Phenolic Compounds	2.5E-05		2.5E-05	E
Sulfur	1.3E-04		1.3E-04	E
Sulfates	0.0069		0.0069	E
Sulfides	2.2E-06		2.2E-06	E
Oil	0.0011	0.0024	0.0035	D
Hydrocarbons	1.0E-05		1.0E-05	E
Ammonia	9.0E-04		9.0E-04	E
Ammonium	2.0E-06		2.0E-06	E
Aluminum	0.0040		0.0040	E
Antimony	2.5E-06		2.5E-06	E
Arsenic	1.4E-05		1.4E-05	E
Barium	0.055		0.055	E
Beryllium	7.4E-07		7.4E-07	E
Cadmium	2.0E-06		2.0E-06	E
Chromium (unspecified)	1.1E-04		1.1E-04	E
Cobalt	1.1E-06		1.1E-06	E
Copper	1.4E-05		1.4E-05	E

Table A-14a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF ANTHRACITE COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of anthracite coal)

	Precombustion (1)		Total	DQI
Waterborne Emissions				
Iron	0.030		0.030	E
Lead	2.8E-05		2.8E-05	E
Lithium	0.0080		0.0080	E
Magnesium	0.032		0.032	E
Manganese	0.015		0.015	E
Mercury	4.4E-08		4.4E-08	E
Molybdenum	1.2E-06		1.2E-06	E
Nickel	1.3E-05		1.3E-05	E
Selenium	1.2E-06		1.2E-06	E
Silver	1.1E-04		1.1E-04	E
Sodium	0.51		0.51	E
Strontium	0.0028		0.0028	E
Thallium	5.3E-07		5.3E-07	E
Tin	1.1E-05		1.1E-05	E
Titanium	3.8E-05		3.8E-05	E
Vanadium	1.4E-06		1.4E-06	E
Yttrium	3.4E-07		3.4E-07	E
Zinc	9.4E-05		9.4E-05	E
Chlorides (unspecified)	1.82		1.82	E
Chlorides (methyl chloride)	2.0E-09		2.0E-09	E
Calcium	0.16		0.16	E
Fluorine/ Fluorides	3.2E-05		3.2E-05	E
Nitrates	4.9E-06		4.9E-06	E
Nitrogen (ammonia)	1.7E-06		1.7E-06	E
Bromide	0.011		0.011	E
Boron	1.6E-04		1.6E-04	E
Organic Carbon	3.7E-05		3.7E-05	E
Cyanide	3.6E-09		3.6E-09	E
Hardness	0.50		0.50	E
Total Alkalinity	0.0040		0.0040	E
Surfactants	4.3E-05		4.3E-05	E
Acetone	5.0E-07		5.0E-07	E
Alkylated Benzenes	2.2E-06		2.2E-06	E
Alkylated Fluorenes	1.3E-07		1.3E-07	E
Alkylated Naphthalenes	3.6E-08		3.6E-08	E
Alkylated Phenanthrenes	1.5E-08		1.5E-08	E
Benzene	8.5E-05		8.5E-05	E
Cresols	3.0E-06		3.0E-06	E
Cymene	5.0E-09		5.0E-09	E
Dibenzofuran	9.6E-09		9.6E-09	E
Dibenzothiophene	7.8E-09		7.8E-09	E
2,4 dimethylphenol	1.4E-06		1.4E-06	E
Ethylbenzene	4.8E-06		4.8E-06	E
2-Hexanone	3.3E-07		3.3E-07	E
Methyl ethyl Ketone (MEK)	4.1E-09		4.1E-09	E
1-methylfluorene	5.7E-09		5.7E-09	E
2-methyl naphthalene	8.0E-07		8.0E-07	E
4-methyl- 2-pentanone	2.1E-07		2.1E-07	E
Naphthalene	9.2E-07		9.2E-07	E
Pentamethyl benzene	3.8E-09		3.8E-09	E
Phenanthrene	1.3E-08		1.3E-08	E
Toluene	8.0E-05		8.0E-05	E
Total Biphenyls	1.4E-07		1.4E-07	E
Total dibenzo- thiophenes	4.4E-10		4.4E-10	E
Xylenes	4.2E-05		4.2E-05	E
Radionuclides (unspecified)	3.5E-09		3.5E-09	E
Solid Waste	274	37.8	311	B

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-5, A-64 through A-72, A-74.

Source: Franklin Associates, A Division of ERG

Table A-14b

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF BITUMINOUS AND SUBBITUMINOUS COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of bituminous/subbituminous coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	1.65		1.65	B
Particulates (PM10)	0.021	0.094	0.12	D
Nitrogen Oxides	0.77	6.13	6.89	B
Hydrocarbons (unspecified)	0.036		0.036	D
VOC (unspecified)	0.054		0.054	D
TNMOC (unspecified)	7.4E-04	0.056	0.057	B
Sulfur Dioxide	0.25	15.3	15.6	B
Sulfur Oxides	0.081		0.081	B
Carbon Monoxide	0.43	0.25	0.68	B
Fossil CO2	92.5	2,250	2,343	B
Non-Fossil CO2	0.64		0.64	D
Aldehydes (Formaldehyde)	4.5E-05	1.2E-04	1.6E-04	C
Aldehydes (Acetaldehyde)	1.3E-05		1.3E-05	D
Aldehydes (Propionaldehyde)	8.3E-08		8.3E-08	D
Aldehydes (unspecified)	7.5E-04	4.8E-04	0.0012	C
Organics (unspecified)	3.7E-05	0.0030	0.0031	D
Ammonia	3.7E-04		3.7E-04	D
Ammonia Chloride	4.5E-06		4.5E-06	D
Methane	4.15	0.019	4.17	B
Kerosene	8.0E-06		8.0E-06	D
Chorine	2.6E-06		2.6E-06	D
HCl	0.0084	0.60	0.61	C
HF	9.4E-04	0.075	0.076	C
Metals (unspecified)	1.4E-04		1.4E-04	D
Mercaptan	4.7E-05		4.7E-05	D
Antimony	1.4E-07	9.0E-06	9.1E-06	C
Arsenic	3.5E-06	2.1E-04	2.1E-04	C
Beryllium	5.9E-07	1.1E-05	1.1E-05	C
Cadmium	9.4E-07	2.6E-05	2.6E-05	C
Chromium (VI)	5.0E-07	4.0E-05	4.0E-05	C
Chromium (unspecified)	2.4E-06	1.3E-04	1.3E-04	D
Cobalt	1.9E-06	5.0E-05	5.2E-05	C
Copper	8.9E-07		8.9E-07	D
Lead	5.2E-06	2.1E-04	2.2E-04	C
Magnesium	7.0E-05	0.0055	0.0056	C
Manganese	9.9E-06	2.5E-04	2.5E-04	C
Mercury	1.3E-06	4.2E-05	4.3E-05	C
Nickel	2.0E-05	1.4E-04	1.6E-04	C
Selenium	1.1E-05	6.5E-04	6.6E-04	C
Zinc	5.9E-07		5.9E-07	D
Acetophenone	3.3E-09		3.3E-09	D
Acrolein	1.6E-05	1.5E-04	1.6E-04	D
Nitrous Oxide	0.0018	0.055	0.057	C
Benzene	3.1E-04	6.5E-04	9.6E-04	D
Benzyl Chloride	1.5E-07		1.5E-07	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-08		1.6E-08	D
1,3 Butadiene	5.1E-07		5.1E-07	D
2-Chloroacetophenone	1.5E-09		1.5E-09	D
Chlorobenzene	4.8E-09		4.8E-09	D
2,4-Dinitrotoluene	6.1E-11		6.1E-11	D
Ethyl Chloride	9.2E-09		9.2E-09	D
Ethylbenzene	3.1E-05		3.1E-05	D
Ethylene Dibromide	2.6E-10		2.6E-10	D
Ethylene Dichloride	8.7E-09		8.7E-09	D
Hexane	1.5E-08		1.5E-08	D
Isophorone (C9H14O)	1.3E-07		1.3E-07	D
Methyl Bromide	3.5E-08		3.5E-08	D
Methyl Chloride	1.2E-07		1.2E-07	D
Methyl Ethyl Ketone	8.5E-08		8.5E-08	D
Methyl Hydrazine	3.7E-08		3.7E-08	D
Methyl Methacrylate	4.4E-09		4.4E-09	D
Methyl Tert Butyl Ether (MTBE)	7.6E-09		7.6E-09	D

Table A-14b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF BITUMINOUS AND SUBBITUMINOUS COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of bituminous/subbituminous coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Naphthalene	6.0E-07		6.0E-07	D
Propylene	3.3E-05		3.3E-05	D
Styrene	5.5E-09		5.5E-09	D
Toluene	4.1E-04		4.1E-04	D
Trichloroethane	6.1E-09		6.1E-09	D
Vinyl Acetate	1.7E-09		1.7E-09	D
Xylenes	2.4E-04		2.4E-04	D
Bromoform	8.5E-09		8.5E-09	D
Chloroform	1.3E-08		1.3E-08	D
Carbon Disulfide	2.8E-08		2.8E-08	D
Dimethyl Sulfate	1.0E-08		1.0E-08	D
Cumene	1.2E-09		1.2E-09	D
Cyanide	5.5E-07		5.5E-07	D
Perchloroethylene	3.7E-07	2.2E-05	2.2E-05	D
Methylene Chloride	8.6E-06	1.5E-04	1.6E-04	D
Carbon Tetrachloride	1.5E-07		1.5E-07	D
Phenols	4.6E-06	8.0E-06	1.3E-05	D
Fluorides	1.0E-05		1.0E-05	D
Polyaromatic Hydrocarbons (total)	2.3E-06	1.0E-05	1.3E-05	E
Biphenyl	1.1E-08	8.5E-07	8.6E-07	E
Acenaphthene	3.2E-09	2.6E-07	2.6E-07	E
Acenaphthylene	1.6E-09	1.3E-07	1.3E-07	E
Anthracene	1.3E-09	1.1E-07	1.1E-07	E
Benzo(a)anthracene	5.1E-10	4.0E-08	4.1E-08	E
Benzo(a)pyrene	2.4E-10	1.9E-08	1.9E-08	E
Benzo(b,j,k)fluroanthene	7.0E-10	5.5E-08	5.6E-08	E
Benzo(g,h,i) perylene	1.7E-10	1.4E-08	1.4E-08	E
Chrysene	6.3E-10	5.0E-08	5.1E-08	E
Fluoranthene	4.5E-09	3.6E-07	3.6E-07	E
Fluorene	5.8E-09	4.6E-07	4.6E-07	E
Indeno(1,2,3-cd)pyrene	3.9E-10	3.1E-08	3.1E-08	E
Naphthanlene	8.2E-08	6.5E-06	6.6E-06	E
Phenanthrene	1.7E-08	1.4E-06	1.4E-06	E
Pyrene	2.1E-09	1.7E-07	1.7E-07	E
5-methyl Chrysene	1.4E-10	1.1E-08	1.1E-08	E
Dioxins (unspecified)	5.5E-09	3.9E-10	5.9E-09	D
Furans (unspecified)	2.8E-11	2.5E-09	2.5E-09	D
CFC12	2.0E-09		2.0E-09	D
Radionuclides (unspecified)	4.5E-04	3.5E-04	8.0E-04	C
Waterborne Emissions				
Acid (unspecified)	1.5E-05		1.5E-05	E
Acid (benzoic)	7.8E-05		7.8E-05	E
Acid (hexanoic)	1.6E-05		1.6E-05	E
Metal (unspecified)	0.18		0.18	E
Dissolved Solids	3.42		3.42	E
Suspended Solids	0.29	2.8E-04	0.29	D
BOD	0.0091		0.0091	E
COD	0.0075		0.0075	E
Phenol/Phenolic Compounds	3.8E-05		3.8E-05	E
Sulfur	2.0E-04		2.0E-04	E
Sulfates	0.011		0.011	E
Sulfides	3.3E-06		3.3E-06	E
Oil	0.0017	1.4E-04	0.0019	D
Hydrocarbons	1.5E-05		1.5E-05	E
Ammonia	0.0014		0.0014	E
Ammonium	3.6E-06		3.6E-06	E
Aluminum	0.0061		0.0061	E
Antimony	3.8E-06		3.8E-06	E
Arsenic	2.1E-05		2.1E-05	E
Barium	0.083		0.083	E
Beryllium	1.1E-06		1.1E-06	E
Cadmium	3.1E-06		3.1E-06	E
Chromium (unspecified)	1.7E-04		1.7E-04	E
Cobalt	1.7E-06		1.7E-06	E
Copper	2.2E-05		2.2E-05	E

Table A-14b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF BITUMINOUS AND SUBBITUMINOUS COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of bituminous/subbituminous coal)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.021		0.021	E
Lead	4.2E-05		4.2E-05	E
Lithium	0.013		0.013	E
Magnesium	0.048		0.048	E
Manganese	0.0059		0.0059	E
Mercury	6.7E-08		6.7E-08	E
Molybdenum	1.8E-06		1.8E-06	E
Nickel	2.0E-05		2.0E-05	E
Selenium	2.0E-06		2.0E-06	E
Silver	1.6E-04		1.6E-04	E
Sodium	0.78		0.78	E
Strontium	0.0042		0.0042	E
Thallium	7.9E-07		7.9E-07	E
Tin	1.6E-05		1.6E-05	E
Titanium	5.8E-05		5.8E-05	E
Vanadium	2.1E-06		2.1E-06	E
Yttrium	5.2E-07		5.2E-07	E
Zinc	1.4E-04		1.4E-04	E
Chlorides (unspecified)	2.77		2.77	E
Chlorides (methyl chloride)	3.1E-09		3.1E-09	E
Calcium	0.25		0.25	E
Fluorine/ Fluorides	5.8E-05		5.8E-05	E
Nitrates	8.9E-06		8.9E-06	E
Nitrogen (ammonia)	3.1E-06		3.1E-06	E
Bromide	0.016		0.016	E
Boron	2.4E-04		2.4E-04	E
Organic Carbon	6.0E-05		6.0E-05	E
Cyanide	5.5E-09		5.5E-09	E
Hardness	0.76		0.76	E
Total Alkalinity	0.0061		0.0061	E
Surfactants	6.6E-05		6.6E-05	E
Acetone	7.7E-07		7.7E-07	E
Alkylated Benzenes	3.3E-06		3.3E-06	E
Alkylated Fluorenes	1.9E-07		1.9E-07	E
Alkylated Naphthalenes	5.4E-08		5.4E-08	E
Alkylated Phenanthrenes	2.2E-08		2.2E-08	E
Benzene	1.3E-04		1.3E-04	E
Cresols	4.5E-06		4.5E-06	E
Cymene	7.7E-09		7.7E-09	E
Dibenzofuran	1.5E-08		1.5E-08	E
Dibenzothiophene	1.2E-08		1.2E-08	E
2,4 dimethylphenol	2.2E-06		2.2E-06	E
Ethylbenzene	7.2E-06		7.2E-06	E
2-Hexanone	5.0E-07		5.0E-07	E
Methyl ethyl Ketone (MEK)	6.2E-09		6.2E-09	E
1-methylfluorene	8.7E-09		8.7E-09	E
2-methyl naphthalene	1.2E-06		1.2E-06	E
4-methyl- 2-pentanone	3.2E-07		3.2E-07	E
Naphthalene	1.4E-06		1.4E-06	E
Pentamethyl benzene	5.8E-09		5.8E-09	E
Phenanthrene	2.0E-08		2.0E-08	E
Toluene	1.2E-04		1.2E-04	E
Total Biphenyls	2.1E-07		2.1E-07	E
total dibenzo- thiophenes	6.6E-10		6.6E-10	E
Xylenes	6.5E-05		6.5E-05	E
Radionuclides (unspecified)	6.3E-09		6.3E-09	E
Solid Waste	240	91.7	331	B

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-16, A-62, A-65 through A-73.

Source: Franklin Associates, A Division of ERG

Table A-14c

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIGNITE COAL IN UTILITY BOILERS

(pounds of pollutants per 1,000 pounds of lignite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	0.13	1.42	1.55	C
Particulates (PM10)	0.010		0.010	D
Nitrogen Oxides	0.33	4.43	4.77	C
Hydrocarbons (unspecified)	0.038		0.038	D
VOC (unspecified)	0.010		0.010	D
TNMOC (unspecified)	8.5E-04	0.029	0.030	C
Sulfur Dioxide	0.31	7.21	7.52	B
Sulfur Oxides	0.14	5.53	5.67	C
Carbon Monoxide	0.47	0.13	0.60	C
Fossil CO2	106	1,392	1,497	B
Non-Fossil CO2	0.85		0.85	D
Aldehydes (Formaldehyde)	1.2E-04	1.2E-04	2.4E-04	C
Aldehydes (Acetaldehyde)	2.0E-05		2.0E-05	D
Aldehydes (Propionaldehyde)	7.0E-08		7.0E-08	D
Aldehydes (unspecified)	7.8E-04	4.8E-04	0.0013	C
Organics (unspecified)	4.7E-05	0.0032	0.0033	D
Ammonia	3.9E-04		3.9E-04	D
Ammonia Chloride	5.9E-06		5.9E-06	D
Methane	1.30	0.020	1.32	C
Kerosene	1.1E-05		1.1E-05	D
Chorine	3.4E-06		3.4E-06	D
HCl	0.011	0.60	0.61	C
HF	0.0012	0.075	0.076	C
Metals (unspecified)	1.9E-04		1.9E-04	D
Mercaptan	8.2E-07		8.2E-07	D
Antimony	1.8E-07	9.0E-06	9.2E-06	C
Arsenic	5.9E-06	2.1E-04	2.1E-04	C
Beryllium	3.0E-07	1.1E-05	1.1E-05	C
Cadmium	1.3E-06	2.6E-05	2.7E-05	C
Chromium (VI)	6.2E-07	4.0E-05	4.0E-05	C
Chromium (unspecified)	3.9E-06	1.3E-04	1.3E-04	D
Cobalt	1.2E-05	5.0E-05	6.2E-05	C
Copper	1.6E-07		1.6E-07	D
Lead	3.1E-05	2.1E-04	2.4E-04	C
Magnesium	8.6E-05	0.0055	0.0056	C
Manganese	1.7E-05	2.5E-04	2.6E-04	C
Mercury	1.2E-06	4.2E-05	4.3E-05	C
Nickel	1.6E-04	1.4E-04	3.0E-04	C
Selenium	1.2E-05	6.5E-04	6.6E-04	C
Zinc	1.1E-07		1.1E-07	D
Acetophenone	2.8E-09		2.8E-09	D
Acrolein	2.2E-05	1.5E-04	1.7E-04	D
Nitrous Oxide	0.0014	0.032	0.033	C
Benzene	3.9E-04	6.5E-04	0.0010	D
Benzyl Chloride	1.3E-07		1.3E-07	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.3E-08		1.3E-08	D
1,3 Butadiene	8.5E-07		8.5E-07	D
2-Chloroacetophenone	1.3E-09		1.3E-09	D
Chlorobenzene	4.0E-09		4.0E-09	D
2,4-Dinitrotoluene	5.2E-11		5.2E-11	D
Ethyl Chloride	7.7E-09		7.7E-09	D
Ethylbenzene	3.9E-05		3.9E-05	D
Ethylene Dibromide	2.2E-10		2.2E-10	D
Ethylene Dichloride	7.4E-09		7.4E-09	D
Hexane	1.2E-08		1.2E-08	D
Isophorone ($C_9H_{14}O$)	1.1E-07		1.1E-07	D
Methyl Bromide	2.9E-08		2.9E-08	D
Methyl Chloride	9.8E-08		9.8E-08	D
Methyl Ethyl Ketone	7.2E-08		7.2E-08	D
Methyl Hydrazine	3.1E-08		3.1E-08	D
Methyl Methacrylate	3.7E-09		3.7E-09	D
Methyl Tert Butyl Ether (MTBE)	6.4E-09		6.4E-09	D

Table A-14c (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIGNITE COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of lignite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Naphthalene	2.6E-06		2.6E-06	D
Propylene	5.6E-05		5.6E-05	D
Styrene	4.6E-09		4.6E-09	D
Toluene	5.1E-04		5.1E-04	D
Trichloroethane	5.5E-09		5.5E-09	D
Vinyl Acetate	1.4E-09		1.4E-09	D
Xylenes	3.0E-04		3.0E-04	D
Bromoform	7.2E-09		7.2E-09	D
Chloroform	1.1E-08		1.1E-08	D
Carbon Disulfide	2.4E-08		2.4E-08	D
Dimethyl Sulfate	8.8E-09		8.8E-09	D
Cumene	9.8E-10		9.8E-10	D
Cyanide	4.6E-07		4.6E-07	D
Perchloroethylene	4.9E-07	2.2E-05	2.2E-05	D
Methylene Chloride	1.4E-05	1.5E-04	1.6E-04	D
Carbon Tetrachloride	2.0E-07		2.0E-07	D
Phenols	8.0E-06	8.0E-06	1.6E-05	D
Fluorides	6.6E-07		6.6E-07	D
Polyaromatic Hydrocarbons (total)	3.8E-06	1.0E-05	1.4E-05	E
Biphenyl	1.3E-08	8.5E-07	8.6E-07	E
Acenaphthene	4.0E-09	2.6E-07	2.6E-07	E
Acenaphthylene	2.0E-09	1.3E-07	1.3E-07	E
Anthracene	1.6E-09	1.1E-07	1.1E-07	E
Benzo(a)anthracene	6.3E-10	4.0E-08	4.1E-08	E
Benzo(a)pyrene	3.0E-10	1.9E-08	1.9E-08	E
Benzo(b,j,k)fluroanthene	8.6E-10	5.5E-08	5.6E-08	E
Benzo(g,h,i) perylene	2.1E-10	1.4E-08	1.4E-08	E
Chrysene	7.8E-10	5.0E-08	5.1E-08	E
Fluoranthene	5.5E-09	3.6E-07	3.6E-07	E
Fluorene	7.1E-09	4.6E-07	4.6E-07	E
Indeno(1,2,3-cd)pyrene	4.8E-10	3.1E-08	3.1E-08	E
Naphthanlene	1.0E-07	6.5E-06	6.6E-06	E
Phenanthrene	2.1E-08	1.4E-06	1.4E-06	E
Pyrene	2.6E-09	1.7E-07	1.7E-07	E
5-methyl Chrysene	1.7E-10	1.1E-08	1.1E-08	E
Dioxins (unspecified)	7.3E-09		7.3E-09	D
Furans (unspecified)	3.5E-11		3.5E-11	D
CFC12	2.1E-09		2.1E-09	D
Radionuclides (unspecified)	6.0E-04	3.5E-04	9.4E-04	C
Waterborne Emissions				
Acid (unspecified)	1.8E-05		1.8E-05	E
Acid (benzoic)	8.4E-05		8.4E-05	E
Acid (hexanoic)	1.7E-05		1.7E-05	E
Metal (unspecified)	0.23		0.23	E
Dissolved Solids	3.69		3.69	E
Suspended Solids	0.20	2.5E-03	0.20	D
BOD	0.012		0.012	E
COD	0.0086		0.0086	E
Phenol/Phenolic Compounds	4.1E-05		4.1E-05	E
Sulfur	2.2E-04		2.2E-04	E
Sulfates	0.014		0.014	E
Sulfides	3.4E-06		3.4E-06	E
Oil	0.0019	1.2E-03	0.0031	D
Hydrocarbons	1.7E-05		1.7E-05	E
Ammonia	0.0015		0.0015	E
Ammonium	4.7E-06		4.7E-06	E
Aluminum	0.0064		0.0064	E
Antimony	4.0E-06		4.0E-06	E
Arsenic	2.2E-05		2.2E-05	E
Barium	0.088		0.088	E
Beryllium	1.2E-06		1.2E-06	E
Cadmium	3.3E-06		3.3E-06	E
Chromium (unspecified)	1.8E-04		1.8E-04	E
Cobalt	1.8E-06		1.8E-06	E
Copper	2.4E-05		2.4E-05	E

Table A-14c (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIGNITE COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of lignite coal)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.013		0.013	E
Lead	4.5E-05		4.5E-05	E
Lithium	0.016		0.016	E
Magnesium	0.052		0.052	E
Manganese	3.6E-04		3.6E-04	E
Mercury	7.1E-08		7.1E-08	E
Molybdenum	1.9E-06		1.9E-06	E
Nickel	2.1E-05		2.1E-05	E
Selenium	2.4E-06		2.4E-06	E
Silver	1.7E-04		1.7E-04	E
Sodium	0.84		0.84	E
Strontium	0.0045		0.0045	E
Thallium	8.4E-07		8.4E-07	E
Tin	1.7E-05		1.7E-05	E
Titanium	6.1E-05		6.1E-05	E
Vanadium	2.3E-06		2.3E-06	E
Yttrium	5.6E-07		5.6E-07	E
Zinc	1.5E-04		1.5E-04	E
Chlorides (unspecified)	2.99		2.99	E
Chlorides (methyl chloride)	3.3E-09		3.3E-09	E
Calcium	0.27		0.27	E
Fluorine/ Fluorides	7.7E-05		7.7E-05	E
Nitrates	1.2E-05		1.2E-05	E
Nitrogen (ammonia)	4.1E-06		4.1E-06	E
Bromide	0.018		0.018	E
Boron	2.6E-04		2.6E-04	E
Organic Carbon	7.6E-05		7.6E-05	E
Cyanide	6.0E-09		6.0E-09	E
Hardness	0.82		0.82	E
Total Alkalinity	0.0066		0.0066	E
Surfactants	7.1E-05		7.1E-05	E
Acetone	8.3E-07		8.3E-07	E
Alkylated Benzenes	3.5E-06		3.5E-06	E
Alkylated Fluorenes	2.0E-07		2.0E-07	E
Alkylated Naphthalenes	5.7E-08		5.7E-08	E
Alkylated Phenanthrenes	2.4E-08		2.4E-08	E
Benzene	1.4E-04		1.4E-04	E
Cresols	4.9E-06		4.9E-06	E
Cymene	8.3E-09		8.3E-09	E
Dibenzofuran	1.6E-08		1.6E-08	E
Dibenzothiophene	1.3E-08		1.3E-08	E
2,4 dimethylphenol	2.3E-06		2.3E-06	E
Ethylbenzene	7.8E-06		7.8E-06	E
2-Hexanone	5.4E-07		5.4E-07	E
Methyl ethyl Ketone (MEK)	6.7E-09		6.7E-09	E
1-methylfluorene	9.4E-09		9.4E-09	E
2-methyl naphthalene	1.3E-06		1.3E-06	E
4-methyl- 2-pentanone	3.5E-07		3.5E-07	E
Naphthalene	1.5E-06		1.5E-06	E
Pentamethyl benzene	6.2E-09		6.2E-09	E
Phenanthrene	2.1E-08		2.1E-08	E
Toluene	1.3E-04		1.3E-04	E
Total Biphenyls	2.3E-07		2.3E-07	E
Total dibenzo- thiophenes	7.0E-10		7.0E-10	E
Xylenes	7.0E-05		7.0E-05	E
Radionuclides (unspecified)	8.4E-09		8.4E-09	E
Solid Waste	5.77	182	188	B

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-65, A-67 through A-72, A-74, A-76.

Source: Franklin Associates, A Division of ERG

Table A-15a

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF ANTHRACITE COAL IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 pounds of anthracite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.11	3.22	5.34	C
Particulates (PM10)	0.0060	0.45	0.46	D
Nitrogen Oxides	0.25	7.12	7.37	C
Hydrocarbons (unspecified)	0.024		0.024	D
VOC (unspecified)	0.042		0.042	D
TNMOC (unspecified)	3.7E-04	0.068	0.069	C
Sulfur Dioxide	0.15	45.4	45.6	C
Sulfur Oxides	0.051		0.051	C
Carbon Monoxide	0.24	0.68	0.92	C
Fossil CO2	58.1	2,840	2,898	C
Non-Fossil CO2	0.35		0.35	D
Aldehydes (Formaldehyde)	2.7E-05	0.0066	0.0067	C
Aldehydes (Acetaldehyde)	4.9E-06	3.7E-04	3.7E-04	D
Aldehydes (Propionaldehyde)	6.5E-10		6.5E-10	D
Aldehydes (unspecified)	5.0E-04		5.0E-04	C
Organics (unspecified)	1.9E-05		1.9E-05	D
Ammonia	2.5E-04		2.5E-04	D
Ammonia Chloride	2.4E-06		2.4E-06	D
Methane	1.69	0.020	1.71	C
Kerosene	4.4E-06		4.4E-06	D
Chorine	1.4E-06		1.4E-06	D
HCl	0.0043		0.0043	C
HF	6.6E-04	0.50	0.50	C
Metals (unspecified)	7.7E-05		7.7E-05	D
Mercaptan	3.5E-07		3.5E-07	D
Antimony	7.1E-08		7.1E-08	C
Arsenic	1.9E-06	1.0E-04	1.0E-04	C
Beryllium	2.9E-07	8.0E-05	8.0E-05	C
Cadmium	5.0E-07	4.9E-05	5.0E-05	C
Chromium (VI)	2.5E-07		2.5E-07	C
Chromium (unspecified)	4.0E-06	0.0070	0.0070	D
Cobalt	1.7E-06		1.7E-06	C
Copper	3.7E-07		3.7E-07	D
Lead	3.4E-06	0.0029	0.0029	C
Magnesium	3.5E-05		3.5E-05	C
Manganese	5.9E-06	9.6E-04	9.6E-04	C
Mercury	7.5E-07	6.7E-04	6.7E-04	C
Nickel	2.3E-05	0.0066	0.0066	C
Selenium	5.4E-06	6.5E-04	6.6E-04	C
Zinc	2.5E-07		2.5E-07	D
Acetophenone	2.6E-11		2.6E-11	D
Acrolein	8.5E-06	4.4E-06	1.3E-05	D
Nitrous Oxide	0.0011		0.0011	C
Benzene	2.1E-04	0.095	0.095	D
Benzyl Chloride	1.2E-09		1.2E-09	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.3E-10		1.3E-10	D
1,3 Butadiene	1.7E-07		1.7E-07	D
2-Chloroacetophenone	1.2E-11		1.2E-11	D
Chlorobenzene	3.8E-11		3.8E-11	D
2,4-Dinitrotoluene	4.8E-13		4.8E-13	D
Ethyl Chloride	7.2E-11		7.2E-11	D
Ethylbenzene	1.9E-05		1.9E-05	D
Ethylene Dibromide	2.1E-12		2.1E-12	D
Ethylene Dichloride	6.9E-11		6.9E-11	D
Hexane	1.2E-10		1.2E-10	D
Isophorone ($C_9H_{14}O$)	1.0E-09		1.0E-09	D
Methyl Bromide	2.7E-10		2.7E-10	D
Methyl Chloride	9.1E-10		9.1E-10	D
Methyl Ethyl Ketone	6.7E-10		6.7E-10	D
Methyl Hydrazine	2.9E-10		2.9E-10	D
Methyl Methacrylate	3.4E-11		3.4E-11	D
Methyl Tert Butyl Ether (MTBE)	6.0E-11		6.0E-11	D
Naphthalene	4.6E-07		4.6E-07	D

Table A-15a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF ANTHRACITE COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of anthracite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Propylene	1.1E-05		1.1E-05	D
Styrene	4.3E-11		4.3E-11	D
Toluene	2.5E-04		2.5E-04	D
Trichloroethane	1.2E-09		1.2E-09	D
Vinyl Acetate	1.3E-11		1.3E-11	D
Xylenes	1.5E-04		1.5E-04	D
Bromoform	6.7E-11		6.7E-11	D
Chloroform	1.0E-10		1.0E-10	D
Carbon Disulfide	2.2E-10		2.2E-10	D
Dimethyl Sulfate	8.2E-11		8.2E-11	D
Cumene	9.1E-12		9.1E-12	D
Cyanide	4.3E-09		4.3E-09	D
Perchloroethylene	1.9E-07		1.9E-07	D
Methylene Chloride	4.6E-06		4.6E-06	D
Carbon Tetrachloride	8.1E-08		8.1E-08	D
Phenols	2.5E-06		2.5E-06	D
Fluorides	2.8E-07		2.8E-07	D
Polyaromatic Hydrocarbons (total)	3.2E-05	0.081	0.081	E
Biphenyl	4.8E-06	0.013	0.013	E
Acenaphthene	1.6E-09		1.6E-09	E
Acenaphthylene	7.9E-10		7.9E-10	E
Anthracene	6.6E-10		6.6E-10	E
Benzo(a)anthracene	2.5E-10		2.5E-10	E
Benzo(a)pyrene	1.2E-10		1.2E-10	E
Benzo(b,j,k)fluroanthene	3.5E-10		3.5E-10	E
Benzo(g,h,i) perylene	8.5E-11		8.5E-11	E
Chrysene	3.2E-10		3.2E-10	E
Fluoranthene	2.2E-09		2.2E-09	E
Fluorene	2.9E-09		2.9E-09	E
Indeno(1,2,3-cd)pyrene	1.9E-10		1.9E-10	E
Naphthalene	2.5E-05	0.065	0.065	E
Phenanthrene	1.3E-06	0.0034	0.0034	E
Pyrene	1.0E-09		1.0E-09	E
5-methyl Chrysene	6.9E-11		6.9E-11	E
Dioxins (unspecified)	3.0E-09		3.0E-09	D
Furans (unspecified)	1.4E-11		1.4E-11	D
CFC12	1.4E-09		1.4E-09	D
Radionuclides (unspecified)	2.5E-04		2.5E-04	C
Waterborne Emissions				
Acid (unspecified)	9.0E-06		9.0E-06	E
Acid (benzoic)	5.1E-05		5.1E-05	E
Acid (hexanoic)	1.1E-05		1.1E-05	E
Metal (unspecified)	0.11		0.11	E
Dissolved Solids	2.25		2.25	E
Suspended Solids	0.38	2.2E-03	0.39	D
BOD	0.0052		0.0052	E
COD	0.0049		0.0049	E
Phenol/Phenolic Compounds	2.5E-05		2.5E-05	E
Sulfur	1.3E-04		1.3E-04	E
Sulfates	0.0069		0.0069	E
Sulfides	2.2E-06		2.2E-06	E
Oil	0.0011	1.1E-03	0.0022	D
Hydrocarbons	1.0E-05		1.0E-05	E
Ammonia	9.0E-04		9.0E-04	E
Ammonium	2.0E-06		2.0E-06	E
Aluminum	0.0040		0.0040	E
Antimony	2.5E-06		2.5E-06	E
Arsenic	1.4E-05		1.4E-05	E
Barium	0.055		0.055	E
Beryllium	7.4E-07		7.4E-07	E
Cadmium	2.0E-06		2.0E-06	E
Chromium (unspecified)	1.1E-04		1.1E-04	E
Cobalt	1.1E-06		1.1E-06	E
Copper	1.4E-05		1.4E-05	E

Table A-15a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF ANTHRACITE COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of anthracite coal)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.030		0.030	E
Lead	2.8E-05		2.8E-05	E
Lithium	0.0080		0.0080	E
Magnesium	0.032		0.032	E
Manganese	0.015		0.015	E
Mercury	4.4E-08		4.4E-08	E
Molybdenum	1.2E-06		1.2E-06	E
Nickel	1.3E-05		1.3E-05	E
Selenium	1.2E-06		1.2E-06	E
Silver	1.1E-04		1.1E-04	E
Sodium	0.51		0.51	E
Strontium	0.0028		0.0028	E
Thallium	5.3E-07		5.3E-07	E
Tin	1.1E-05		1.1E-05	E
Titanium	3.8E-05		3.8E-05	E
Vanadium	1.4E-06		1.4E-06	E
Yttrium	3.4E-07		3.4E-07	E
Zinc	9.4E-05		9.4E-05	E
Chlorides (unspecified)	1.82		1.82	E
Chlorides (methyl chloride)	2.0E-09		2.0E-09	E
Calcium	0.16		0.16	E
Fluorine/ Fluorides	3.2E-05		3.2E-05	E
Nitrates	4.9E-06		4.9E-06	E
Nitrogen (ammonia)	1.7E-06		1.7E-06	E
Bromide	0.011		0.011	E
Boron	1.6E-04		1.6E-04	E
Organic Carbon	3.7E-05		3.7E-05	E
Cyanide	3.6E-09		3.6E-09	E
Hardness	0.50		0.50	E
Total Alkalinity	0.0040		0.0040	E
Surfactants	4.3E-05		4.3E-05	E
Acetone	5.0E-07		5.0E-07	E
Alkylated Benzenes	2.2E-06		2.2E-06	E
Alkylated Fluorenes	1.3E-07		1.3E-07	E
Alkylated Naphthalenes	3.6E-08		3.6E-08	E
Alkylated Phenanthrenes	1.5E-08		1.5E-08	E
Benzene	8.5E-05		8.5E-05	E
Cresols	3.0E-06		3.0E-06	E
Cymene	5.0E-09		5.0E-09	E
Dibenzofuran	9.6E-09		9.6E-09	E
Dibenzothiophene	7.8E-09		7.8E-09	E
2,4 dimethylphenol	1.4E-06		1.4E-06	E
Ethylbenzene	4.8E-06		4.8E-06	E
2-Hexanone	3.3E-07		3.3E-07	E
Methyl ethyl Ketone (MEK)	4.1E-09		4.1E-09	E
1-methylfluorene	5.7E-09		5.7E-09	E
2-methyl naphthalene	8.0E-07		8.0E-07	E
4-methyl- 2-pentanone	2.1E-07		2.1E-07	E
Naphthalene	9.2E-07		9.2E-07	E
Pentamethyl benzene	3.8E-09		3.8E-09	E
Phenanthrene	1.3E-08		1.3E-08	E
Toluene	8.0E-05		8.0E-05	E
Total Biphenyls	1.4E-07		1.4E-07	E
Total dibenzo- thiophenes	4.4E-10		4.4E-10	E
Xylenes	4.2E-05		4.2E-05	E
Radionuclides (unspecified)	3.5E-09		3.5E-09	E
Solid Waste	274	10.6	284	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-5, A-15, A-64, A-66 through A-68, A-72, A-74, A-77 through A-80, A-82, A-83.

Source: Franklin Associates, A Division of ERG

Table A-15b

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF BITUMINOUS AND SUBBITUMINOUS COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of bituminous/subbituminous coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	1.65		1.65	C
Particulates (PM10)	0.021	2.00	2.02	D
Nitrogen Oxides	0.77	5.75	6.52	C
Hydrocarbons (unspecified)	0.036		0.036	D
VOC (unspecified)	0.054		0.054	D
TNMOC (unspecified)	7.4E-04	0.14	0.14	C
Sulfur Dioxide	0.25	16.6	16.8	C
Sulfur Oxides	0.081		0.081	C
Carbon Monoxide	0.43	2.89	3.32	C
Fossil CO2	92.5	2,634	2,727	C
Non-Fossil CO2	0.64		0.64	D
Aldehydes (Formaldehyde)	4.5E-05	0.0034	0.0034	C
Aldehydes (Acetaldehyde)	1.3E-05	2.9E-04	3.0E-04	D
Aldehydes (Propionaldehyde)	8.3E-08	1.9E-04	1.9E-04	D
Aldehydes (unspecified)	7.5E-04		7.5E-04	C
Organics (unspecified)	3.7E-05		3.7E-05	D
Ammonia	3.7E-04		3.7E-04	D
Ammonia Chloride	4.5E-06		4.5E-06	D
Methane	4.15	0.12	4.26	B
Kerosene	8.0E-06		8.0E-06	D
Chorine	2.6E-06		2.6E-06	D
HCl	0.0084	0.31	0.31	C
HF	9.4E-04	0.052	0.053	C
Metals (unspecified)	1.4E-04		1.4E-04	D
Mercaptan	4.7E-05	0.11	0.11	D
Antimony	1.4E-07	9.0E-06	9.1E-06	C
Arsenic	3.5E-06	1.6E-04	1.6E-04	C
Beryllium	5.9E-07	7.8E-06	8.3E-06	C
Cadmium	9.4E-07	4.4E-05	4.5E-05	C
Chromium (VI)	5.0E-07	4.0E-05	4.0E-05	C
Chromium (unspecified)	2.4E-06	9.9E-05	1.0E-04	D
Cobalt	1.9E-06	5.0E-05	5.2E-05	C
Copper	8.9E-07		8.9E-07	D
Lead	5.2E-06	0.0018	0.0018	C
Magnesium	7.0E-05	0.0055	0.0056	C
Manganese	9.9E-06	1.8E-04	1.9E-04	C
Mercury	1.3E-06	6.5E-04	6.6E-04	C
Nickel	2.0E-05	1.7E-04	1.9E-04	C
Selenium	1.1E-05	6.5E-04	6.6E-04	C
Zinc	5.9E-07		5.9E-07	D
Acetophenone	3.3E-09	7.5E-06	7.5E-06	D
Acrolein	1.6E-05	7.5E-05	9.1E-05	D
Nitrous Oxide	0.0018	0.37	0.37	C
Benzene	3.1E-04	0.048	0.048	D
Benzyl Chloride	1.5E-07	3.5E-04	3.5E-04	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-08	3.7E-05	3.7E-05	D
1,3 Butadiene	5.1E-07		5.1E-07	D
2-Chloroacetophenone	1.5E-09	3.5E-06	3.5E-06	D
Chlorobenzene	4.8E-09	1.1E-05	1.1E-05	D
2,4-Dinitrotoluene	6.1E-11	1.4E-07	1.4E-07	D
Ethyl Chloride	9.2E-09	2.1E-05	2.1E-05	D
Ethylbenzene	3.1E-05	4.7E-05	7.8E-05	D
Ethylene Dibromide	2.6E-10	6.0E-07	6.0E-07	D
Ethylene Dichloride	8.7E-09	2.0E-05	2.0E-05	D
Hexane	1.5E-08	3.4E-05	3.4E-05	D
Isophorone ($C_9H_{14}O$)	1.3E-07	2.9E-04	2.9E-04	D
Methyl Bromide	3.5E-08	8.0E-05	8.0E-05	D
Methyl Chloride	1.2E-07	2.7E-04	2.7E-04	D
Methyl Ethyl Ketone	8.5E-08	2.0E-04	2.0E-04	D
Methyl Hydrazine	3.7E-08	8.5E-05	8.5E-05	D
Methyl Methacrylate	4.4E-09	1.0E-05	1.0E-05	D
Methyl Tert Butyl Ether (MTBE)	7.6E-09	1.8E-05	1.8E-05	D
Naphthalene	6.0E-07		6.0E-07	D

Table A-15b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF BITUMINOUS AND SUBBITUMINOUS COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of bituminous/subbituminous coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Propylene	3.3E-05		3.3E-05	D
Styrene	5.5E-09	1.3E-05	1.3E-05	D
Toluene	4.1E-04	1.2E-04	5.3E-04	D
Trichloroethane	6.1E-09	1.0E-05	1.0E-05	D
Vinyl Acetate	1.7E-09	3.8E-06	3.8E-06	D
Xylenes	2.4E-04	1.9E-05	2.6E-04	D
Bromoform	8.5E-09	2.0E-05	2.0E-05	D
Chloroform	1.3E-08	3.0E-05	3.0E-05	D
Carbon Disulfide	2.8E-08	6.5E-05	6.5E-05	D
Dimethyl Sulfate	1.0E-08	2.4E-05	2.4E-05	D
Cumene	1.2E-09	2.7E-06	2.7E-06	D
Cyanide	5.5E-07	0.0013	0.0013	D
Perchloroethylene	3.7E-07	2.2E-05	2.2E-05	D
Methylene Chloride	8.6E-06	1.5E-04	1.5E-04	D
Carbon Tetrachloride	1.5E-07		1.5E-07	D
Phenols	4.6E-06	8.0E-06	1.3E-05	D
Fluorides	1.0E-05	0.022	0.022	D
Polyaromatic Hydrocarbons (total)	2.3E-06	1.0E-05	1.3E-05	E
Biphenyl	1.1E-08	8.5E-07	8.6E-07	E
Acenaphthene	3.2E-09	2.6E-07	2.6E-07	E
Acenaphthylene	1.6E-09	1.3E-07	1.3E-07	E
Anthracene	1.3E-09	1.1E-07	1.1E-07	E
Benzo(a)anthracene	5.1E-10	4.0E-08	4.1E-08	E
Benzo(a)pyrene	2.4E-10	1.9E-08	1.9E-08	E
Benzo(b,j,k)fluroanthene	7.0E-10	5.5E-08	5.6E-08	E
Benzo(g,h,i) perylene	1.7E-10	1.4E-08	1.4E-08	E
Chrysene	6.3E-10	5.0E-08	5.1E-08	E
Fluoranthene	4.5E-09	3.6E-07	3.6E-07	E
Fluorene	5.8E-09	4.6E-07	4.6E-07	E
Indeno(1,2,3-cd)pyrene	3.9E-10	3.1E-08	3.1E-08	E
Naphthanlene	8.2E-08	6.5E-06	6.6E-06	E
Phenanthrene	1.7E-08	1.4E-06	1.4E-06	E
Pyrene	2.1E-09	1.7E-07	1.7E-07	E
5-methyl Chrysene	1.4E-10	1.1E-08	1.1E-08	E
Dioxins (unspecified)	5.5E-09		5.5E-09	D
Furans (unspecified)	2.8E-11		2.8E-11	D
CFC12	2.0E-09		2.0E-09	D
Radionuclides (unspecified)	4.5E-04		4.5E-04	C
Waterborne Emissions				
Acid (unspecified)	1.5E-05		1.5E-05	E
Acid (benzoic)	7.8E-05		7.8E-05	E
Acid (hexanoic)	1.6E-05		1.6E-05	E
Metal (unspecified)	0.18		0.18	E
Dissolved Solids	3.42		3.42	E
Suspended Solids	0.29	2.0E-03	0.29	D
BOD	0.0091		0.0091	E
COD	0.0075		0.0075	E
Phenol/Phenolic Compounds	3.8E-05		3.8E-05	E
Sulfur	2.0E-04		2.0E-04	E
Sulfates	0.011		0.011	E
Sulfides	3.3E-06		3.3E-06	E
Oil	0.0017	1.0E-03	0.0027	D
Hydrocarbons	1.5E-05		1.5E-05	E
Ammonia	0.0014		0.0014	E
Ammonium	3.6E-06		3.6E-06	E
Aluminum	0.0061		0.0061	E
Antimony	3.8E-06		3.8E-06	E
Arsenic	2.1E-05		2.1E-05	E
Barium	0.083		0.083	E
Beryllium	1.1E-06		1.1E-06	E
Cadmium	3.1E-06		3.1E-06	E
Chromium (unspecified)	1.7E-04		1.7E-04	E
Cobalt	1.7E-06		1.7E-06	E
Copper	2.2E-05		2.2E-05	E

Table A-15b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF BITUMINOUS AND SUBBITUMINOUS COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of bituminous/subbituminous coal)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.021		0.021	E
Lead	4.2E-05		4.2E-05	E
Lithium	0.013		0.013	E
Magnesium	0.048		0.048	E
Manganese	0.0059		0.0059	E
Mercury	6.7E-08		6.7E-08	E
Molybdenum	1.8E-06		1.8E-06	E
Nickel	2.0E-05		2.0E-05	E
Selenium	2.0E-06		2.0E-06	E
Silver	1.6E-04		1.6E-04	E
Sodium	0.78		0.78	E
Strontium	0.0042		0.0042	E
Thallium	7.9E-07		7.9E-07	E
Tin	1.6E-05		1.6E-05	E
Titanium	5.8E-05		5.8E-05	E
Vanadium	2.1E-06		2.1E-06	E
Yttrium	5.2E-07		5.2E-07	E
Zinc	1.4E-04		1.4E-04	E
Chlorides (unspecified)	2.77		2.77	E
Chlorides (methyl chloride)	3.1E-09		3.1E-09	E
Calcium	0.25		0.25	E
Fluorine/ Fluorides	5.8E-05		5.8E-05	E
Nitrates	8.9E-06		8.9E-06	E
Nitrogen (ammonia)	3.1E-06		3.1E-06	E
Bromide	0.016		0.016	E
Boron	2.4E-04		2.4E-04	E
Organic Carbon	6.0E-05		6.0E-05	E
Cyanide	5.5E-09		5.5E-09	E
Hardness	0.76		0.76	E
Total Alkalinity	0.0061		0.0061	E
Surfactants	6.6E-05		6.6E-05	E
Acetone	7.7E-07		7.7E-07	E
Alkylated Benzenes	3.3E-06		3.3E-06	E
Alkylated Fluorenes	1.9E-07		1.9E-07	E
Alkylated Naphthalenes	5.4E-08		5.4E-08	E
Alkylated Phenanthrenes	2.2E-08		2.2E-08	E
Benzene	1.3E-04		1.3E-04	E
Cresols	4.5E-06		4.5E-06	E
Cymene	7.7E-09		7.7E-09	E
Dibenzofuran	1.5E-08		1.5E-08	E
Dibenzothiophene	1.2E-08		1.2E-08	E
2,4 dimethylphenol	2.2E-06		2.2E-06	E
Ethylbenzene	7.2E-06		7.2E-06	E
2-Hexanone	5.0E-07		5.0E-07	E
Methyl ethyl Ketone (MEK)	6.2E-09		6.2E-09	E
1-methylfluorene	8.7E-09		8.7E-09	E
2-methyl naphthalene	1.2E-06		1.2E-06	E
4-methyl- 2-pentanone	3.2E-07		3.2E-07	E
Naphthalene	1.4E-06		1.4E-06	E
Pentamethyl benzene	5.8E-09		5.8E-09	E
Phenanthrene	2.0E-08		2.0E-08	E
Toluene	1.2E-04		1.2E-04	E
Total Biphenyls	2.1E-07		2.1E-07	E
total dibenzo- thiophenes	6.6E-10		6.6E-10	E
Xylenes	6.5E-05		6.5E-05	E
Radionuclides (unspecified)	6.3E-09		6.3E-09	E
Solid Waste	240	62.1	302	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-5, A-15, A-64, A-66 through A-68, A-74, A-77 through A-80, A-82, and A-83.

Source: Franklin Associates, A Division of ERG

Table A-15c

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIGNITE COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of lignite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	0.13	8.59	8.72	C
Particulates (PM10)	0.010	0.37	0.38	D
Nitrogen Oxides	0.33	5.97	6.31	C
Hydrocarbons (unspecified)	0.038		0.038	D
VOC (unspecified)	0.010		0.010	D
TNMOC (unspecified)	8.5E-04	0.032	0.032	C
Sulfur Dioxide	0.31	12.9	13.2	C
Sulfur Oxides	0.14		0.14	C
Carbon Monoxide	0.47	0.40	0.88	C
Fossil CO2	106	2,300	2,406	C
Non-Fossil CO2	0.85		0.85	D
Aldehydes (Formaldehyde)	1.2E-04	0.0034	0.0035	C
Aldehydes (Acetaldehyde)	2.0E-05	2.9E-04	3.1E-04	D
Aldehydes (Propionaldehyde)	7.0E-08	1.9E-04	1.9E-04	D
Aldehydes (unspecified)	7.8E-04		7.8E-04	C
Organics (unspecified)	4.7E-05		4.7E-05	D
Ammonia	3.9E-04		3.9E-04	D
Ammonia Chloride	5.9E-06		5.9E-06	D
Methane	1.30	0.020	1.32	C
Kerosene	1.1E-05		1.1E-05	D
Chorine	3.4E-06		3.4E-06	D
HCl	0.011	0.60	0.61	C
HF	0.0012	0.075	0.076	C
Metals (unspecified)	1.9E-04		1.9E-04	D
Mercaptan	8.2E-07		8.2E-07	D
Antimony	1.8E-07	9.0E-06	9.2E-06	C
Arsenic	5.9E-06	1.6E-04	1.6E-04	C
Beryllium	3.0E-07	7.8E-06	8.1E-06	C
Cadmium	1.3E-06	4.4E-05	4.6E-05	C
Chromium (VI)	6.2E-07	4.0E-05	4.0E-05	C
Chromium (unspecified)	3.9E-06	9.9E-05	1.0E-04	D
Cobalt	1.2E-05	5.0E-05	6.2E-05	C
Copper	1.6E-07		1.6E-07	D
Lead	3.1E-05	0.069	0.069	C
Magnesium	8.6E-05	0.0055	0.0056	C
Manganese	1.7E-05	1.8E-04	2.0E-04	C
Mercury	1.2E-06	6.5E-04	6.6E-04	C
Nickel	1.6E-04	1.7E-04	3.4E-04	C
Selenium	1.2E-05	6.5E-04	6.6E-04	C
Zinc	1.1E-07		1.1E-07	D
Acetophenone	2.8E-09	7.5E-06	7.5E-06	D
Acrolein	2.2E-05	7.5E-05	9.6E-05	D
Nitrous Oxide	0.0014		0.0014	C
Benzene	3.9E-04	0.048	0.048	D
Benzyl Chloride	1.3E-07	3.5E-04	3.5E-04	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.3E-08	3.7E-05	3.7E-05	D
1,3 Butadiene	8.5E-07		8.5E-07	D
2-Chloroacetophenone	1.3E-09	3.5E-06	3.5E-06	D
Chlorobenzene	4.0E-09	1.1E-05	1.1E-05	D
2,4-Dinitrotoluene	5.2E-11	1.4E-07	1.4E-07	D
Ethyl Chloride	7.7E-09	2.1E-05	2.1E-05	D
Ethylbenzene	3.9E-05	4.7E-05	8.6E-05	D
Ethylene Dibromide	2.2E-10	6.0E-07	6.0E-07	D
Ethylene Dichloride	7.4E-09	2.0E-05	2.0E-05	D
Hexane	1.2E-08	3.4E-05	3.4E-05	D
Isophorone ($C_9H_{14}O$)	1.1E-07	2.9E-04	2.9E-04	D
Methyl Bromide	2.9E-08	8.0E-05	8.0E-05	D
Methyl Chloride	9.8E-08	2.7E-04	2.7E-04	D
Methyl Ethyl Ketone	7.2E-08	2.0E-04	2.0E-04	D
Methyl Hydrazine	3.1E-08	8.5E-05	8.5E-05	D
Methyl Methacrylate	3.7E-09	1.0E-05	1.0E-05	D
Methyl Tert Butyl Ether (MTBE)	6.4E-09	1.8E-05	1.8E-05	D
Naphthalene	2.6E-06		2.6E-06	D

Table A-15c (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIGNITE COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of lignite coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Propylene	5.6E-05		5.6E-05	D
Styrene	4.6E-09	1.3E-05	1.3E-05	D
Toluene	5.1E-04	1.2E-04	6.3E-04	D
Trichloroethane	5.5E-09	1.0E-05	1.0E-05	D
Vinyl Acetate	1.4E-09	3.8E-06	3.8E-06	D
Xylenes	3.0E-04	1.9E-05	3.2E-04	D
Bromoform	7.2E-09	2.0E-05	2.0E-05	D
Chloroform	1.1E-08	3.0E-05	3.0E-05	D
Carbon Disulfide	2.4E-08	6.5E-05	6.5E-05	D
Dimethyl Sulfate	8.8E-09	2.4E-05	2.4E-05	D
Cumene	9.8E-10	2.7E-06	2.7E-06	D
Cyanide	4.6E-07	0.0013	0.0013	D
Perchloroethylene	4.9E-07	2.2E-05	2.2E-05	D
Methylene Chloride	1.4E-05	1.5E-04	1.6E-04	D
Carbon Tetrachloride	2.0E-07		2.0E-07	D
Phenols	8.0E-06	8.0E-06	1.6E-05	D
Fluorides	6.6E-07		6.6E-07	D
Polyaromatic Hydrocarbons (total)	3.8E-06	1.0E-05	1.4E-05	E
Biphenyl	1.3E-08	8.5E-07	8.6E-07	E
Acenaphthene	4.0E-09	2.6E-07	2.6E-07	E
Acenaphthylene	2.0E-09	1.3E-07	1.3E-07	E
Anthracene	1.6E-09	1.1E-07	1.1E-07	E
Benzo(a)anthracene	6.3E-10	4.0E-08	4.1E-08	E
Benzo(a)pyrene	3.0E-10	1.9E-08	1.9E-08	E
Benzo(b,j,k)fluroanthene	8.6E-10	5.5E-08	5.6E-08	E
Benzo(g,h,i) perylene	2.1E-10	1.4E-08	1.4E-08	E
Chrysene	7.8E-10	5.0E-08	5.1E-08	E
Fluoranthene	5.5E-09	3.6E-07	3.6E-07	E
Fluorene	7.1E-09	4.6E-07	4.6E-07	E
Indeno(1,2,3-cd)pyrene	4.8E-10	3.1E-08	3.1E-08	E
Naphthanlene	1.0E-07	6.5E-06	6.6E-06	E
Phenanthrene	2.1E-08	1.4E-06	1.4E-06	E
Pyrene	2.6E-09	1.7E-07	1.7E-07	E
5-methyl Chrysene	1.7E-10	1.1E-08	1.1E-08	E
Dioxins (unspecified)	7.3E-09		7.3E-09	D
Furans (unspecified)	3.5E-11		3.5E-11	D
CFC12	2.1E-09		2.1E-09	D
Radionuclides (unspecified)	6.0E-04		6.0E-04	C
Waterborne Emissions				
Acid (unspecified)	1.8E-05		1.8E-05	E
Acid (benzoic)	8.4E-05		8.4E-05	E
Acid (hexanoic)	1.7E-05		1.7E-05	E
Metal (unspecified)	0.23		0.23	E
Dissolved Solids	3.69		3.69	E
Suspended Solids	0.20	1.6E-03	0.20	D
BOD	0.012		0.012	E
COD	0.0086		0.0086	E
Phenol/Phenolic Compounds	4.1E-05		4.1E-05	E
Sulfur	2.2E-04		2.2E-04	E
Sulfates	0.014		0.014	E
Sulfides	3.4E-06		3.4E-06	E
Oil	0.0019	8.0E-04	0.0027	D
Hydrocarbons	1.7E-05		1.7E-05	E
Ammonia	0.0015		0.0015	E
Ammonium	4.7E-06		4.7E-06	E
Aluminum	0.0064		0.0064	E
Antimony	4.0E-06		4.0E-06	E
Arsenic	2.2E-05		2.2E-05	E
Barium	0.088		0.088	E
Beryllium	1.2E-06		1.2E-06	E
Cadmium	3.3E-06		3.3E-06	E
Chromium (unspecified)	1.8E-04		1.8E-04	E
Cobalt	1.8E-06		1.8E-06	E
Copper	2.4E-05		2.4E-05	E

Table A-15c (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIGNITE COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of lignite coal)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.013		0.013	E
Lead	4.5E-05		4.5E-05	E
Lithium	0.016		0.016	E
Magnesium	0.052		0.052	E
Manganese	3.6E-04		3.6E-04	E
Mercury	7.1E-08		7.1E-08	E
Molybdenum	1.9E-06		1.9E-06	E
Nickel	2.1E-05		2.1E-05	E
Selenium	2.4E-06		2.4E-06	E
Silver	1.7E-04		1.7E-04	E
Sodium	0.84		0.84	E
Strontium	0.0045		0.0045	E
Thallium	8.4E-07		8.4E-07	E
Tin	1.7E-05		1.7E-05	E
Titanium	6.1E-05		6.1E-05	E
Vanadium	2.3E-06		2.3E-06	E
Yttrium	5.6E-07		5.6E-07	E
Zinc	1.5E-04		1.5E-04	E
Chlorides (unspecified)	2.99		2.99	E
Chlorides (methyl chloride)	3.3E-09		3.3E-09	E
Calcium	0.27		0.27	E
Fluorine/ Fluorides	7.7E-05		7.7E-05	E
Nitrates	1.2E-05		1.2E-05	E
Nitrogen (ammonia)	4.1E-06		4.1E-06	E
Bromide	0.018		0.018	E
Boron	2.6E-04		2.6E-04	E
Organic Carbon	7.6E-05		7.6E-05	E
Cyanide	6.0E-09		6.0E-09	E
Hardness	0.82		0.82	E
Total Alkalinity	0.0066		0.0066	E
Surfactants	7.1E-05		7.1E-05	E
Acetone	8.3E-07		8.3E-07	E
Alkylated Benzenes	3.5E-06		3.5E-06	E
Alkylated Fluorenes	2.0E-07		2.0E-07	E
Alkylated Naphthalenes	5.7E-08		5.7E-08	E
Alkylated Phenanthrenes	2.4E-08		2.4E-08	E
Benzene	1.4E-04		1.4E-04	E
Cresols	4.9E-06		4.9E-06	E
Cymene	8.3E-09		8.3E-09	E
Dibenzofuran	1.6E-08		1.6E-08	E
Dibenzothiophene	1.3E-08		1.3E-08	E
2,4 dimethylphenol	2.3E-06		2.3E-06	E
Ethylbenzene	7.8E-06		7.8E-06	E
2-Hexanone	5.4E-07		5.4E-07	E
Methyl ethyl Ketone (MEK)	6.7E-09		6.7E-09	E
1-methylfluorene	9.4E-09		9.4E-09	E
2-methyl naphthalene	1.3E-06		1.3E-06	E
4-methyl- 2-pentanone	3.5E-07		3.5E-07	E
Naphthalene	1.5E-06		1.5E-06	E
Pentamethyl benzene	6.2E-09		6.2E-09	E
Phenanthrene	2.1E-08		2.1E-08	E
Toluene	1.3E-04		1.3E-04	E
Total Biphenyls	2.3E-07		2.3E-07	E
Total dibenzo- thiophenes	7.0E-10		7.0E-10	E
Xylenes	7.0E-05		7.0E-05	E
Radionuclides (unspecified)	8.4E-09		8.4E-09	E
Solid Waste	5.77	61.6	67.4	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-5, A-15, A-64, A-66 through A-68, A-74, A-77 through A-80, A-82, A-83, A-112, and A-113.

Source: Franklin Associates, A Division of ERG

Residual Fuel Oil

Utility Boilers. Fuel oils accounted for 2.8 percent of the total megawatt hours produced by electric utilities in 2000 (Reference A-62). Residual fuel oil represents the majority of the fuel oil consumed by electric utilities. The calculations and assumptions used for estimating the environmental emissions from residual fuel oil combustion in utility boilers are discussed below.

Air emissions from residual fuel oil combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

No data are available for waterborne emissions from utility boilers. Waterborne emissions do not result from the combustion-side of utility boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases from utility boilers (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Utilities using oil-fired boilers do not currently employ flue gas desulfurization units (Reference A-69), which eliminates the possibility of solid wastes from desulfurization equipment. To calculate the solid waste resulting from bottom ash, the fly ash emissions (which are assumed to be equivalent to the airborne particulate emissions) were subtracted from the quantity of ash in the incoming fuel. This appendix assumes an ash content 0.16 percent by weight for residual fuel oil (Reference A-67), resulting in an estimated 10.7 pounds of bottom ash per 1,000 gallons of combusted residual fuel oil.

Industrial Boilers. The calculations and assumptions used for estimating the environmental emissions from residual fuel oil combustion in industrial boilers are discussed below.

Air emissions from residual fuel oil combustion were taken from the GREET transportation model (Reference 1). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (References A-86 and A-50).

No data are available for waterborne emissions from industrial boilers. Waterborne emissions are a negligible part of an industrial facility's total effluent and clean-up system (Reference A-80). Waterborne emissions do not result from the combustion-side of industrial boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Industrial boilers rarely employ flue gas desulfurization units (Reference A-69), which eliminates the possibility of solid wastes from desulfurization equipment. To calculate the solid waste resulting from bottom ash, the fly ash emissions (which are assumed to be equivalent to the airborne particulate emissions) were subtracted from the quantity of ash in the incoming fuel. This appendix assumes an ash content 0.16 percent by weight for residual fuel oil (Reference A-67), resulting in an estimated 10.7 pounds of bottom ash per 1,000 gallons of combusted residual fuel oil.

Distillate Fuel Oil

Utility Boilers. Distillate fuel oil represents a small percentage of the fuel oil burned by utility boilers. The calculations and assumptions used for estimating the environmental emissions from distillate fuel oil combustion in utility boilers are discussed below.

Air emissions from distillate fuel oil combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50). No data are available for distillate fuel oil combustion in utility boilers, so distillate fuel oil combustion in industrial boilers was used as a surrogate.

No data are available for waterborne emissions from utility boilers. Waterborne emissions do not result from the combustion-side of utility boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases from utility boilers (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. The sulfur content of distillate fuel oil is 0.035 percent by weight (Reference A-85), making desulfurization equipment unnecessary. Distillate fuel oil also has a low ash content (Reference A-67), resulting in negligible quantities of bottom ash as well as eliminating the need for particulate controls. Thus, this appendix assumes that negligible solid wastes result from the combustion of distillate fuel oil in utility boilers.

Industrial Boilers. The calculations and assumptions used for estimating the environmental emissions from distillate fuel oil combustion in industrial boilers are discussed below.

Air emissions from distillate fuel oil combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

No data are available for waterborne emissions from industrial boilers. Waterborne emissions are a negligible part of an industrial facility's total effluent and clean-up system (Reference A-80). Waterborne emissions do not result from the combustion-side of industrial boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Such emissions were estimated from federal limits on waterborne releases (Reference A-68) and flow rates of water streams from boiler systems (Reference A-67). Waterborne emissions can include low concentrations of metals, resulting from equipment corrosion, and low concentrations of chlorinated compounds, resulting from cleaning chemicals.

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. The sulfur content of distillate fuel oil is 0.035 percent by weight (Reference A-85), making desulfurization equipment unnecessary. Also, industrial boilers rarely employ desulfurization equipment, regardless of the sulfur content of the fuel. Distillate fuel oil also has a low ash content (Reference A-67), resulting in negligible quantities of bottom ash as well as eliminating the need for particulate controls. Thus, this appendix assumes that negligible solid wastes result from the combustion of distillate fuel oil in utility boilers.

Table A-16

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN UTILITY BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.71		2.71	C
Particulates (PM10)	0.70	1.90	2.60	B
Nitrogen Oxides	27.3	32.0	59.3	B
Hydrocarbons (unspecified)	17.0		17.0	D
VOC (unspecified)	1.08	0.76	1.84	B
TNMOC (unspecified)	0.023		0.023	C
Sulfur Dioxide	15.2		15.2	C
Sulfur Oxides	23.4	40.0	63.4	B
Carbon Monoxide	115	5.00	120	B
Fossil CO2	3,548	25,495	29,043	B
Non-Fossil CO2	24.9		24.9	D
Aldehydes (Formaldehyde)	0.0024	0.033	0.035	B
Aldehydes (Acetaldehyde)	1.9E-04		1.9E-04	D
Aldehydes (Propionaldehyde)	4.2E-08		4.2E-08	D
Aldehydes (unspecified)	0.35		0.35	C
Organics (unspecified)	0.0013		0.0013	D
Ammonia	0.18		0.18	D
Ammonia Chloride	1.7E-04		1.7E-04	D
Methane	38.1	0.28	38.3	B
Kerosene	3.1E-04		3.1E-04	D
Chlorine	1.0E-04		1.0E-04	D
HCl	0.28	0.70	0.97	C
HF	0.031		0.031	C
Metals (unspecified)	0.0055		0.0055	D
Mercaptan	2.3E-05		2.3E-05	D
Antimony	4.8E-06		4.8E-06	C
Arsenic	1.3E-04	0.0013	0.0015	B
Beryllium	6.2E-06	2.8E-05	3.4E-05	B
Cadmium	3.3E-05	4.0E-04	4.3E-04	B
Chromium (VI)	1.7E-05		1.7E-05	C
Chromium (unspecified)	9.4E-05	8.5E-04	9.4E-04	B
Cobalt	2.0E-04	0.0060	0.0062	B
Copper	1.5E-06		1.5E-06	D
Lead	1.5E-04	0.0015	0.0017	B
Magnesium	0.0023		0.0023	C
Manganese	4.0E-04	0.0030	0.0034	B
Mercury	2.4E-05	1.1E-04	1.4E-04	B
Nickel	0.0026	0.085	0.087	B
Selenium	3.0E-04	6.8E-04	9.8E-04	B
Zinc	1.0E-06		1.0E-06	D
Acetophenone	1.7E-09		1.7E-09	D
Acrolein	5.8E-04		5.8E-04	D
Nitrous Oxide	0.066	0.11	0.18	B
Benzene	0.037	2.1E-04	0.037	B
Benzyl Chloride	7.8E-08		7.8E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.2E-09		8.2E-09	D
1,3 Butadiene	4.0E-06		4.0E-06	D
2-Chloroacetophenone	7.8E-10		7.8E-10	D
Chlorobenzene	2.5E-09		2.5E-09	D
2,4-Dinitrotoluene	3.1E-11		3.1E-11	D
Ethyl Chloride	4.7E-09		4.7E-09	D
Ethylbenzene	0.0043		0.0043	D
Ethylene Dibromide	1.3E-10		1.3E-10	D
Ethylene Dichloride	4.5E-09		4.5E-09	D
Hexane	7.5E-09		7.5E-09	D
Isophorone ($C_9H_{14}O$)	6.5E-08		6.5E-08	D
Methyl Bromide	1.8E-08		1.8E-08	D
Methyl Chloride	5.9E-08		5.9E-08	D
Methyl Ethyl Ketone	4.4E-08		4.4E-08	D
Methyl Hydrazine	1.9E-08		1.9E-08	D
Methyl Methacrylate	2.2E-09		2.2E-09	D
Methyl Tert Butyl Ether (MTBE)	3.9E-09		3.9E-09	D
Naphthalene	5.1E-05		5.1E-05	D

Table A-16 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN UTILITY BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Propylene	2.6E-04		2.6E-04	D
Styrene	2.8E-09		2.8E-09	D
Toluene	0.055		0.055	D
Trichloroethane	8.1E-07		8.1E-07	D
Vinyl Acetate	8.5E-10		8.5E-10	D
Xylenes	0.032		0.032	D
Bromoform	4.4E-09		4.4E-09	D
Chloroform	6.6E-09		6.6E-09	D
Carbon Disulfide	1.5E-08		1.5E-08	D
Dimethyl Sulfate	5.4E-09		5.4E-09	D
Cumene	5.9E-10		5.9E-10	D
Cyanide	2.8E-07		2.8E-07	D
Perchloroethylene	1.1E-05	8.2E-05	9.3E-05	C
Methylene Chloride	2.5E-04	0.0048	0.0051	C
Carbon Tetrachloride	5.8E-06		5.8E-06	D
Phenols	1.3E-04	0.0036	0.0038	C
Fluorides	1.9E-05		1.9E-05	D
Polyaromatic Hydrocarbons (total)	2.1E-05		2.1E-05	E
Biphenyl	3.6E-07		3.6E-07	E
Acenaphthene	1.1E-07		1.1E-07	E
Acenaphthylene	5.2E-08		5.2E-08	E
Anthracene	4.4E-08		4.4E-08	E
Benzo(a)anthracene	1.7E-08		1.7E-08	E
Benzo(a)pyrene	7.9E-09		7.9E-09	E
Benzo(b,j,k)fluroanthene	2.3E-08		2.3E-08	E
Benzo(g,h,i) perylene	5.6E-09		5.6E-09	E
Chrysene	2.1E-08		2.1E-08	E
Fluoranthene	1.5E-07		1.5E-07	E
Fluorene	1.9E-07		1.9E-07	E
Indeno(1,2,3-cd)pyrene	1.3E-08		1.3E-08	E
Naphthalene	2.7E-06	0.0011	0.0011	B
Phenanthrene	5.6E-07		5.6E-07	E
Pyrene	6.9E-08		6.9E-08	E
5-methyl Chrysene	4.6E-09		4.6E-09	E
Dioxins (unspecified)	2.1E-07	1.5E-08	2.3E-07	C
Furans (unspecified)	9.5E-10		9.5E-10	D
CFC12	9.6E-07		9.6E-07	D
Radionuclides (unspecified)	0.018	1.2E-05	0.018	C
Waterborne Emissions				
Acid (unspecified)	0.0020		0.0020	E
Acid (benzoic)	0.033		0.033	E
Acid (hexanoic)	0.0068		0.0068	E
Metal (unspecified)	25.5		25.5	E
Dissolved Solids	1,443		1,443	E
Suspended Solids	85.8	0.010	85.8	D
BOD	0.82		0.82	E
COD	2.42		2.42	E
Phenol/Phenolic Compounds	0.016		0.016	E
Sulfur	0.086		0.086	E
Sulfates	2.58		2.58	E
Sulfides	0.0016		0.0016	E
Oil	0.74	0.0050	0.75	D
Hydrocarbons	0.0065		0.0065	E
Ammonia	0.59		0.59	E
Ammonium	1.4E-04		1.4E-04	E
Aluminum	2.79		2.79	E
Antimony	0.0017		0.0017	E
Arsenic	0.0089		0.0089	E
Barium	38.2		38.2	E
Beryllium	4.9E-04		4.9E-04	E
Cadmium	0.0013		0.0013	E
Chromium (unspecified)	0.079		0.079	E
Cobalt	7.2E-04		7.2E-04	E

Table A-16 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN UTILITY BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Copper	0.0091	3.3E-04	0.0095	D
Iron	5.56	3.3E-04	5.56	D
Lead	0.019		0.019	E
Lithium	1.80		1.80	E
Magnesium	20.3		20.3	E
Manganese	0.035		0.035	E
Mercury	3.1E-05		3.1E-05	E
Molybdenum	7.4E-04		7.4E-04	E
Nickel	0.0087		0.0087	E
Selenium	3.9E-04		3.9E-04	E
Silver	0.068		0.068	E
Sodium	330		330	E
Strontium	1.77		1.77	E
Thallium	3.7E-04		3.7E-04	E
Tin	0.0071		0.0071	E
Titanium	0.027		0.027	E
Vanadium	8.8E-04		8.8E-04	E
Yttrium	2.2E-04		2.2E-04	E
Zinc	0.064		0.064	E
Chlorides (unspecified)	1,170	6.6E-05	1,170	D
Chlorides (methyl chloride)	1.3E-06		1.3E-06	E
Calcium	104		104	E
Fluorine/ Fluorides	0.0023		0.0023	E
Nitrates	3.5E-04		3.5E-04	E
Nitrogen (ammonia)	1.2E-04		1.2E-04	E
Bromide	6.94		6.94	E
Boron	0.10		0.10	E
Organic Carbon	0.0083		0.0083	E
Cyanide	2.3E-06		2.3E-06	E
Hardness	321		321	E
Total Alkalinity	2.55		2.55	E
Surfactants	0.027		0.027	E
Acetone	3.2E-04		3.2E-04	E
Alkylated Benzenes	0.0015		0.0015	E
Alkylated Fluorenes	8.9E-05		8.9E-05	E
Alkylated Naphthalenes	2.5E-05		2.5E-05	E
Alkylated Phenanthrenes	1.0E-05		1.0E-05	E
Benzene	0.054		0.054	E
Cresols	0.0019		0.0019	E
Cymene	3.2E-06		3.2E-06	E
Dibenzofuran	6.2E-06		6.2E-06	E
Dibenzothiophene	5.0E-06		5.0E-06	E
2,4-dimethylphenol	9.1E-04		9.1E-04	E
Ethylbenzene	0.0031		0.0031	E
2-Hexanone	2.1E-04		2.1E-04	E
Methyl ethyl Ketone (MEK)	2.6E-06		2.6E-06	E
1-methylfluorene	3.7E-06		3.7E-06	E
2-methyl naphthalene	5.1E-04		5.1E-04	E
4-methyl-2-pentanone	1.4E-04		1.4E-04	E
Naphthalene	5.9E-04		5.9E-04	E
Pentamethyl benzene	2.4E-06		2.4E-06	E
Phenanthrene	9.0E-06		9.0E-06	E
Toluene	0.051		0.051	E
Total Biphenyls	9.9E-05		9.9E-05	E
Total dibenzo-thiophenes	3.1E-07		3.1E-07	E
Xylenes	0.027		0.027	E
Radionuclides (unspecified)	2.5E-07		2.5E-07	E
Solid Waste	421	10.7	432	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-68, A-70, A-71, A-85, A-86, and A-88.

Source: Franklin Associates, A Division of ERG

Table A-17

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.71		2.71	C
Particulates (PM10)	0.70	2.03	2.72	B
Nitrogen Oxides	27.3	58.7	86.0	B
Hydrocarbons (unspecified)	17.0		17.0	D
VOC (unspecified)	1.08	0.30	1.38	B
TNMOC (unspecified)	0.023		0.023	C
Sulfur Dioxide	15.2		15.2	C
Sulfur Oxides	23.4	42.7	66.1	B
Carbon Monoxide	115	5.33	120	B
Fossil CO2	3,548	27,224	30,773	B
Non-Fossil CO2	24.9		24.9	D
Aldehydes (Formaldehyde)	0.0024	0.033	0.035	B
Aldehydes (Acetaldehyde)	1.9E-04		1.9E-04	D
Aldehydes (Propionaldehyde)	4.2E-08		4.2E-08	D
Aldehydes (unspecified)	0.35		0.35	C
Organics (unspecified)	0.0013		0.0013	D
Ammonia	0.18		0.18	D
Ammonia Chloride	1.7E-04		1.7E-04	D
Methane	38.1	1.07	39.1	B
Kerosene	3.1E-04		3.1E-04	D
Chlorine	1.0E-04		1.0E-04	D
HCl	0.28	0.70	0.97	C
HF	0.031		0.031	C
Metals (unspecified)	0.0055		0.0055	D
Mercaptan	2.3E-05		2.3E-05	D
Antimony	4.8E-06		4.8E-06	C
Arsenic	1.3E-04	0.0013	0.0015	B
Beryllium	6.2E-06	2.8E-05	3.4E-05	B
Cadmium	3.3E-05	4.0E-04	4.3E-04	B
Chromium (VI)	1.7E-05		1.7E-05	C
Chromium (unspecified)	9.4E-05	8.5E-04	9.4E-04	B
Cobalt	2.0E-04	0.0060	0.0062	B
Copper	1.5E-06		1.5E-06	D
Lead	1.5E-04	0.0015	0.0017	B
Magnesium	0.0023		0.0023	C
Manganese	4.0E-04	0.0030	0.0034	B
Mercury	2.4E-05	1.1E-04	1.4E-04	B
Nickel	0.0026	0.085	0.087	B
Selenium	3.0E-04	6.8E-04	9.8E-04	B
Zinc	1.0E-06		1.0E-06	D
Acetophenone	1.7E-09		1.7E-09	D
Acrolein	5.8E-04		5.8E-04	D
Nitrous Oxide	0.066	0.12	0.18	B
Benzene	0.037	2.1E-04	0.037	B
Benzyl Chloride	7.8E-08		7.8E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.2E-09		8.2E-09	D
1,3 Butadiene	4.0E-06		4.0E-06	D
2-Chloroacetophenone	7.8E-10		7.8E-10	D
Chlorobenzene	2.5E-09		2.5E-09	D
2,4-Dinitrotoluene	3.1E-11		3.1E-11	D
Ethyl Chloride	4.7E-09		4.7E-09	D
Ethylbenzene	0.0043		0.0043	D
Ethylene Dibromide	1.3E-10		1.3E-10	D
Ethylene Dichloride	4.5E-09		4.5E-09	D
Hexane	7.5E-09		7.5E-09	D
Isophorone ($C_9H_{14}O$)	6.5E-08		6.5E-08	D
Methyl Bromide	1.8E-08		1.8E-08	D
Methyl Chloride	5.9E-08		5.9E-08	D
Methyl Ethyl Ketone	4.4E-08		4.4E-08	D
Methyl Hydrazine	1.9E-08		1.9E-08	D
Methyl Methacrylate	2.2E-09		2.2E-09	D
Methyl Tert Butyl Ether (MTBE)	3.9E-09		3.9E-09	D
Naphthalene	5.1E-05		5.1E-05	D
Propylene	2.6E-04		2.6E-04	D

Table A-17 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.8E-09		2.8E-09	D
Toluene	0.055		0.055	D
Trichloroethane	8.1E-07		8.1E-07	D
Vinyl Acetate	8.5E-10		8.5E-10	D
Xylenes	0.032		0.032	D
Bromoform	4.4E-09		4.4E-09	D
Chloroform	6.6E-09		6.6E-09	D
Carbon Disulfide	1.5E-08		1.5E-08	D
Dimethyl Sulfate	5.4E-09		5.4E-09	D
Cumene	5.9E-10		5.9E-10	D
Cyanide	2.8E-07		2.8E-07	D
Perchloroethylene	1.1E-05	7.0E-05	8.1E-05	C
Methylene Chloride	2.5E-04	0.0048	0.0051	C
Carbon Tetrachloride	5.8E-06		5.8E-06	D
Phenols	1.3E-04	0.0036	0.0038	C
Fluorides	1.9E-05		1.9E-05	D
Polyaromatic Hydrocarbons (total)	2.1E-05		2.1E-05	E
Biphenyl	3.6E-07		3.6E-07	E
Acenaphthene	1.1E-07		1.1E-07	E
Acenaphthylene	5.2E-08		5.2E-08	E
Anthracene	4.4E-08		4.4E-08	E
Benzo(a)anthracene	1.7E-08		1.7E-08	E
Benzo(a)pyrene	7.9E-09		7.9E-09	E
Benzo(b,j,k)fluroanthene	2.3E-08		2.3E-08	E
Benzo(g,h,i) perylene	5.6E-09		5.6E-09	E
Chrysene	2.1E-08		2.1E-08	E
Fluoranthene	1.5E-07		1.5E-07	E
Fluorene	1.9E-07		1.9E-07	E
Indeno(1,2,3-cd)pyrene	1.3E-08		1.3E-08	E
Naphthalene	2.7E-06	0.0011	0.0011	B
Phenanthrene	5.6E-07		5.6E-07	E
Pyrene	6.9E-08		6.9E-08	E
5-methyl Chrysene	4.6E-09		4.6E-09	E
Dioxins (unspecified)	2.1E-07	1.5E-08	2.3E-07	C
Furans (unspecified)	9.5E-10		9.5E-10	D
CFC12	9.6E-07		9.6E-07	D
Radionuclides (unspecified)	0.018	1.0E-05	0.018	C
Waterborne Emissions				
Acid (unspecified)	0.0020		0.0020	E
Acid (benzoic)	0.033		0.033	E
Acid (hexanoic)	0.0068		0.0068	E
Metal (unspecified)	25.5		25.5	E
Dissolved Solids	1,443		1,443	E
Suspended Solids	85.8	0.011	85.8	D
BOD	0.82		0.82	E
COD	2.42		2.42	E
Phenol/Phenolic Compounds	0.016		0.016	E
Sulfur	0.086		0.086	E
Sulfates	2.58		2.58	E
Sulfides	0.0016		0.0016	E
Oil	0.74	0.0054	0.75	D
Hydrocarbons	0.0065		0.0065	E
Ammonia	0.59		0.59	E
Ammonium	1.4E-04		1.4E-04	E
Aluminum	2.79		2.79	E
Antimony	0.0017		0.0017	E
Arsenic	0.0089		0.0089	E
Barium	38.2		38.2	E
Beryllium	4.9E-04		4.9E-04	E
Cadmium	0.0013		0.0013	E
Chromium (unspecified)	0.079		0.079	E
Cobalt	7.2E-04		7.2E-04	E
Copper	0.0091	3.6E-04	0.0095	D

Table A-17 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of residual oil)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5.56	3.6E-04	5.57	D
Lead	0.019		0.019	E
Lithium	1.80		1.80	E
Magnesium	20.3		20.3	E
Manganese	0.035		0.035	E
Mercury	3.1E-05		3.1E-05	E
Molybdenum	7.4E-04		7.4E-04	E
Nickel	0.0087		0.0087	E
Selenium	3.9E-04		3.9E-04	E
Silver	0.068		0.068	E
Sodium	330		330	E
Strontium	1.77		1.77	E
Thallium	3.7E-04		3.7E-04	E
Tin	0.0071		0.0071	E
Titanium	0.027		0.027	E
Vanadium	8.8E-04		8.8E-04	E
Yttrium	2.2E-04		2.2E-04	E
Zinc	0.064		0.064	E
Chlorides (unspecified)	1,170	7.2E-05	1,170	D
Chlorides (methyl chloride)	1.3E-06		1.3E-06	E
Calcium	104		104	E
Fluorine/ Fluorides	0.0023		0.0023	E
Nitrates	3.5E-04		3.5E-04	E
Nitrogen (ammonia)	1.2E-04		1.2E-04	E
Bromide	6.94		6.94	E
Boron	0.10		0.10	E
Organic Carbon	0.0083		0.0083	E
Cyanide	2.3E-06		2.3E-06	E
Hardness	321		321	E
Total Alkalinity	2.55		2.55	E
Surfactants	0.027		0.027	E
Acetone	3.2E-04		3.2E-04	E
Alkylated Benzenes	0.0015		0.0015	E
Alkylated Fluorenes	8.9E-05		8.9E-05	E
Alkylated Naphthalenes	2.5E-05		2.5E-05	E
Alkylated Phenanthrenes	1.0E-05		1.0E-05	E
Benzene	0.054		0.054	E
Cresols	0.0019		0.0019	E
Cymene	3.2E-06		3.2E-06	E
Dibenzofuran	6.2E-06		6.2E-06	E
Dibenzothiophene	5.0E-06		5.0E-06	E
2,4-dimethylphenol	9.1E-04		9.1E-04	E
Ethylbenzene	0.0031		0.0031	E
2-Hexanone	2.1E-04		2.1E-04	E
Methyl ethyl Ketone (MEK)	2.6E-06		2.6E-06	E
1-methylfluorene	3.7E-06		3.7E-06	E
2-methyl naphthalene	5.1E-04		5.1E-04	E
4-methyl-2-pentanone	1.4E-04		1.4E-04	E
Naphthalene	5.9E-04		5.9E-04	E
Pentamethyl benzene	2.4E-06		2.4E-06	E
Phenanthrene	9.0E-06		9.0E-06	E
Toluene	0.051		0.051	E
Total Biphenyls	9.9E-05		9.9E-05	E
Total dibenzo-thiophenes	3.1E-07		3.1E-07	E
Xylenes	0.027		0.027	E
Radionuclides (unspecified)	2.5E-07		2.5E-07	E
Solid Waste	421	10.6	432	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-68, A-70, A-71, A-85, A-86, and A-88.

Source: Franklin Associates, A Division of ERG

Table A-18

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN UTILITY BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.49		2.49	C
Particulates (PM10)	0.64	1.08	1.72	B
Nitrogen Oxides	25.0	25.9	50.9	B
Hydrocarbons (unspecified)	15.6		15.6	D
VOC (unspecified)	0.99	0.22	1.21	B
TNMOC (unspecified)	0.021		0.021	C
Sulfur Dioxide	14.0		14.0	C
Sulfur Oxides	21.5	5.39	26.9	B
Carbon Monoxide	106	5.41	111	B
Fossil CO2	3,258	24,563	27,821	B
Non-Fossil CO2	22.8		22.8	D
Aldehydes (Formaldehyde)	0.0022	0.033	0.035	B
Aldehydes (Acetaldehyde)	1.7E-04		1.7E-04	D
Aldehydes (Propionaldehyde)	3.9E-08		3.9E-08	D
Aldehydes (unspecified)	0.32		0.32	C
Organics (unspecified)	0.0012		0.0012	D
Ammonia	0.16		0.16	D
Ammonia Chloride	1.6E-04		1.6E-04	D
Methane	34.9	0.055	35.0	B
Kerosene	2.9E-04		2.9E-04	D
Chlorine	9.3E-05		9.3E-05	D
HCl	0.25	0.70	0.95	C
HF	0.029		0.029	C
Metals (unspecified)	0.0050		0.0050	D
Mercaptan	2.1E-05		2.1E-05	D
Antimony	4.4E-06		4.4E-06	C
Arsenic	1.2E-04	0.0013	0.0014	B
Beryllium	5.7E-06	2.8E-05	3.4E-05	B
Cadmium	3.0E-05	4.0E-04	4.3E-04	B
Chromium (VI)	1.5E-05		1.5E-05	C
Chromium (unspecified)	8.7E-05	8.5E-04	9.3E-04	B
Cobalt	1.9E-04	0.0060	0.0062	B
Copper	1.4E-06		1.4E-06	D
Lead	1.3E-04	0.0015	0.0016	B
Magnesium	0.0021		0.0021	C
Manganese	3.7E-04	0.0030	0.0034	B
Mercury	2.2E-05	1.1E-04	1.4E-04	B
Nickel	0.0024	0.085	0.087	B
Selenium	2.7E-04	6.8E-04	9.6E-04	B
Zinc	9.3E-07		9.3E-07	D
Acetophenone	1.5E-09		1.5E-09	D
Acrolein	5.3E-04		5.3E-04	D
Nitrous Oxide	0.060	0.12	0.18	B
Benzene	0.034	2.1E-04	0.034	B
Benzyl Chloride	7.2E-08		7.2E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09		7.5E-09	D
1,3 Butadiene	3.7E-06		3.7E-06	D
2-Chloroacetophenone	7.2E-10		7.2E-10	D
Chlorobenzene	2.3E-09		2.3E-09	D
2,4-Dinitrotoluene	2.9E-11		2.9E-11	D
Ethyl Chloride	4.3E-09		4.3E-09	D
Ethylbenzene	0.0039		0.0039	D
Ethylene Dibromide	1.2E-10		1.2E-10	D
Ethylene Dichloride	4.1E-09		4.1E-09	D
Hexane	6.9E-09		6.9E-09	D
Isophorone ($C_9H_{14}O$)	5.9E-08		5.9E-08	D
Methyl Bromide	1.6E-08		1.6E-08	D
Methyl Chloride	5.4E-08		5.4E-08	D
Methyl Ethyl Ketone	4.0E-08		4.0E-08	D
Methyl Hydrazine	1.7E-08		1.7E-08	D
Methyl Methacrylate	2.1E-09		2.1E-09	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09		3.6E-09	D
Naphthalene	4.7E-05		4.7E-05	D

Table A-18 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN UTILITY BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Propylene	2.4E-04		2.4E-04	D
Styrene	2.6E-09		2.6E-09	D
Toluene	0.051		0.051	D
Trichloroethane	7.5E-07		7.5E-07	D
Vinyl Acetate	7.8E-10		7.8E-10	D
Xylenes	0.030		0.030	D
Bromoform	4.0E-09		4.0E-09	D
Chloroform	6.1E-09		6.1E-09	D
Carbon Disulfide	1.3E-08		1.3E-08	D
Dimethyl Sulfate	4.9E-09		4.9E-09	D
Cumene	5.4E-10		5.4E-10	D
Cyanide	2.6E-07		2.6E-07	D
Perchloroethylene	1.0E-05	7.6E-05	8.7E-05	C
Methylene Chloride	2.3E-04	0.0045	0.0047	C
Carbon Tetrachloride	5.4E-06		5.4E-06	D
Phenols	1.2E-04	0.0034	0.0035	C
Fluorides	1.8E-05		1.8E-05	D
Polyaromatic Hydrocarbons (total)	2.0E-05		2.0E-05	E
Biphenyl	3.3E-07		3.3E-07	E
Acenaphthene	9.8E-08		9.8E-08	E
Acenaphthylene	4.8E-08		4.8E-08	E
Anthracene	4.0E-08		4.0E-08	E
Benzo(a)anthracene	1.5E-08		1.5E-08	E
Benzo(a)pyrene	7.3E-09		7.3E-09	E
Benzo(b,j,k)fluroanthene	2.1E-08		2.1E-08	E
Benzo(g,h,i) perylene	5.2E-09		5.2E-09	E
Chrysene	1.9E-08		1.9E-08	E
Fluoranthene	1.4E-07		1.4E-07	E
Fluorene	1.7E-07		1.7E-07	E
Indeno(1,2,3-cd)pyrene	1.2E-08		1.2E-08	E
Naphthalene	2.5E-06	0.0011	0.0011	B
Phenanthrene	5.2E-07		5.2E-07	E
Pyrene	6.3E-08		6.3E-08	E
5-methyl Chrysene	4.2E-09		4.2E-09	E
Dioxins (unspecified)	2.0E-07	1.4E-08	2.1E-07	C
Furans (unspecified)	8.7E-10		8.7E-10	D
CFC12	8.9E-07		8.9E-07	D
Radionuclides (unspecified)	0.016	1.1E-05	0.016	C
Waterborne Emissions				
Acid (unspecified)	0.0018		0.0018	E
Acid (benzoic)	0.030		0.030	E
Acid (hexanoic)	0.0062		0.0062	E
Metal (unspecified)	23.4		23.4	E
Dissolved Solids	1,325		1,325	E
Suspended Solids	78.8	0.0089	78.8	D
BOD	0.75		0.75	E
COD	2.22		2.22	E
Phenol/Phenolic Compounds	0.015		0.015	E
Sulfur	0.079		0.079	E
Sulfates	2.37		2.37	E
Sulfides	0.0014		0.0014	E
Oil	0.68	0.0045	0.69	D
Hydrocarbons	0.0059		0.0059	E
Ammonia	0.54		0.54	E
Ammonium	1.3E-04		1.3E-04	E
Aluminum	2.56		2.56	E
Antimony	0.0016		0.0016	E
Arsenic	0.0081		0.0081	E
Barium	35.1		35.1	E
Beryllium	4.5E-04		4.5E-04	E
Cadmium	0.0012		0.0012	E
Chromium (unspecified)	0.073		0.073	E
Cobalt	6.6E-04		6.6E-04	E

Table A-18 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN UTILITY BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Copper	0.0084	3.0E-04	0.0087	D
Iron	5.11	3.0E-04	5.11	D
Lead	0.017		0.017	E
Lithium	1.65		1.65	E
Magnesium	18.7		18.7	E
Manganese	0.032		0.032	E
Mercury	2.8E-05		2.8E-05	E
Molybdenum	6.8E-04		6.8E-04	E
Nickel	0.0080		0.0080	E
Selenium	3.5E-04		3.5E-04	E
Silver	0.062		0.062	E
Sodium	303		303	E
Strontium	1.62		1.62	E
Thallium	3.4E-04		3.4E-04	E
Tin	0.0065		0.0065	E
Titanium	0.025		0.025	E
Vanadium	8.1E-04		8.1E-04	E
Yttrium	2.0E-04		2.0E-04	E
Zinc	0.059		0.059	E
Chlorides (unspecified)	1,074	5.9E-05	1,074	D
Chlorides (methyl chloride)	1.2E-06		1.2E-06	E
Calcium	95.5		95.5	E
Fluorine/ Fluorides	0.0021		0.0021	E
Nitrates	3.2E-04		3.2E-04	E
Nitrogen (ammonia)	1.1E-04		1.1E-04	E
Bromide	6.37		6.37	E
Boron	0.093		0.093	E
Organic Carbon	0.0076		0.0076	E
Cyanide	2.1E-06		2.1E-06	E
Hardness	294		294	E
Total Alkalinity	2.34		2.34	E
Surfactants	0.025		0.025	E
Acetone	3.0E-04		3.0E-04	E
Alkylated Benzenes	0.0014		0.0014	E
Alkylated Fluorenes	8.1E-05		8.1E-05	E
Alkylated Naphthalenes	2.3E-05		2.3E-05	E
Alkylated Phenanthrenes	9.5E-06		9.5E-06	E
Benzene	0.050		0.050	E
Cresols	0.0018		0.0018	E
Cymene	3.0E-06		3.0E-06	E
Dibenzofuran	5.7E-06		5.7E-06	E
Dibenzothiophene	4.6E-06		4.6E-06	E
2,4-dimethylphenol	8.3E-04		8.3E-04	E
Ethylbenzene	0.0028		0.0028	E
2-Hexanone	1.9E-04		1.9E-04	E
Methyl ethyl Ketone (MEK)	2.4E-06		2.4E-06	E
1-methylfluorene	3.4E-06		3.4E-06	E
2-methyl naphthalene	4.7E-04		4.7E-04	E
4-methyl-2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.4E-04		5.4E-04	E
Pentamethyl benzene	2.2E-06		2.2E-06	E
Phenanthrene	8.2E-06		8.2E-06	E
Toluene	0.047		0.047	E
Total Biphenyls	9.1E-05		9.1E-05	E
Total dibenzo-thiophenes	2.8E-07		2.8E-07	E
Xylenes	0.025		0.025	E
Radionuclides (unspecified)	2.3E-07		2.3E-07	E
Solid Waste	387		387	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-68, A-70, A-71, A-85, A-86, and A-88.

Source: Franklin Associates, A Division of ERG

Table A-19

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.49		2.49	C
Particulates (PM10)	0.64	1.00	1.64	B
Nitrogen Oxides	25.0	24.0	49.0	B
Hydrocarbons (unspecified)	15.6		15.6	D
VOC (unspecified)	0.99	0.20	1.19	B
TNMOC (unspecified)	0.021		0.021	C
Sulfur Dioxide	14.0		14.0	C
Sulfur Oxides	21.5	5.00	26.5	B
Carbon Monoxide	106	5.01	111	B
Fossil CO2	3,258	22,757	26,015	B
Non-Fossil CO2	22.8		22.8	D
Aldehydes (Formaldehyde)	0.0022		0.0022	B
Aldehydes (Acetaldehyde)	1.7E-04		1.7E-04	D
Aldehydes (Propionaldehyde)	3.9E-08		3.9E-08	D
Aldehydes (unspecified)	0.32		0.32	C
Organics (unspecified)	0.0012		0.0012	D
Ammonia	0.16		0.16	D
Ammonia Chloride	1.6E-04		1.6E-04	D
Methane	34.9	0.051	35.0	B
Kerosene	2.9E-04		2.9E-04	D
Chlorine	9.3E-05		9.3E-05	D
HCl	0.25	0.70	0.95	C
HF	0.029		0.029	C
Metals (unspecified)	0.0050		0.0050	D
Mercaptan	2.1E-05		2.1E-05	D
Antimony	4.4E-06		4.4E-06	C
Arsenic	1.2E-04	5.5E-04	6.7E-04	B
Beryllium	5.7E-06	4.2E-04	4.2E-04	B
Cadmium	3.0E-05	4.2E-04	4.5E-04	B
Chromium (VI)	1.5E-05		1.5E-05	C
Chromium (unspecified)	8.7E-05	4.2E-04	5.0E-04	B
Cobalt	1.9E-04		1.9E-04	B
Copper	1.4E-06	8.3E-04	8.3E-04	B
Lead	1.3E-04	0.0012	0.0014	B
Magnesium	0.0021		0.0021	C
Manganese	3.7E-04	8.3E-04	0.0012	B
Mercury	2.2E-05	4.2E-04	4.4E-04	B
Nickel	0.0024	4.2E-04	0.0028	B
Selenium	2.7E-04	0.0021	0.0024	B
Zinc	9.3E-07	5.5E-04	5.6E-04	B
Acetophenone	1.5E-09		1.5E-09	D
Acrolein	5.3E-04		5.3E-04	D
Nitrous Oxide	0.060	0.11	0.17	B
Benzene	0.034		0.034	B
Benzyl Chloride	7.2E-08		7.2E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09		7.5E-09	D
1,3 Butadiene	3.7E-06		3.7E-06	D
2-Chloroacetophenone	7.2E-10		7.2E-10	D
Chlorobenzene	2.3E-09		2.3E-09	D
2,4-Dinitrotoluene	2.9E-11		2.9E-11	D
Ethyl Chloride	4.3E-09		4.3E-09	D
Ethylbenzene	0.0039		0.0039	D
Ethylene Dibromide	1.2E-10		1.2E-10	D
Ethylene Dichloride	4.1E-09		4.1E-09	D
Hexane	6.9E-09		6.9E-09	D
Isophorone ($C_9H_{14}O$)	5.9E-08		5.9E-08	D
Methyl Bromide	1.6E-08		1.6E-08	D
Methyl Chloride	5.4E-08		5.4E-08	D
Methyl Ethyl Ketone	4.0E-08		4.0E-08	D
Methyl Hydrazine	1.7E-08		1.7E-08	D
Methyl Methacrylate	2.1E-09		2.1E-09	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09		3.6E-09	D
Naphthalene	4.7E-05		4.7E-05	D
Propylene	2.4E-04		2.4E-04	D

Table A-19 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.6E-09		2.6E-09	D
Toluene	0.051		0.051	D
Trichloroethane	7.5E-07		7.5E-07	D
Vinyl Acetate	7.8E-10		7.8E-10	D
Xylenes	0.030		0.030	D
Bromoform	4.0E-09		4.0E-09	D
Chloroform	6.1E-09		6.1E-09	D
Carbon Disulfide	1.3E-08		1.3E-08	D
Dimethyl Sulfate	4.9E-09		4.9E-09	D
Cumene	5.4E-10		5.4E-10	D
Cyanide	2.6E-07		2.6E-07	D
Perchloroethylene	1.0E-05	7.6E-05	8.7E-05	C
Methylene Chloride	2.3E-04	0.0045	0.0047	C
Carbon Tetrachloride	5.4E-06		5.4E-06	D
Phenols	1.2E-04	0.0034	0.0035	C
Fluorides	1.8E-05		1.8E-05	D
Polyaromatic Hydrocarbons (total)	2.0E-05		2.0E-05	E
Biphenyl	3.3E-07		3.3E-07	E
Acenaphthene	9.8E-08		9.8E-08	E
Acenaphthylene	4.8E-08		4.8E-08	E
Anthracene	4.0E-08		4.0E-08	E
Benzo(a)anthracene	1.5E-08		1.5E-08	E
Benzo(a)pyrene	7.3E-09		7.3E-09	E
Benzo(b,j,k)fluroanthene	2.1E-08		2.1E-08	E
Benzo(g,h,i) perylene	5.2E-09		5.2E-09	E
Chrysene	1.9E-08		1.9E-08	E
Fluoranthene	1.4E-07		1.4E-07	E
Fluorene	1.7E-07		1.7E-07	E
Indeno(1,2,3-cd)pyrene	1.2E-08		1.2E-08	E
Naphthalene	2.5E-06		2.5E-06	B
Phenanthrene	5.2E-07		5.2E-07	E
Pyrene	6.3E-08		6.3E-08	E
5-methyl Chrysene	4.2E-09		4.2E-09	E
Dioxins (unspecified)	2.0E-07	1.4E-08	2.1E-07	C
Furans (unspecified)	8.7E-10		8.7E-10	D
CFC12	8.9E-07		8.9E-07	D
Radionuclides (unspecified)	0.016	1.1E-05	0.016	C
Waterborne Emissions				
Acid (unspecified)	0.0018		0.0018	E
Acid (benzoic)	0.030		0.030	E
Acid (hexanoic)	0.0062		0.0062	E
Metal (unspecified)	23.4		23.4	E
Dissolved Solids	1,325		1,325	E
Suspended Solids	78.8	0.0089	78.8	D
BOD	0.75		0.75	E
COD	2.22		2.22	E
Phenol/Phenolic Compounds	0.015		0.015	E
Sulfur	0.079		0.079	E
Sulfates	2.37		2.37	E
Sulfides	0.0014		0.0014	E
Oil	0.68	0.0045	0.69	D
Hydrocarbons	0.0059		0.0059	E
Ammonia	0.54		0.54	E
Ammonium	1.3E-04		1.3E-04	E
Aluminum	2.56		2.56	E
Antimony	0.0016		0.0016	E
Arsenic	0.0081		0.0081	E
Barium	35.1		35.1	E
Beryllium	4.5E-04		4.5E-04	E
Cadmium	0.0012		0.0012	E
Chromium (unspecified)	0.073		0.073	E
Cobalt	6.6E-04		6.6E-04	E
Copper	0.0084	3.0E-04	0.0087	D

Table A-19 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of distillate oil)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5.11	3.0E-04	5.11	D
Lead	0.017		0.017	E
Lithium	1.65		1.65	E
Magnesium	18.7		18.7	E
Manganese	0.032		0.032	E
Mercury	2.8E-05		2.8E-05	E
Molybdenum	6.8E-04		6.8E-04	E
Nickel	0.0080		0.0080	E
Selenium	3.5E-04		3.5E-04	E
Silver	0.062		0.062	E
Sodium	303		303	E
Strontium	1.62		1.62	E
Thallium	3.4E-04		3.4E-04	E
Tin	0.0065		0.0065	E
Titanium	0.025		0.025	E
Vanadium	8.1E-04		8.1E-04	E
Yttrium	2.0E-04		2.0E-04	E
Zinc	0.059		0.059	E
Chlorides (unspecified)	1,074	5.9E-05	1,074	D
Chlorides (methyl chloride)	1.2E-06		1.2E-06	E
Calcium	95.5		95.5	E
Fluorine/ Fluorides	0.0021		0.0021	E
Nitrates	3.2E-04		3.2E-04	E
Nitrogen (ammonia)	1.1E-04		1.1E-04	E
Bromide	6.37		6.37	E
Boron	0.093		0.093	E
Organic Carbon	0.0076		0.0076	E
Cyanide	2.1E-06		2.1E-06	E
Hardness	294		294	E
Total Alkalinity	2.34		2.34	E
Surfactants	0.025		0.025	E
Acetone	3.0E-04		3.0E-04	E
Alkylated Benzenes	0.0014		0.0014	E
Alkylated Fluorenes	8.1E-05		8.1E-05	E
Alkylated Naphthalenes	2.3E-05		2.3E-05	E
Alkylated Phenanthrenes	9.5E-06		9.5E-06	E
Benzene	0.050		0.050	E
Cresols	0.0018		0.0018	E
Cymene	3.0E-06		3.0E-06	E
Dibenzofuran	5.7E-06		5.7E-06	E
Dibenzothiophene	4.6E-06		4.6E-06	E
2,4-dimethylphenol	8.3E-04		8.3E-04	E
Ethylbenzene	0.0028		0.0028	E
2-Hexanone	1.9E-04		1.9E-04	E
Methyl ethyl Ketone (MEK)	2.4E-06		2.4E-06	E
1-methylfluorene	3.4E-06		3.4E-06	E
2-methyl naphthalene	4.7E-04		4.7E-04	E
4-methyl-2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.4E-04		5.4E-04	E
Pentamethyl benzene	2.2E-06		2.2E-06	E
Phenanthrene	8.2E-06		8.2E-06	E
Toluene	0.047		0.047	E
Total Biphenyls	9.1E-05		9.1E-05	E
Total dibenzo-thiophenes	2.8E-07		2.8E-07	E
Xylenes	0.025		0.025	E
Radionuclides (unspecified)	2.3E-07		2.3E-07	E
Solid Waste	387		387	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-68, A-70, A-71, A-85, A-86, and A-88.

Source: Franklin Associates, A Division of ERG

Natural Gas

Utility Boilers. Natural gas represented 15.9 percent of the total megawatt hours produced by U.S. electric utilities in 2000 (Reference A-62). The calculations and assumptions used for estimating the environmental emissions from natural gas combustion in utility boilers are discussed below.

Air emissions from natural gas combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50). Since natural gas has a low sulfur and ash content, the sulfur dioxide and particulate emissions from natural gas emissions are very low when compared to other fossil fuels. The major pollutants from the burning of natural gas are nitrogen oxides. Nitrogen oxides are usually controlled by adjusting the firing parameters of a boiler.

No data are available for waterborne emissions from utility boilers. Waterborne emissions do not result from the combustion-side of utility boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Since natural gas is a clean burning fuel, this appendix assumes that the cleaning of natural gas boilers is rare and thus produces negligible waterborne emissions (Reference A-95).

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Natural gas is a clean burning fuel with virtually no sulfur or particulate emissions. Thus, desulfurization and particulate controls are not employed for natural gas combustion. Also, due to its low ash content, natural gas combustion produces virtually no bottom ash or other solid wastes (Reference A-67). Thus, this appendix assumes that negligible solid wastes result from the combustion of natural gas in utility boilers.

Industrial Boilers. The calculations and assumptions used for estimating the environmental emissions from natural gas combustion in industrial boilers are discussed below.

Air emissions from natural gas combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50). Since natural gas has a low sulfur and ash content, the sulfur dioxide and particulate emissions from natural gas emissions are very low when compared to other fossil fuels. The major pollutants from the burning of natural gas are nitrogen oxides. Nitrogen oxides are usually controlled by adjusting the firing parameters of a boiler.

No data are available for waterborne emissions from industrial boilers. Waterborne emissions do not result from the combustion-side of industrial boilers, but they do result from ancillary processes such as cooling water systems and boiler cleaning operations (Reference A-67). Since natural gas is a clean burning fuel, this appendix assumes that the cleaning of natural gas boilers is rare and thus produces negligible waterborne emissions (Reference A-95).

Solid waste emissions from fossil fuel combustion result from wastes from environmental controls (particulate and desulfurization controls) and bottom ash. Natural gas is a clean burning fuel with virtually no sulfur or particulate emissions. Thus, desulfurization and particulate controls are not employed for natural gas combustion. Also, due to its low ash content, natural gas combustion produces virtually no bottom ash or other solid wastes (Reference A-72). Thus, this appendix assumes that negligible solid wastes result from the combustion of natural gas in industrial boilers.

Industrial Equipment. Natural gas is used to power industrial equipment, including compressors used for pipeline transportation of natural gas. The calculations and assumptions used for estimating the environmental emissions associated with the combustion of natural gas in industrial equipment are discussed below.

Air emissions from natural gas combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-96). Since natural gas has a low sulfur and ash content, the sulfur dioxide and particulate emissions from natural gas emissions are very low when compared to other fossil fuels.

Since natural gas has a low sulfur and ash content, it is a clean-burning fuel. This appendix thus assumes that the combustion of natural gas in industrial equipment produces negligible waterborne or solid waste emissions (References A-67 and A-95).

Table A-20

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN UTILITY BOILERS
(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	0.0014		0.0014	C
Particulates (PM10)	8.2E-04	0.0076	0.0084	B
Nitrogen Oxides	0.016	0.10	0.12	B
Hydrocarbons (unspecified)	4.2E-04		4.2E-04	D
VOC (unspecified)	0.039	0.0055	0.044	B
TNMOC (unspecified)	4.6E-05		4.6E-05	C
Sulfur Dioxide	1.21		1.21	C
Sulfur Oxides	0.0015	6.3E-04	0.0021	B
Carbon Monoxide	0.014	0.084	0.098	B
Fossil CO2	11.5	122	134	B
Non-Fossil CO2	0.046		0.046	D
Aldehydes (Formaldehyde)	1.9E-05	7.5E-05	9.4E-05	B
Aldehydes (Acetaldehyde)	1.3E-06		1.3E-06	D
Aldehydes (Propionaldehyde)	8.4E-11		8.4E-11	D
Aldehydes (unspecified)	9.0E-06		9.0E-06	C
Organics (unspecified)	2.5E-06		2.5E-06	D
Ammonia	4.4E-06		4.4E-06	D
Ammonia Chloride	3.2E-07		3.2E-07	D
Methane	0.70	0.0022	0.71	B
Kerosene	5.7E-07		5.7E-07	D
Chlorine	1.8E-07		1.8E-07	D
HCl	5.1E-04		5.1E-04	C
HF	6.2E-05		6.2E-05	C
Metals (unspecified)	1.0E-05		1.0E-05	D
Mercaptan	4.5E-08		4.5E-08	D
Antimony	9.3E-09		9.3E-09	C
Arsenic	2.0E-07	2.0E-07	4.0E-07	B
Beryllium	1.4E-08	1.2E-08	2.6E-08	B
Cadmium	9.2E-08	1.1E-06	1.2E-06	B
Chromium (VI)	3.3E-08		3.3E-08	C
Chromium (unspecified)	2.0E-07	1.4E-06	1.6E-06	B
Cobalt	1.0E-07	8.4E-08	1.9E-07	B
Copper	7.6E-09		7.6E-09	D
Lead	2.4E-07	5.0E-07	7.4E-07	B
Magnesium	4.5E-06		4.5E-06	C
Manganese	6.3E-07	3.8E-07	1.0E-06	B
Mercury	5.5E-08	2.6E-07	3.2E-07	B
Nickel	1.0E-06	2.1E-06	3.1E-06	B
Selenium	5.6E-07	2.4E-08	5.9E-07	B
Zinc	5.1E-09		5.1E-09	D
Acetophenone	3.3E-12		3.3E-12	D
Acrolein	1.2E-06		1.2E-06	D
Nitrous Oxide	2.4E-04	0.0022	0.0025	B
Benzene	0.0048	2.1E-06	0.0048	B
Benzyl Chloride	1.5E-10		1.5E-10	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-11		1.6E-11	D
1,3 Butadiene	3.0E-08		3.0E-08	D
2-Chloroacetophenone	1.5E-12		1.5E-12	D
Chlorobenzene	4.9E-12		4.9E-12	D
2,4-Dinitrotoluene	6.2E-14		6.2E-14	D
Ethyl Chloride	9.3E-12		9.3E-12	D
Ethylbenzene	5.7E-04		5.7E-04	D
Ethylene Dibromide	2.7E-13		2.7E-13	D
Ethylene Dichloride	8.8E-12		8.8E-12	D
Hexane	1.5E-11		1.5E-11	D
Isophorone ($C_9H_{14}O$)	1.3E-10		1.3E-10	D
Methyl Bromide	3.5E-11		3.5E-11	D
Methyl Chloride	1.2E-10		1.2E-10	D
Methyl Ethyl Ketone	8.6E-11		8.6E-11	D
Methyl Hydrazine	3.8E-11		3.8E-11	D
Methyl Methacrylate	4.4E-12		4.4E-12	D
Methyl Tert Butyl Ether (MTBE)	7.7E-12		7.7E-12	D
Naphthalene	9.1E-08	6.1E-07	7.0E-07	C
Propylene	2.0E-06		2.0E-06	D

Table A-20 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN UTILITY BOILERS
(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	5.5E-12		5.5E-12	D
Toluene	0.0074		0.0074	D
Trichloroethane	2.4E-11		2.4E-11	D
Vinyl Acetate	1.7E-12		1.7E-12	D
Xylenes	0.0043		0.0043	D
Bromoform	8.6E-12		8.6E-12	D
Chloroform	1.3E-11		1.3E-11	D
Carbon Disulfide	2.9E-11		2.9E-11	D
Dimethyl Sulfate	1.1E-11		1.1E-11	D
Cumene	1.2E-12		1.2E-12	D
Cyanide	5.5E-10		5.5E-10	D
Perchloroethylene	1.9E-08		1.9E-08	D
Methylene Chloride	2.8E-07		2.8E-07	D
Carbon Tetrachloride	1.1E-08		1.1E-08	D
Phenols	8.3E-08		8.3E-08	D
Fluorides	3.6E-08		3.6E-08	D
Polyaromatic Hydrocarbons (total)	1.4E-07		1.4E-07	E
Biphenyl	7.0E-10		7.0E-10	E
Acenaphthene	2.1E-10		2.1E-10	E
Acenaphthylene	1.0E-10		1.0E-10	E
Anthracene	8.7E-11		8.7E-11	E
Benzo(a)anthracene	3.3E-11		3.3E-11	E
Benzo(a)pyrene	1.6E-11		1.6E-11	E
Benzo(b,j,k)fluroanthene	4.5E-11		4.5E-11	E
Benzo(g,h,i) perylene	1.1E-11		1.1E-11	E
Chrysene	4.1E-11		4.1E-11	E
Fluoranthene	2.9E-10		2.9E-10	E
Fluorene	3.8E-10		3.8E-10	E
Indeno(1,2,3-cd)pyrene	2.5E-11		2.5E-11	E
Naphthalene	5.4E-09		5.4E-09	E
Phenanthrene	1.1E-09		1.1E-09	E
Pyrene	1.4E-10		1.4E-10	E
5-methyl Chrysene	9.1E-12		9.1E-12	E
Dioxins (unspecified)	3.9E-10		3.9E-10	D
Furans (unspecified)	1.9E-12		1.9E-12	D
CFC12	2.4E-11		2.4E-11	D
Radionuclides (unspecified)	3.2E-05	2.6E-09	3.2E-05	C
Waterborne Emissions				
Acid (unspecified)	2.7E-04		2.7E-04	E
Acid (benzoic)	2.2E-04		2.2E-04	E
Acid (hexanoic)	4.6E-05		4.6E-05	E
Metal (unspecified)	3.39		3.39	E
Dissolved Solids	9.76		9.76	E
Suspended Solids	0.14		0.14	E
BOD	0.038		0.038	E
COD	0.063		0.063	E
Phenol/Phenolic Compounds	9.8E-05		9.8E-05	E
Sulfur	5.8E-04		5.8E-04	E
Sulfates	0.017		0.017	E
Sulfides	3.8E-08		3.8E-08	E
Oil	0.0042		0.0042	E
Hydrocarbons	4.4E-05		4.4E-05	E
Ammonia	0.0033		0.0033	E
Ammonium	2.5E-07		2.5E-07	E
Aluminum	0.0041		0.0041	E
Antimony	2.5E-06		2.5E-06	E
Arsenic	4.8E-05		4.8E-05	E
Barium	0.063		0.063	E
Beryllium	2.2E-06		2.2E-06	E
Cadmium	7.1E-06		7.1E-06	E
Chromium (unspecified)	1.1E-04		1.1E-04	E
Cobalt	4.9E-06		4.9E-06	E
Copper	3.1E-05		3.1E-05	E

Table A-20 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN UTILITY BOILERS

(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.013		0.013	E
Lead	7.0E-05		7.0E-05	E
Lithium	0.23		0.23	E
Magnesium	0.14		0.14	E
Manganese	2.3E-04		2.3E-04	E
Mercury	4.4E-08		4.4E-08	E
Molybdenum	5.0E-06		5.0E-06	E
Nickel	3.8E-05		3.8E-05	E
Selenium	5.8E-07		5.8E-07	E
Silver	4.6E-04		4.6E-04	E
Sodium	2.23		2.23	E
Strontium	0.012		0.012	E
Thallium	5.3E-07		5.3E-07	E
Tin	2.4E-05		2.4E-05	E
Titanium	3.8E-05		3.8E-05	E
Vanadium	5.9E-06		5.9E-06	E
Yttrium	1.5E-06		1.5E-06	E
Zinc	1.1E-04		1.1E-04	E
Chlorides (unspecified)	7.91		7.91	E
Chlorides (methyl chloride)	8.8E-09		8.8E-09	E
Calcium	0.70		0.70	E
Fluorine/ Fluorides	4.2E-06		4.2E-06	E
Nitrates	6.3E-07		6.3E-07	E
Nitrogen (ammonia)	2.2E-07		2.2E-07	E
Bromide	0.047		0.047	E
Boron	6.9E-04		6.9E-04	E
Organic Carbon	0.0011		0.0011	E
Cyanide	1.6E-08		1.6E-08	E
Hardness	2.17		2.17	E
Total Alkalinity	0.018		0.018	E
Surfactants	2.2E-04		2.2E-04	E
Acetone	2.2E-06		2.2E-06	E
Alkylated Benzenes	2.2E-06		2.2E-06	E
Alkylated Fluorenes	1.3E-07		1.3E-07	E
Alkylated Naphthalenes	3.6E-08		3.6E-08	E
Alkylated Phenanthrenes	1.5E-08		1.5E-08	E
Benzene	3.7E-04		3.7E-04	E
Cresols	1.3E-05		1.3E-05	E
Cymene	2.2E-08		2.2E-08	E
Dibenzofuran	4.2E-08		4.2E-08	E
Dibenzothiophene	3.4E-08		3.4E-08	E
2,4-dimethylphenol	6.1E-06		6.1E-06	E
Ethylbenzene	2.1E-05		2.1E-05	E
2-Hexanone	1.4E-06		1.4E-06	E
Methyl ethyl Ketone (MEK)	1.8E-08		1.8E-08	E
1-methylfluorene	2.5E-08		2.5E-08	E
2-methyl naphthalene	3.5E-06		3.5E-06	E
4-methyl-2-pentanone	9.2E-07		9.2E-07	E
Naphthalene	4.0E-06		4.0E-06	E
Pentamethyl benzene	1.6E-08		1.6E-08	E
Phenanthrene	2.8E-08		2.8E-08	E
Toluene	3.5E-04		3.5E-04	E
Total Biphenyls	1.4E-07		1.4E-07	E
Total dibenzo-thiophenes	4.4E-10		4.4E-10	E
Xylenes	1.8E-04		1.8E-04	E
Radionuclides (unspecified)	4.6E-10		4.6E-10	E
Solid Waste	1.60		1.60	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-71, A-85, A-86, A-88, and A-95.

Source: Franklin Associates, A Division of ERG

Table A-21

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	0.0014		0.0014	C
Particulates (PM10)	8.2E-04	0.0076	0.0084	B
Nitrogen Oxides	0.016	0.10	0.12	B
Hydrocarbons (unspecified)	4.2E-04		4.2E-04	D
VOC (unspecified)	0.039	0.0055	0.044	B
TNMOC (unspecified)	4.6E-05		4.6E-05	C
Sulfur Dioxide	1.21		1.21	C
Sulfur Oxides	0.0015	6.3E-04	0.0021	B
Carbon Monoxide	0.014	0.084	0.098	B
Fossil CO2	11.5	122	134	B
Non-Fossil CO2	0.046		0.046	D
Aldehydes (Formaldehyde)	1.9E-05	7.5E-05	9.4E-05	C
Aldehydes (Acetaldehyde)	1.3E-06		1.3E-06	D
Aldehydes (Propionaldehyde)	8.4E-11		8.4E-11	D
Aldehydes (unspecified)	9.0E-06		9.0E-06	C
Organics (unspecified)	2.5E-06		2.5E-06	D
Ammonia	4.4E-06		4.4E-06	D
Ammonia Chloride	3.2E-07		3.2E-07	D
Methane	0.70	0.0022	0.71	C
Kerosene	5.7E-07		5.7E-07	D
Chlorine	1.8E-07		1.8E-07	D
HCl	5.1E-04		5.1E-04	C
HF	6.2E-05		6.2E-05	C
Metals (unspecified)	1.0E-05		1.0E-05	D
Mercaptan	4.5E-08		4.5E-08	D
Antimony	9.3E-09		9.3E-09	C
Arsenic	2.0E-07	2.0E-07	4.0E-07	C
Beryllium	1.4E-08	1.2E-08	2.6E-08	C
Cadmium	9.2E-08	1.1E-06	1.2E-06	C
Chromium (VI)	3.3E-08		3.3E-08	C
Chromium (unspecified)	2.0E-07	1.4E-06	1.6E-06	C
Cobalt	1.0E-07	8.4E-08	1.9E-07	C
Copper	7.6E-09		7.6E-09	D
Lead	2.4E-07	5.0E-07	7.4E-07	C
Magnesium	4.5E-06		4.5E-06	C
Manganese	6.3E-07	3.8E-07	1.0E-06	C
Mercury	5.5E-08	2.6E-07	3.2E-07	C
Nickel	1.0E-06	2.1E-06	3.1E-06	C
Selenium	5.6E-07	2.4E-08	5.9E-07	C
Zinc	5.1E-09		5.1E-09	D
Acetophenone	3.3E-12		3.3E-12	D
Acrolein	1.2E-06		1.2E-06	D
Nitrous Oxide	2.4E-04	0.0022	0.0025	B
Benzene	0.0048	2.1E-06	0.0048	C
Benzyl Chloride	1.5E-10		1.5E-10	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-11		1.6E-11	D
1,3 Butadiene	3.0E-08		3.0E-08	D
2-Chloroacetophenone	1.5E-12		1.5E-12	D
Chlorobenzene	4.9E-12		4.9E-12	D
2,4-Dinitrotoluene	6.2E-14		6.2E-14	D
Ethyl Chloride	9.3E-12		9.3E-12	D
Ethylbenzene	5.7E-04		5.7E-04	D
Ethylene Dibromide	2.7E-13		2.7E-13	D
Ethylene Dichloride	8.8E-12		8.8E-12	D
Hexane	1.5E-11		1.5E-11	D
Isophorone (C9H14O)	1.3E-10		1.3E-10	D
Methyl Bromide	3.5E-11		3.5E-11	D
Methyl Chloride	1.2E-10		1.2E-10	D
Methyl Ethyl Ketone	8.6E-11		8.6E-11	D
Methyl Hydrazine	3.8E-11		3.8E-11	D
Methyl Methacrylate	4.4E-12		4.4E-12	D
Methyl Tert Butyl Ether (MTBE)	7.7E-12		7.7E-12	D
Naphthalene	9.1E-08	6.1E-07	7.0E-07	C
Propylene	2.0E-06		2.0E-06	D

Table A-21 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	5.5E-12		5.5E-12	D
Toluene	0.0074		0.0074	D
Trichloroethane	2.4E-11		2.4E-11	D
Vinyl Acetate	1.7E-12		1.7E-12	D
Xylenes	0.0043		0.0043	D
Bromoform	8.6E-12		8.6E-12	D
Chloroform	1.3E-11		1.3E-11	D
Carbon Disulfide	2.9E-11		2.9E-11	D
Dimethyl Sulfate	1.1E-11		1.1E-11	D
Cumene	1.2E-12		1.2E-12	D
Cyanide	5.5E-10		5.5E-10	D
Perchloroethylene	1.9E-08		1.9E-08	D
Methylene Chloride	2.8E-07		2.8E-07	D
Carbon Tetrachloride	1.1E-08		1.1E-08	D
Phenols	8.3E-08		8.3E-08	D
Fluorides	3.6E-08		3.6E-08	D
Polyaromatic Hydrocarbons (total)	1.4E-07		1.4E-07	E
Biphenyl	7.0E-10		7.0E-10	E
Acenaphthene	2.1E-10		2.1E-10	E
Acenaphthylene	1.0E-10		1.0E-10	E
Anthracene	8.7E-11		8.7E-11	E
Benzo(a)anthracene	3.3E-11		3.3E-11	E
Benzo(a)pyrene	1.6E-11		1.6E-11	E
Benzo(b,j,k)fluroanthene	4.5E-11		4.5E-11	E
Benzo(g,h,i) perylene	1.1E-11		1.1E-11	E
Chrysene	4.1E-11		4.1E-11	E
Fluoranthene	2.9E-10		2.9E-10	E
Fluorene	3.8E-10		3.8E-10	E
Indeno(1,2,3-cd)pyrene	2.5E-11		2.5E-11	E
Naphthalene	5.4E-09		5.4E-09	E
Phenanthrene	1.1E-09		1.1E-09	E
Pyrene	1.4E-10		1.4E-10	E
5-methyl Chrysene	9.1E-12		9.1E-12	E
Dioxins (unspecified)	3.9E-10		3.9E-10	D
Furans (unspecified)	1.9E-12		1.9E-12	D
CFC12	2.4E-11		2.4E-11	D
Radionuclides (unspecified)	3.2E-05	2.6E-09	3.2E-05	D
Waterborne Emissions				
Acid (unspecified)	2.7E-04		2.7E-04	E
Acid (benzoic)	2.2E-04		2.2E-04	E
Acid (hexanoic)	4.6E-05		4.6E-05	E
Metal (unspecified)	3.39		3.39	E
Dissolved Solids	9.76		9.76	E
Suspended Solids	0.14		0.14	E
BOD	0.038		0.038	E
COD	0.063		0.063	E
Phenol/Phenolic Compounds	9.8E-05		9.8E-05	E
Sulfur	5.8E-04		5.8E-04	E
Sulfates	0.017		0.017	E
Sulfides	3.8E-08		3.8E-08	E
Oil	0.0042		0.0042	E
Hydrocarbons	4.4E-05		4.4E-05	E
Ammonia	0.0033		0.0033	E
Ammonium	2.5E-07		2.5E-07	E
Aluminum	0.0041		0.0041	E
Antimony	2.5E-06		2.5E-06	E
Arsenic	4.8E-05		4.8E-05	E
Barium	0.063		0.063	E
Beryllium	2.2E-06		2.2E-06	E
Cadmium	7.1E-06		7.1E-06	E
Chromium (unspecified)	1.1E-04		1.1E-04	E
Cobalt	4.9E-06		4.9E-06	E
Copper	3.1E-05		3.1E-05	E

Table A-21 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL BOILERS (pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	0.013		0.013	E
Lead	7.0E-05		7.0E-05	E
Lithium	0.23		0.23	E
Magnesium	0.14		0.14	E
Manganese	2.3E-04		2.3E-04	E
Mercury	4.4E-08		4.4E-08	E
Molybdenum	5.0E-06		5.0E-06	E
Nickel	3.8E-05		3.8E-05	E
Selenium	5.8E-07		5.8E-07	E
Silver	4.6E-04		4.6E-04	E
Sodium	2.23		2.23	E
Strontium	0.012		0.012	E
Thallium	5.3E-07		5.3E-07	E
Tin	2.4E-05		2.4E-05	E
Titanium	3.8E-05		3.8E-05	E
Vanadium	5.9E-06		5.9E-06	E
Yttrium	1.5E-06		1.5E-06	E
Zinc	1.1E-04		1.1E-04	E
Chlorides (unspecified)	7.91		7.91	E
Chlorides (methyl chloride)	8.8E-09		8.8E-09	E
Calcium	0.70		0.70	E
Fluorine/ Fluorides	4.2E-06		4.2E-06	E
Nitrates	6.3E-07		6.3E-07	E
Nitrogen (ammonia)	2.2E-07		2.2E-07	E
Bromide	0.047		0.047	E
Boron	6.9E-04		6.9E-04	E
Organic Carbon	0.0011		0.0011	E
Cyanide	1.6E-08		1.6E-08	E
Hardness	2.17		2.17	E
Total Alkalinity	0.018		0.018	E
Surfactants	2.2E-04		2.2E-04	E
Acetone	2.2E-06		2.2E-06	E
Alkylated Benzenes	2.2E-06		2.2E-06	E
Alkylated Fluorenes	1.3E-07		1.3E-07	E
Alkylated Naphthalenes	3.6E-08		3.6E-08	E
Alkylated Phenanthrenes	1.5E-08		1.5E-08	E
Benzene	3.7E-04		3.7E-04	E
Cresols	1.3E-05		1.3E-05	E
Cymene	2.2E-08		2.2E-08	E
Dibenzofuran	4.2E-08		4.2E-08	E
Dibenzothiophene	3.4E-08		3.4E-08	E
2,4-dimethylphenol	6.1E-06		6.1E-06	E
Ethylbenzene	2.1E-05		2.1E-05	E
2-Hexanone	1.4E-06		1.4E-06	E
Methyl ethyl Ketone (MEK)	1.8E-08		1.8E-08	E
1-methylfluorene	2.5E-08		2.5E-08	E
2-methyl naphthalene	3.5E-06		3.5E-06	E
4-methyl-2-pentanone	9.2E-07		9.2E-07	E
Naphthalene	4.0E-06		4.0E-06	E
Pentamethyl benzene	1.6E-08		1.6E-08	E
Phenanthrene	2.8E-08		2.8E-08	E
Toluene	3.5E-04		3.5E-04	E
Total Biphenyls	1.4E-07		1.4E-07	E
Total dibenzo-thiophenes	4.4E-10		4.4E-10	E
Xylenes	1.8E-04		1.8E-04	E
Radionuclides (unspecified)	4.6E-10		4.6E-10	E
Solid Waste	1.60		1.60	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-71, A-85, A-86, and A-95.

Source: Franklin Associates, A Division of ERG

Table A-22

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	0.0014		0.0014	C
Particulates (PM10)	8.2E-04	0.0067	0.0075	B
Nitrogen Oxides	0.016	0.10	0.12	B
Hydrocarbons (unspecified)	4.2E-04		4.2E-04	D
VOC (unspecified)	0.039	0.0021	0.041	B
TNMOC (unspecified)	4.6E-05		4.6E-05	C
Sulfur Dioxide	1.21		1.21	C
Sulfur Oxides	0.0015	6.3E-04	0.0021	B
Carbon Monoxide	0.014	0.015	0.029	B
Fossil CO2	11.5	122	134	B
Non-Fossil CO2	0.046		0.046	D
Aldehydes (Formaldehyde)	1.9E-05	7.2E-04	7.4E-04	C
Aldehydes (Acetaldehyde)	1.3E-06	4.1E-05	4.2E-05	C
Aldehydes (Propionaldehyde)	8.4E-11		8.4E-11	D
Aldehydes (unspecified)	9.0E-06		9.0E-06	C
Organics (unspecified)	2.5E-06		2.5E-06	D
Ammonia	4.4E-06		4.4E-06	D
Ammonia Chloride	3.2E-07		3.2E-07	D
Methane	0.70	0.0087	0.71	B
Kerosene	5.7E-07		5.7E-07	D
Chlorine	1.8E-07		1.8E-07	D
HCl	5.1E-04		5.1E-04	C
HF	6.2E-05		6.2E-05	C
Metals (unspecified)	1.0E-05		1.0E-05	D
Mercaptan	4.5E-08		4.5E-08	D
Antimony	9.3E-09		9.3E-09	C
Arsenic	2.0E-07		2.0E-07	C
Beryllium	1.4E-08		1.4E-08	C
Cadmium	9.2E-08		9.2E-08	C
Chromium (VI)	3.3E-08		3.3E-08	C
Chromium (unspecified)	2.0E-07		2.0E-07	D
Cobalt	1.0E-07		1.0E-07	C
Copper	7.6E-09		7.6E-09	D
Lead	2.4E-07		2.4E-07	C
Magnesium	4.5E-06		4.5E-06	C
Manganese	6.3E-07		6.3E-07	C
Mercury	5.5E-08		5.5E-08	C
Nickel	1.0E-06		1.0E-06	C
Selenium	5.6E-07		5.6E-07	C
Zinc	5.1E-09		5.1E-09	D
Acetophenone	3.3E-12		3.3E-12	D
Acrolein	1.2E-06	6.5E-06	7.7E-06	D
Nitrous Oxide	2.4E-04	0.0031	0.0033	B
Benzene	0.0048	1.2E-05	0.0048	B
Benzyl Chloride	1.5E-10		1.5E-10	D
Bis(2-ethylhexyl) Phthalate (DEHP)	1.6E-11		1.6E-11	D
1,3 Butadiene	3.0E-08	4.4E-07	4.7E-07	D
2-Chloroacetophenone	1.5E-12		1.5E-12	D
Chlorobenzene	4.9E-12		4.9E-12	D
2,4-Dinitrotoluene	6.2E-14		6.2E-14	D
Ethyl Chloride	9.3E-12		9.3E-12	D
Ethylbenzene	5.7E-04	3.3E-05	6.0E-04	D
Ethylene Dibromide	2.7E-13		2.7E-13	D
Ethylene Dichloride	8.8E-12		8.8E-12	D
Hexane	1.5E-11		1.5E-11	D
Isophorone ($C_9H_{14}O$)	1.3E-10		1.3E-10	D
Methyl Bromide	3.5E-11		3.5E-11	D
Methyl Chloride	1.2E-10		1.2E-10	D
Methyl Ethyl Ketone	8.6E-11		8.6E-11	D
Methyl Hydrazine	3.8E-11		3.8E-11	D
Methyl Methacrylate	4.4E-12		4.4E-12	D
Methyl Tert Butyl Ether (MTBE)	7.7E-12		7.7E-12	D
Naphthalene	9.1E-08		9.1E-08	D
Propylene	2.0E-06		2.0E-06	D

Table A-22 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Propylene Oxide		3.0E-05	3.0E-05	D
Styrene	5.5E-12		5.5E-12	D
Toluene	0.0074	1.3E-04	0.0075	D
Trichloroethane	2.4E-11		2.4E-11	D
Vinyl Acetate	1.7E-12		1.7E-12	D
Xylenes	0.0043	6.5E-05	0.0044	D
Bromoform	8.6E-12		8.6E-12	D
Chloroform	1.3E-11		1.3E-11	D
Carbon Disulfide	2.9E-11		2.9E-11	D
Dimethyl Sulfate	1.1E-11		1.1E-11	D
Cumene	1.2E-12		1.2E-12	D
Cyanide	5.5E-10		5.5E-10	D
Perchloroethylene	1.9E-08		1.9E-08	D
Methylene Chloride	2.8E-07		2.8E-07	D
Carbon Tetrachloride	1.1E-08		1.1E-08	D
Phenols	8.3E-08		8.3E-08	D
Fluorides	3.6E-08		3.6E-08	D
Polyaromatic Hydrocarbons (total)	1.4E-07	2.2E-06	2.4E-06	D
Biphenyl	7.0E-10		7.0E-10	E
Acenaphthene	2.1E-10		2.1E-10	E
Acenaphthylene	1.0E-10		1.0E-10	E
Anthracene	8.7E-11		8.7E-11	E
Benzo(a)anthracene	3.3E-11		3.3E-11	E
Benzo(a)pyrene	1.6E-11		1.6E-11	E
Benzo(b,j,k)fluroanthene	4.5E-11		4.5E-11	E
Benzo(g,h,i) perylene	1.1E-11		1.1E-11	E
Chrysene	4.1E-11		4.1E-11	E
Fluoranthene	2.9E-10		2.9E-10	E
Fluorene	3.8E-10		3.8E-10	E
Indeno(1,2,3-cd)pyrene	2.5E-11		2.5E-11	E
Naphthalene	5.4E-09	1.2E-05	1.2E-05	B
Phenanthrene	1.1E-09		1.1E-09	E
Pyrene	1.4E-10		1.4E-10	E
5-methyl Chrysene	9.1E-12		9.1E-12	E
Dioxins (unspecified)	3.9E-10		3.9E-10	D
Furans (unspecified)	1.9E-12		1.9E-12	D
CFC12	2.4E-11		2.4E-11	D
Radionuclides (unspecified)	3.2E-05		3.2E-05	C
Waterborne Emissions				
Acid (unspecified)	2.7E-04		2.7E-04	E
Acid (benzoic)	2.2E-04		2.2E-04	E
Acid (hexanoic)	4.6E-05		4.6E-05	E
Metal (unspecified)	3.39		3.39	E
Dissolved Solids	9.76		9.76	E
Suspended Solids	0.14		0.14	E
BOD	0.038		0.038	E
COD	0.063		0.063	E
Phenol/Phenolic Compounds	9.8E-05		9.8E-05	E
Sulfur	5.8E-04		5.8E-04	E
Sulfates	0.017		0.017	E
Sulfides	3.8E-08		3.8E-08	E
Oil	0.0042		0.0042	E
Hydrocarbons	4.4E-05		4.4E-05	E
Ammonia	0.0033		0.0033	E
Ammonium	2.5E-07		2.5E-07	E
Aluminum	0.0041		0.0041	E
Antimony	2.5E-06		2.5E-06	E
Arsenic	4.8E-05		4.8E-05	E
Barium	0.063		0.063	E
Beryllium	2.2E-06		2.2E-06	E
Cadmium	7.1E-06		7.1E-06	E
Chromium (unspecified)	1.1E-04		1.1E-04	E
Cobalt	4.9E-06		4.9E-06	E

Table A-22 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL EQUIPMENT

(pounds of pollutants per 1,000 cubic feet of natural gas)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Copper	3.1E-05		3.1E-05	E
Iron	0.013		0.013	E
Lead	7.0E-05		7.0E-05	E
Lithium	0.23		0.23	E
Magnesium	0.14		0.14	E
Manganese	2.3E-04		2.3E-04	E
Mercury	4.4E-08		4.4E-08	E
Molybdenum	5.0E-06		5.0E-06	E
Nickel	3.8E-05		3.8E-05	E
Selenium	5.8E-07		5.8E-07	E
Silver	4.6E-04		4.6E-04	E
Sodium	2.23		2.23	E
Strontium	0.012		0.012	E
Thallium	5.3E-07		5.3E-07	E
Tin	2.4E-05		2.4E-05	E
Titanium	3.8E-05		3.8E-05	E
Vanadium	5.9E-06		5.9E-06	E
Yttrium	1.5E-06		1.5E-06	E
Zinc	1.1E-04		1.1E-04	E
Chlorides (unspecified)	7.91		7.91	E
Chlorides (methyl chloride)	8.8E-09		8.8E-09	E
Calcium	0.70		0.70	E
Fluorine/ Fluorides	4.2E-06		4.2E-06	E
Nitrates	6.3E-07		6.3E-07	E
Nitrogen (ammonia)	2.2E-07		2.2E-07	E
Bromide	0.047		0.047	E
Boron	6.9E-04		6.9E-04	E
Organic Carbon	0.0011		0.0011	E
Cyanide	1.6E-08		1.6E-08	E
Hardness	2.17		2.17	E
Total Alkalinity	0.018		0.018	E
Surfactants	2.2E-04		2.2E-04	E
Acetone	2.2E-06		2.2E-06	E
Alkylated Benzenes	2.2E-06		2.2E-06	E
Alkylated Fluorenes	1.3E-07		1.3E-07	E
Alkylated Naphthalenes	3.6E-08		3.6E-08	E
Alkylated Phenanthrenes	1.5E-08		1.5E-08	E
Benzene	3.7E-04		3.7E-04	E
Cresols	1.3E-05		1.3E-05	E
Cymene	2.2E-08		2.2E-08	E
Dibenzofuran	4.2E-08		4.2E-08	E
Dibenzothiophene	3.4E-08		3.4E-08	E
2,4-dimethylphenol	6.1E-06		6.1E-06	E
Ethylbenzene	2.1E-05		2.1E-05	E
2-Hexanone	1.4E-06		1.4E-06	E
Methyl ethyl Ketone (MEK)	1.8E-08		1.8E-08	E
1-methylfluorene	2.5E-08		2.5E-08	E
2-methyl naphthalene	3.5E-06		3.5E-06	E
4-methyl-2-pentanone	9.2E-07		9.2E-07	E
Naphthalene	4.0E-06		4.0E-06	E
Pentamethyl benzene	1.6E-08		1.6E-08	E
Phenanthrene	2.8E-08		2.8E-08	E
Toluene	3.5E-04		3.5E-04	E
Total Biphenyls	1.4E-07		1.4E-07	E
Total dibenzo-thiophenes	4.4E-10		4.4E-10	E
Xylenes	1.8E-04		1.8E-04	E
Radionuclides (unspecified)	4.6E-10		4.6E-10	E
Solid Waste	1.60		1.60	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-67, A-85, A-95, and A-96.

Source: Franklin Associates, A Division of ERG

Diesel

Industrial Equipment. Diesel is used in a wide variety of industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment. The calculations and assumptions used for estimating the environmental emissions from diesel combustion in industrial equipment are discussed below.

Air emissions for diesel combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-97).

Diesel-powered industrial equipment does not employ particulate or sulfur control equipment, nor does it rely on flows of cooling water or steam (Reference A-95). It is thus assumed that the combustion of diesel in industrial equipment produces no solid waste or waterborne emissions.

Gasoline

Industrial Equipment. Gasoline is used in a wide variety of industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment. The calculations and assumptions used for estimating the environmental emissions from gasoline combustion in industrial equipment are discussed below.

Air emissions for gasoline combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-97).

Gasoline-powered industrial equipment does not employ particulate or sulfur control equipment, nor does it rely on flows of cooling water or steam (Reference A-95). It is thus assumed that the combustion of gasoline in industrial equipment produces no solid waste or waterborne emissions.

Liquefied Petroleum Gases

Industrial Equipment. Liquefied petroleum gas (LPG) consists of propane, butane, or a mixture of the two. This gas is obtained both from natural gas liquids plants and as a byproduct of petroleum refinery operations. LPG is used in industrial boilers. The calculations and assumptions used for estimating the environmental emissions from LPG combustion in industrial boilers are discussed below.

Air emissions for LPG combustion were taken from the GREET transportation model (Reference A-85). The GREET model includes emission data for both stationary and mobile sources. Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-95).

LPG is a clean-burning fuel and produces neglible ash and sulfur oxide emissions (References A-67 and A-95). This eliminates the need for post-combustion control equipment and reduces the frequency at which combustion equipment is cleaned. It is thus assumed that LPG combustion produces no solid waste or waterborne emissions.

Fuel Grade Uranium

Nuclear energy accounted for 19.8 percent of the total megawatt hours produced by U.S. electric utilities in 2000 (Reference A-62). Nuclear utilities generate electricity by harnessing the thermal energy from controlled nuclear fission reactions. These reactions are used to produce steam, which in turn drives a turbine-generator to produce electricity.

The quantity of uranium fuel (UO_2) consumed per kilowatt-hour of electricity production was calculated by comparing the quantity of uranium fuel loaded into U.S. nuclear reactors to the kilowatt-hours of electricity produced by U.S. nuclear reactors. From 1999 through 2001, an annual average of 54.3 million pounds of uranium concentrate (U_3O_8) was used to produce uranium fuel (UO_2) used in U.S. nuclear reactors (Reference A-103). During the same time period, an annual average of 750 billion kilowatt-hours of electricity was generated by U.S. nuclear reactors (Reference A-93). Using a conversion of 10.89 pounds of uranium concentrate per production of 1 pound of uranium fuel (Reference A-94), 0.0067 pounds of uranium fuel are required for the production of 1,000 kilowatt-hours of electricity.

Unlike utilities that require a daily or hourly supply of fuel (such as coal-fired utilities), the fuel for nuclear reactors does not need to be continuously recharged. A fuel load in a nuclear reactor can last up to three years (Reference A-60).

No data are available for the environmental emissions associated with the consumption of uranium fuel by nuclear power plants. Nuclear fission reactions are carefully controlled and spent nuclear fuel is encapsulated, so it is assumed that negligible environmental emissions result directly from uranium consumption. The ancillary processes in a nuclear power plant, including cooling water and steam generation processes, may result in environmental emissions. However, on the basis of the quantity of fuel consumed per unit of electrical output (Reference A-60), the extent of such emissions are also assumed to be negligible.

Table A-23

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DIESEL POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.49	13.8	16.3	B
Particulates (PM10)	0.64		0.64	D
Nitrogen Oxides	25.0	441	466	B
Hydrocarbons (unspecified)	15.6		15.6	D
VOC (unspecified)	0.99	11.3	12.3	B
TNMOC (unspecified)	0.021		0.021	C
Sulfur Dioxide	14.0		14.0	C
Sulfur Oxides	21.5	5.00	26.5	B
Carbon Monoxide	106	117	223	B
Fossil CO2	3,258	22,543	25,802	B
Non-Fossil CO2	22.8		22.8	C
Aldehydes (Formaldehyde)	0.0022	0.16	0.17	C
Aldehydes (Acetaldehyde)	1.7E-04	0.11	0.11	C
Aldehydes (Propionaldehyde)	3.9E-08		3.9E-08	D
Aldehydes (unspecified)	0.32		0.32	C
Organics (unspecified)	0.0012		0.0012	D
Ammonia	0.16		0.16	D
Ammonia Chloride	1.6E-04		1.6E-04	D
Methane	34.9	1.12	36.1	C
Kerosene	2.9E-04		2.9E-04	D
Chlorine	9.3E-05		9.3E-05	D
HCl	0.25		0.25	C
HF	0.029		0.029	C
Metals (unspecified)	0.0050		0.0050	D
Mercaptan	2.1E-05		2.1E-05	D
Antimony	4.4E-06		4.4E-06	C
Arsenic	1.2E-04		1.2E-04	C
Beryllium	5.7E-06		5.7E-06	C
Cadmium	3.0E-05		3.0E-05	C
Chromium (VI)	1.5E-05		1.5E-05	C
Chromium (unspecified)	8.7E-05		8.7E-05	D
Cobalt	1.9E-04		1.9E-04	C
Copper	1.4E-06		1.4E-06	D
Lead	1.3E-04		1.3E-04	C
Magnesium	0.0021		0.0021	C
Manganese	3.7E-04		3.7E-04	C
Mercury	2.2E-05		2.2E-05	C
Nickel	0.0024		0.0024	C
Selenium	2.7E-04		2.7E-04	C
Zinc	9.3E-07		9.3E-07	D
Acetophenone	1.5E-09		1.5E-09	D
Acrolein	5.3E-04	0.013	0.013	C
Nitrous Oxide	0.060	0.57	0.63	C
Benzene	0.034	0.13	0.16	C
Benzyl Chloride	7.2E-08		7.2E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09		7.5E-09	D
1,3 Butadiene	3.7E-06	0.0054	0.0054	C
2-Chloroacetophenone	7.2E-10		7.2E-10	D
Chlorobenzene	2.3E-09		2.3E-09	D
2,4-Dinitrotoluene	2.9E-11		2.9E-11	D
Ethyl Chloride	4.3E-09		4.3E-09	D
Ethylbenzene	0.0039		0.0039	D
Ethylene Dibromide	1.2E-10		1.2E-10	D
Ethylene Dichloride	4.1E-09		4.1E-09	D
Hexane	6.9E-09		6.9E-09	D
Isophorone ($C_9H_{14}O$)	5.9E-08		5.9E-08	D
Methyl Bromide	1.6E-08		1.6E-08	D
Methyl Chloride	5.4E-08		5.4E-08	D
Methyl Ethyl Ketone	4.0E-08		4.0E-08	D
Methyl Hydrazine	1.7E-08		1.7E-08	D
Methyl Methacrylate	2.1E-09		2.1E-09	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09		3.6E-09	D
Naphthalene	4.7E-05		4.7E-05	D
Propylene	2.4E-04	0.36	0.36	C

Table A-23 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DIESEL POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.6E-09		2.6E-09	D
Toluene	0.051	0.057	0.11	C
Trichloroethane	7.5E-07		7.5E-07	D
Vinyl Acetate	7.8E-10		7.8E-10	D
Xylenes	0.030	0.040	0.069	C
Bromoform	4.0E-09		4.0E-09	D
Chloroform	6.1E-09		6.1E-09	D
Carbon Disulfide	1.3E-08		1.3E-08	D
Dimethyl Sulfate	4.9E-09		4.9E-09	D
Cumene	5.4E-10		5.4E-10	D
Cyanide	2.6E-07		2.6E-07	D
Perchloroethylene	1.0E-05		1.0E-05	D
Methylene Chloride	2.3E-04		2.3E-04	D
Carbon Tetrachloride	5.4E-06		5.4E-06	D
Phenols	1.2E-04		1.2E-04	D
Fluorides	1.8E-05		1.8E-05	D
Polyaromatic Hydrocarbons (total)	2.0E-05	0.023	0.023	C
Biphenyl	3.3E-07		3.3E-07	E
Acenaphthene	9.8E-08		9.8E-08	E
Acenaphthylene	4.8E-08		4.8E-08	E
Anthracene	4.0E-08		4.0E-08	E
Benzo(a)anthracene	1.5E-08		1.5E-08	E
Benzo(a)pyrene	7.3E-09		7.3E-09	E
Benzo(b,j,k)fluroanthene	2.1E-08		2.1E-08	E
Benzo(g,h,i) perylene	5.2E-09		5.2E-09	E
Chrysene	1.9E-08		1.9E-08	E
Fluoranthene	1.4E-07		1.4E-07	E
Fluorene	1.7E-07		1.7E-07	E
Indeno(1,2,3-cd)pyrene	1.2E-08		1.2E-08	E
Naphthalene	2.5E-06		2.5E-06	E
Phenanthrene	5.2E-07		5.2E-07	E
Pyrene	6.3E-08		6.3E-08	E
5-methyl Chrysene	4.2E-09		4.2E-09	E
Dioxins (unspecified)	2.0E-07		2.0E-07	D
Furans (unspecified)	8.7E-10		8.7E-10	D
CFC12	8.9E-07		8.9E-07	D
Radionuclides (unspecified)	0.016		0.016	C
Waterborne Emissions				
Acid (unspecified)	0.0018		0.0018	E
Acid (benzoic)	0.030		0.030	E
Acid (hexanoic)	0.0062		0.0062	E
Metal (unspecified)	23.4		23.4	E
Dissolved Solids	1,325		1,325	E
Suspended Solids	78.8		78.8	E
BOD	0.75		0.75	E
COD	2.22		2.22	E
Phenol/Phenolic Compounds	0.015		0.015	E
Sulfur	0.079		0.079	E
Sulfates	2.37		2.37	E
Sulfides	0.0014		0.0014	E
Oil	0.68		0.68	E
Hydrocarbons	0.0059		0.0059	E
Ammonia	0.54		0.54	E
Ammonium	1.3E-04		1.3E-04	E
Aluminum	2.56		2.56	E
Antimony	0.0016		0.0016	E
Arsenic	0.0081		0.0081	E
Barium	35.1		35.1	E
Beryllium	4.5E-04		4.5E-04	E
Cadmium	0.0012		0.0012	E
Chromium (unspecified)	0.073		0.073	E
Cobalt	6.6E-04		6.6E-04	E
Copper	0.0084		0.0084	E

Table A-23 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DIESEL POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5.11		5.11	E
Lead	0.017		0.017	E
Lithium	1.65		1.65	E
Magnesium	18.7		18.7	E
Manganese	0.032		0.032	E
Mercury	2.8E-05		2.8E-05	E
Molybdenum	6.8E-04		6.8E-04	E
Nickel	0.0080		0.0080	E
Selenium	3.5E-04		3.5E-04	E
Silver	0.062		0.062	E
Sodium	303		303	E
Strontium	1.62		1.62	E
Thallium	3.4E-04		3.4E-04	E
Tin	0.0065		0.0065	E
Titanium	0.025		0.025	E
Vanadium	8.1E-04		8.1E-04	E
Yttrium	2.0E-04		2.0E-04	E
Zinc	0.059		0.059	E
Chlorides (unspecified)	1,074		1,074	E
Chlorides (methyl chloride)	1.2E-06		1.2E-06	E
Calcium	95.5		95.5	E
Fluorine/ Fluorides	0.0021		0.0021	E
Nitrates	3.2E-04		3.2E-04	E
Nitrogen (ammonia)	1.1E-04		1.1E-04	E
Bromide	6.37		6.37	E
Boron	0.093		0.093	E
Organic Carbon	0.0076		0.0076	E
Cyanide	2.1E-06		2.1E-06	E
Hardness	294		294	E
Total Alkalinity	2.34		2.34	E
Surfactants	0.025		0.025	E
Acetone	3.0E-04		3.0E-04	E
Alkylated Benzenes	0.0014		0.0014	E
Alkylated Fluorenes	8.1E-05		8.1E-05	E
Alkylated Naphthalenes	2.3E-05		2.3E-05	E
Alkylated Phenanthrenes	9.5E-06		9.5E-06	E
Benzene	0.050		0.050	E
Cresols	0.0018		0.0018	E
Cymene	3.0E-06		3.0E-06	E
Dibenzofuran	5.7E-06		5.7E-06	E
Dibenzothiophene	4.6E-06		4.6E-06	E
2,4-dimethylphenol	8.3E-04		8.3E-04	E
Ethylbenzene	0.0028		0.0028	E
2-Hexanone	1.9E-04		1.9E-04	E
Methyl ethyl Ketone (MEK)	2.4E-06		2.4E-06	E
1-methylfluorene	3.4E-06		3.4E-06	E
2-methyl naphthalene	4.7E-04		4.7E-04	E
4-methyl-2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.4E-04		5.4E-04	E
Pentamethyl benzene	2.2E-06		2.2E-06	E
Phenanthrene	8.2E-06		8.2E-06	E
Toluene	0.047		0.047	E
Total Biphenyls	9.1E-05		9.1E-05	E
Total dibenzo- thiophenes	2.8E-07		2.8E-07	E
Xylenes	0.025		0.025	E
Radionuclides (unspecified)	2.3E-07		2.3E-07	E
Solid Waste	387		387	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-85 and A-97.

Source: Franklin Associates, A Division of ERG

Table A-24

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF GASOLINE POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.12	2.21	4.33	B
Particulates (PM10)	0.55		0.55	D
Nitrogen Oxides	21.3	279	301	B
Hydrocarbons (unspecified)	13.3		13.3	D
VOC (unspecified)	0.85	23.7	24.5	C
TNMOC (unspecified)	0.018		0.018	C
Sulfur Dioxide	11.9		11.9	C
Sulfur Oxides	18.3	4.18	22.5	B
Carbon Monoxide	90.0	1,130	1,220	B
Fossil CO2	2,776	17,403	20,179	B
Non-Fossil CO2	19.5		19.5	D
Aldehydes (Formaldehyde)	0.0019	0.15	0.15	C
Aldehydes (Acetaldehyde)	1.5E-04	0.096	0.096	C
Aldehydes (Propionaldehyde)	3.3E-08		3.3E-08	D
Aldehydes (unspecified)	0.28		0.28	C
Organics (unspecified)	0.0010		0.0010	D
Ammonia	0.14		0.14	D
Ammonia Chloride	1.4E-04		1.4E-04	D
Methane	29.8	7.68	37.5	B
Kerosene	2.4E-04		2.4E-04	D
Chlorine	7.9E-05		7.9E-05	D
HCl	0.22		0.22	C
HF	0.025		0.025	C
Metals (unspecified)	0.0043		0.0043	D
Mercaptan	1.8E-05		1.8E-05	D
Antimony	3.7E-06		3.7E-06	C
Arsenic	1.0E-04		1.0E-04	C
Beryllium	4.9E-06		4.9E-06	C
Cadmium	2.6E-05		2.6E-05	C
Chromium (VI)	1.3E-05		1.3E-05	C
Chromium (unspecified)	7.4E-05		7.4E-05	D
Cobalt	1.6E-04		1.6E-04	C
Copper	1.2E-06		1.2E-06	D
Lead	1.1E-04		1.1E-04	C
Magnesium	0.0018		0.0018	C
Manganese	3.1E-04		3.1E-04	C
Mercury	1.9E-05		1.9E-05	C
Nickel	0.0021		0.0021	C
Selenium	2.3E-04		2.3E-04	C
Zinc	7.9E-07		7.9E-07	D
Acetophenone	1.3E-09		1.3E-09	D
Acrolein	4.5E-04	0.012	0.012	C
Nitrous Oxide	0.051	0.51	0.56	B
Benzene	0.029	0.12	0.15	C
Benzyl Chloride	6.1E-08		6.1E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	6.4E-09		6.4E-09	D
1,3 Butadiene	3.1E-06	0.0049	0.0049	C
2-Chloroacetophenone	6.1E-10		6.1E-10	D
Chlorobenzene	1.9E-09		1.9E-09	D
2,4-Dinitrotoluene	2.4E-11		2.4E-11	D
Ethyl Chloride	3.7E-09		3.7E-09	D
Ethylbenzene	0.0034		0.0034	D
Ethylene Dibromide	1.0E-10		1.0E-10	D
Ethylene Dichloride	3.5E-09		3.5E-09	D
Hexane	5.9E-09		5.9E-09	D
Isophorone ($C_9H_{14}O$)	5.1E-08		5.1E-08	D
Methyl Bromide	1.4E-08		1.4E-08	D
Methyl Chloride	4.6E-08		4.6E-08	D
Methyl Ethyl Ketone	3.4E-08		3.4E-08	D
Methyl Hydrazine	1.5E-08		1.5E-08	D
Methyl Methacrylate	1.7E-09		1.7E-09	D
Methyl Tert Butyl Ether (MTBE)	3.1E-09		3.1E-09	D
Naphthalene	4.0E-05		4.0E-05	D
Propylene	2.1E-04	0.32	0.32	C

Table A-24 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF GASOLINE POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.2E-09		2.2E-09	D
Toluene	0.043	0.051	0.095	C
Trichloroethane	6.4E-07		6.4E-07	D
Vinyl Acetate	6.6E-10		6.6E-10	D
Xylenes	0.025	0.036	0.061	C
Bromoform	3.4E-09		3.4E-09	D
Chloroform	5.2E-09		5.2E-09	D
Carbon Disulfide	1.1E-08		1.1E-08	D
Dimethyl Sulfate	4.2E-09		4.2E-09	D
Cumene	4.6E-10		4.6E-10	D
Cyanide	2.2E-07		2.2E-07	D
Perchloroethylene	8.8E-06		8.8E-06	D
Methylene Chloride	2.0E-04		2.0E-04	D
Carbon Tetrachloride	4.6E-06		4.6E-06	D
Phenols	9.8E-05		9.8E-05	D
Fluorides	1.5E-05		1.5E-05	D
Polyaromatic Hydrocarbons (total)	1.7E-05	0.021	0.021	C
Biphenyl	2.8E-07		2.8E-07	E
Acenaphthene	8.3E-08		8.3E-08	E
Acenaphthylene	4.1E-08		4.1E-08	E
Anthracene	3.4E-08		3.4E-08	E
Benzo(a)anthracene	1.3E-08		1.3E-08	E
Benzo(a)pyrene	6.2E-09		6.2E-09	E
Benzo(b,j,k)fluroanthene	1.8E-08		1.8E-08	E
Benzo(g,h,i) perylene	4.4E-09		4.4E-09	E
Chrysene	1.6E-08		1.6E-08	E
Fluoranthene	1.2E-07		1.2E-07	E
Fluorene	1.5E-07		1.5E-07	E
Indeno(1,2,3-cd)pyrene	1.0E-08		1.0E-08	E
Naphthalene	2.1E-06		2.1E-06	E
Phenanthrene	4.4E-07		4.4E-07	E
Pyrene	5.4E-08		5.4E-08	E
5-methyl Chrysene	3.6E-09		3.6E-09	E
Dioxins (unspecified)	1.7E-07		1.7E-07	D
Furans (unspecified)	7.4E-10		7.4E-10	D
CFC12	7.5E-07		7.5E-07	D
Radionuclides (unspecified)	0.014		0.014	C
Waterborne Emissions				
Acid (unspecified)	0.0016		0.0016	E
Acid (benzoic)	0.026		0.026	E
Acid (hexanoic)	0.0053		0.0053	E
Metal (unspecified)	20.0		20.0	E
Dissolved Solids	1,129		1,129	E
Suspended Solids	67.1		67.1	E
BOD	0.64		0.64	E
COD	1.89		1.89	E
Phenol/Phenolic Compounds	0.013		0.013	E
Sulfur	0.067		0.067	E
Sulfates	2.02		2.02	E
Sulfides	0.0012		0.0012	E
Oil	0.58		0.58	E
Hydrocarbons	0.0051		0.0051	E
Ammonia	0.46		0.46	E
Ammonium	1.1E-04		1.1E-04	E
Aluminum	2.18		2.18	E
Antimony	0.0014		0.0014	E
Arsenic	0.0069		0.0069	E
Barium	29.9		29.9	E
Beryllium	3.9E-04		3.9E-04	E
Cadmium	0.0010		0.0010	E
Chromium (unspecified)	0.062		0.062	E
Cobalt	5.6E-04		5.6E-04	E
Copper	0.0071		0.0071	E

Table A-24 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF GASOLINE POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	4.35		4.35	E
Lead	0.015		0.015	E
Lithium	1.41		1.41	E
Magnesium	15.9		15.9	E
Manganese	0.028		0.028	E
Mercury	2.4E-05		2.4E-05	E
Molybdenum	5.8E-04		5.8E-04	E
Nickel	0.0068		0.0068	E
Selenium	3.0E-04		3.0E-04	E
Silver	0.053		0.053	E
Sodium	258		258	E
Strontium	1.38		1.38	E
Thallium	2.9E-04		2.9E-04	E
Tin	0.0055		0.0055	E
Titanium	0.021		0.021	E
Vanadium	6.9E-04		6.9E-04	E
Yttrium	1.7E-04		1.7E-04	E
Zinc	0.050		0.050	E
Chlorides (unspecified)	915		915	E
Chlorides (methyl chloride)	1.0E-06		1.0E-06	E
Calcium	81.4		81.4	E
Fluorine/ Fluorides	0.0018		0.0018	E
Nitrates	2.7E-04		2.7E-04	E
Nitrogen (ammonia)	9.5E-05		9.5E-05	E
Bromide	5.43		5.43	E
Boron	0.080		0.080	E
Organic Carbon	0.0065		0.0065	E
Cyanide	1.8E-06		1.8E-06	E
Hardness	251		251	E
Total Alkalinity	2.00		2.00	E
Surfactants	0.021		0.021	E
Acetone	2.5E-04		2.5E-04	E
Alkylated Benzenes	0.0012		0.0012	E
Alkylated Fluorenes	6.9E-05		6.9E-05	E
Alkylated Naphthalenes	2.0E-05		2.0E-05	E
Alkylated Phenanthrenes	8.1E-06		8.1E-06	E
Benzene	0.043		0.043	E
Cresols	0.0015		0.0015	E
Cymene	2.5E-06		2.5E-06	E
Dibenzofuran	4.8E-06		4.8E-06	E
Dibenzothiophene	3.9E-06		3.9E-06	E
2,4-dimethylphenol	7.1E-04		7.1E-04	E
Ethylbenzene	0.0024		0.0024	E
2-Hexanone	1.7E-04		1.7E-04	E
Methyl ethyl Ketone (MEK)	2.0E-06		2.0E-06	E
1-methylfluorene	2.9E-06		2.9E-06	E
2-methyl naphthalene	4.0E-04		4.0E-04	E
4-methyl-2-pentanone	1.1E-04		1.1E-04	E
Naphthalene	4.6E-04		4.6E-04	E
Pentamethyl benzene	1.9E-06		1.9E-06	E
Phenanthrene	7.0E-06		7.0E-06	E
Toluene	0.040		0.040	E
Total Biphenyls	7.7E-05		7.7E-05	E
Total dibenzo- thiophenes	2.4E-07		2.4E-07	E
Xylenes	0.021		0.021	E
Radionuclides (unspecified)	1.9E-07		1.9E-07	E
Solid Waste	330		330	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-85 and A-97

Source: Franklin Associates, A Division of ERG

Table A-25

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIQUEFIED PETROLEUM GAS IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of LPG)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	1.56		1.56	C
Particulates (PM10)	0.40	0.65	1.05	B
Nitrogen Oxides	15.7	21.7	37.4	B
Hydrocarbons (unspecified)	9.76		9.76	D
VOC (unspecified)	0.62	0.38	1.00	C
TNMOC (unspecified)	0.013		0.013	C
Sulfur Dioxide	8.74		8.74	C
Sulfur Oxides	13.4		13.4	C
Carbon Monoxide	66.1	3.70	69.8	B
Fossil CO2	2,037	14,389	16,425	B
Non-Fossil CO2	14.3		14.3	D
Aldehydes (Formaldehyde)	0.0014		0.0014	C
Aldehydes (Acetaldehyde)	1.1E-04		1.1E-04	D
Aldehydes (Propionaldehyde)	2.4E-08		2.4E-08	D
Aldehydes (unspecified)	0.20		0.20	C
Organics (unspecified)	7.3E-04		7.3E-04	D
Ammonia	0.10		0.10	D
Ammonia Chloride	9.9E-05		9.9E-05	D
Methane	21.8	0.22	22.1	B
Kerosene	1.8E-04		1.8E-04	D
Chlorine	5.8E-05		5.8E-05	D
HCl	0.16		0.16	C
HF	0.018		0.018	C
Metals (unspecified)	0.0031		0.0031	D
Mercaptan	1.3E-05		1.3E-05	D
Antimony	2.7E-06		2.7E-06	C
Arsenic	7.5E-05		7.5E-05	C
Beryllium	3.6E-06		3.6E-06	C
Cadmium	1.9E-05		1.9E-05	C
Chromium (VI)	9.5E-06		9.5E-06	C
Chromium (unspecified)	5.4E-05		5.4E-05	D
Cobalt	1.2E-04		1.2E-04	C
Copper	8.7E-07		8.7E-07	D
Lead	8.4E-05		8.4E-05	C
Magnesium	0.0013		0.0013	C
Manganese	2.3E-04		2.3E-04	C
Mercury	1.4E-05		1.4E-05	C
Nickel	0.0015		0.0015	C
Selenium	1.7E-04		1.7E-04	C
Zinc	5.8E-07		5.8E-07	D
Acetophenone	9.6E-10		9.6E-10	D
Acrolein	3.3E-04		3.3E-04	D
Nitrous Oxide	0.038	0.98	1.02	B
Benzene	0.021		0.021	D
Benzyl Chloride	4.5E-08		4.5E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	4.7E-09		4.7E-09	D
1,3 Butadiene	2.3E-06		2.3E-06	D
2-Chloroacetophenone	4.5E-10		4.5E-10	D
Chlorobenzene	1.4E-09		1.4E-09	D
2,4-Dinitrotoluene	1.8E-11		1.8E-11	D
Ethyl Chloride	2.7E-09		2.7E-09	D
Ethylbenzene	0.0025		0.0025	D
Ethylene Dibromide	7.7E-11		7.7E-11	D
Ethylene Dichloride	2.6E-09		2.6E-09	D
Hexane	4.3E-09		4.3E-09	D
Isophorone ($C_9H_{14}O$)	3.7E-08		3.7E-08	D
Methyl Bromide	1.0E-08		1.0E-08	D
Methyl Chloride	3.4E-08		3.4E-08	D
Methyl Ethyl Ketone	2.5E-08		2.5E-08	D
Methyl Hydrazine	1.1E-08		1.1E-08	D
Methyl Methacrylate	1.3E-09		1.3E-09	D
Methyl Tert Butyl Ether (MTBE)	2.2E-09		2.2E-09	D
Naphthalene	3.0E-05		3.0E-05	D
Propylene	1.5E-04		1.5E-04	D

Table A-25 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIQUEFIED PETROLEUM GAS IN INDUSTRIAL BOILERS (pounds of pollutants per 1,000 gallons of LPG)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	1.6E-09		1.6E-09	D
Toluene	0.032		0.032	D
Trichloroethane	4.7E-07		4.7E-07	D
Vinyl Acetate	4.9E-10		4.9E-10	D
Xylenes	0.019		0.019	D
Bromoform	2.5E-09		2.5E-09	D
Chloroform	3.8E-09		3.8E-09	D
Carbon Disulfide	8.3E-09		8.3E-09	D
Dimethyl Sulfate	3.1E-09		3.1E-09	D
Cumene	3.4E-10		3.4E-10	D
Cyanide	1.6E-07		1.6E-07	D
Perchloroethylene	6.5E-06		6.5E-06	D
Methylene Chloride	1.5E-04		1.5E-04	D
Carbon Tetrachloride	3.4E-06		3.4E-06	D
Phenols	7.2E-05		7.2E-05	D
Fluorides	1.1E-05		1.1E-05	D
Polyaromatic Hydrocarbons (total)	1.2E-05		1.2E-05	E
Biphenyl	2.0E-07		2.0E-07	E
Acenaphthene	6.1E-08		6.1E-08	E
Acenaphthylene	3.0E-08		3.0E-08	E
Anthracene	2.5E-08		2.5E-08	E
Benzo(a)anthracene	9.6E-09		9.6E-09	E
Benzo(a)pyrene	4.6E-09		4.6E-09	E
Benzo(b,j,k)fluroanthene	1.3E-08		1.3E-08	E
Benzo(g,h,i) perylene	3.2E-09		3.2E-09	E
Chrysene	1.2E-08		1.2E-08	E
Fluoranthene	8.5E-08		8.5E-08	E
Fluorene	1.1E-07		1.1E-07	E
Indeno(1,2,3-cd)pyrene	7.3E-09		7.3E-09	E
Naphthalene	1.6E-06		1.6E-06	E
Phenanthrene	3.2E-07		3.2E-07	E
Pyrene	4.0E-08		4.0E-08	E
5-methyl Chrysene	2.6E-09		2.6E-09	E
Dioxins (unspecified)	1.2E-07		1.2E-07	D
Furans (unspecified)	5.5E-10		5.5E-10	D
CFC12	5.5E-07		5.5E-07	D
Radionuclides (unspecified)	0.010		0.010	C
Waterborne Emissions				
Acid (unspecified)	0.0012		0.0012	E
Acid (benzoic)	0.019		0.019	E
Acid (hexanoic)	0.0039		0.0039	E
Metal (unspecified)	14.6		14.6	E
Dissolved Solids	828		828	E
Suspended Solids	49.2		49.2	E
BOD	0.47		0.47	E
COD	1.39		1.39	E
Phenol/Phenolic Compounds	0.0094		0.0094	E
Sulfur	0.049		0.049	E
Sulfates	1.48		1.48	E
Sulfides	8.9E-04		8.9E-04	E
Oil	0.43		0.43	E
Hydrocarbons	0.0037		0.0037	E
Ammonia	0.34		0.34	E
Ammonium	8.0E-05		8.0E-05	E
Aluminum	1.60		1.60	E
Antimony	0.0010		0.0010	E
Arsenic	0.0051		0.0051	E
Barium	21.9		21.9	E
Beryllium	2.8E-04		2.8E-04	E
Cadmium	7.5E-04		7.5E-04	E
Chromium (unspecified)	0.045		0.045	E
Cobalt	4.1E-04		4.1E-04	E
Copper	0.0052		0.0052	E

Table A-25 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIQUEFIED PETROLEUM GAS IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 gallons of LPG)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	3.19		3.19	E
Lead	0.011		0.011	E
Lithium	1.03		1.03	E
Magnesium	11.7		11.7	E
Manganese	0.020		0.020	E
Mercury	1.8E-05		1.8E-05	E
Molybdenum	4.3E-04		4.3E-04	E
Nickel	0.0050		0.0050	E
Selenium	2.2E-04		2.2E-04	E
Silver	0.039		0.039	E
Sodium	189		189	E
Strontium	1.01		1.01	E
Thallium	2.1E-04		2.1E-04	E
Tin	0.0041		0.0041	E
Titanium	0.015		0.015	E
Vanadium	5.0E-04		5.0E-04	E
Yttrium	1.3E-04		1.3E-04	E
Zinc	0.037		0.037	E
Chlorides (unspecified)	671		671	E
Chlorides (methyl chloride)	7.5E-07		7.5E-07	E
Calcium	59.7		59.7	E
Fluorine/ Fluorides	0.0013		0.0013	E
Nitrates	2.0E-04		2.0E-04	E
Nitrogen (ammonia)	6.9E-05		6.9E-05	E
Bromide	3.98		3.98	E
Boron	0.058		0.058	E
Organic Carbon	0.0048		0.0048	E
Cyanide	1.3E-06		1.3E-06	E
Hardness	184		184	E
Total Alkalinity	1.47		1.47	E
Surfactants	0.016		0.016	E
Acetone	1.9E-04		1.9E-04	E
Alkylated Benzenes	8.8E-04		8.8E-04	E
Alkylated Fluorenes	5.1E-05		5.1E-05	E
Alkylated Naphthalenes	1.4E-05		1.4E-05	E
Alkylated Phenanthrenes	6.0E-06		6.0E-06	E
Benzene	0.031		0.031	E
Cresols	0.0011		0.0011	E
Cymene	1.9E-06		1.9E-06	E
Dibenzofuran	3.5E-06		3.5E-06	E
Dibenzothiophene	2.9E-06		2.9E-06	E
2,4 dimethylphenol	5.2E-04		5.2E-04	E
Ethylbenzene	0.0018		0.0018	E
2-Hexanone	1.2E-04		1.2E-04	E
Methyl ethyl Ketone (MEK)	1.5E-06		1.5E-06	E
1-methylfluorene	2.1E-06		2.1E-06	E
2-methyl naphthalene	2.9E-04		2.9E-04	E
4-methyl-2-pentanone	7.8E-05		7.8E-05	E
Naphthalene	3.4E-04		3.4E-04	E
Pentamethyl benzene	1.4E-06		1.4E-06	E
Phenanthrene	5.2E-06		5.2E-06	E
Toluene	0.029		0.029	E
Total Biphenyls	5.7E-05		5.7E-05	E
Total dibenzo-thiophenes	1.8E-07		1.8E-07	E
Xylenes	0.016		0.016	E
Radionuclides (unspecified)	1.4E-07		1.4E-07	E
Solid Waste	242		242	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-85.

Source: Franklin Associates, A Division of ERG

Table A-26

ENVIRONMENTAL EMISSIONS FOR THE CONSUMPTION OF FUEL-GRADE URANIUM
(pounds of pollutants per 1,000 pounds of uranium)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	18,786		18,786	D
Particulates (PM10)	384		384	D
Nitrogen Oxides	21,925		21,925	C
Hydrocarbons (unspecified)	3,501		3,501	D
VOC (unspecified)	352		352	D
TNMOC (unspecified)	63.8		63.8	C
Sulfur Dioxide	74,096		74,096	C
Sulfur Oxides	984		984	C
Carbon Monoxide	2,896		2,896	C
Fossil CO2	3,568,987		3,568,987	C
Non-Fossil CO2	60,620		60,620	D
Aldehydes (Formaldehyde)	2.36		2.36	C
Aldehydes (Acetaldehyde)	0.29		0.29	D
Aldehydes (Propionaldehyde)	0.0044		0.0044	D
Aldehydes (unspecified)	5.87		5.87	D
Organics (unspecified)	5.47		5.47	D
Ammonia	46.3		46.3	D
Ammonia Chloride	155		155	D
Methane	9,087		9,087	C
Kerosene	278		278	D
Chlorine	0.25		0.25	D
HCl	677		677	C
HF	83.5		83.5	C
Metals (unspecified)	13.3		13.3	D
Mercaptan	2.52		2.52	D
Antimony	0.013		0.013	C
Arsenic	0.25		0.25	C
Beryllium	0.014		0.014	C
Cadmium	0.041		0.041	C
Chromium (VI)	0.044		0.044	D
Chromium (unspecified)	0.17		0.17	C
Cobalt	0.087		0.087	C
Copper	0.0031		0.0031	D
Lead	0.30		0.30	C
Magnesium	6.16		6.16	C
Manganese	0.79		0.79	C
Mercury	0.066		0.066	C
Nickel	0.59		0.59	C
Selenium	0.74		0.74	C
Zinc	0.0020		0.0020	D
Acetophenone	1.7E-04		1.7E-04	D
Acrolein	1.41		1.41	D
Nitrous Oxide	88.4		88.4	C
Benzene	34.1		34.1	D
Benzyl Chloride	0.0081		0.0081	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.5E-04		8.5E-04	D
1,3 Butadiene	8.5E-04		8.5E-04	D
2-Chloroacetophenone	8.1E-05		8.1E-05	D
Chlorobenzene	2.6E-04		2.6E-04	D
2,4-Dinitrotoluene	3.3E-06		3.3E-06	D
Ethyl Chloride	4.9E-04		4.9E-04	D
Ethylbenzene	3.70		3.70	D
Ethylene Dibromide	1.4E-05		1.4E-05	D
Ethylene Dichloride	4.7E-04		4.7E-04	D
Hexane	7.8E-04		7.8E-04	D
Isophorone ($C_9H_{14}O$)	0.0068		0.0068	D
Methyl Bromide	0.0019		0.0019	D
Methyl Chloride	0.0062		0.0062	D
Methyl Ethyl Ketone	0.0045		0.0045	D
Methyl Hydrazine	0.0020		0.0020	D
Methyl Methacrylate	2.3E-04		2.3E-04	D
Methyl Tert Butyl Ether (MTBE)	4.1E-04		4.1E-04	D
Naphthalene	0.040		0.040	D
Propylene	0.056		0.056	D

Table A-26 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE CONSUMPTION OF FUEL-GRADE URANIUM
(pounds of pollutants per 1,000 pounds of uranium)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.9E-04		2.9E-04	D
Toluene	47.8		47.8	D
Trichloroethane	2.4E-04		2.4E-04	D
Vinyl Acetate	8.8E-05		8.8E-05	D
Xylenes	27.9		27.9	D
Bromoform	4.5E-04		4.5E-04	D
Chloroform	6.9E-04		6.9E-04	D
Carbon Disulfide	0.0015		0.0015	D
Dimethyl Sulfate	5.6E-04		5.6E-04	D
Cumene	6.2E-05		6.2E-05	D
Cyanide	0.029		0.029	D
Perchloroethylene	0.025		0.025	D
Methylene Chloride	0.30		0.30	D
Carbon Tetrachloride	0.014		0.014	D
Phenols	0.055		0.055	D
Fluorides	13.5		13.5	D
Polyaromatic Hydrocarbons (total)	0.015		0.015	E
Biphenyl	9.5E-04		9.5E-04	E
Acenaphthene	2.9E-04		2.9E-04	E
Acenaphthylene	1.4E-04		1.4E-04	E
Anthracene	1.2E-04		1.2E-04	E
Benzo(a)anthracene	4.5E-05		4.5E-05	E
Benzo(a)pyrene	2.1E-05		2.1E-05	E
Benzo(b,j,k)fluroanthene	6.2E-05		6.2E-05	E
Benzo(g,h,i) perylene	1.5E-05		1.5E-05	E
Chrysene	5.6E-05		5.6E-05	E
Fluoranthene	4.0E-04		4.0E-04	E
Fluorene	5.1E-04		5.1E-04	E
Indeno(1,2,3-cd)pyrene	3.4E-05		3.4E-05	E
Naphthalene	0.0073		0.0073	E
Phenanthrene	0.0015		0.0015	E
Pyrene	1.8E-04		1.8E-04	E
5-methyl Chrysene	1.2E-05		1.2E-05	E
Dioxins (unspecified)	5.2E-04		5.2E-04	D
Furans (unspecified)	2.5E-06		2.5E-06	D
CFC12	8.8E-06		8.8E-06	D
Radionuclides (unspecified)	15,520		15,520	C
Waterborne Emissions				
Acid (unspecified)	1.74		1.74	E
Acid (benzoic)	1.72		1.72	E
Acid (hexanoic)	0.36		0.36	E
Metal (unspecified)	22,002		22,002	E
Dissolved Solids	75,717		75,717	E
Suspended Solids	9,455		9,455	E
BOD	854		854	E
COD	426		426	E
Phenol/Phenolic Compounds	0.78		0.78	E
Sulfur	4.50		4.50	E
Sulfates	201,256		201,256	E
Sulfides	0.014		0.014	E
Oil	33.9		33.9	E
Hydrocarbons	0.34		0.34	E
Ammonia	26.4		26.4	E
Ammonium	124		124	E
Aluminum	1,266		1,266	E
Antimony	0.032		0.032	E
Arsenic	3.84		3.84	E
Barium	749		749	E
Beryllium	0.019		0.019	E
Cadmium	1.96		1.96	E
Chromium (unspecified)	1.44		1.44	E
Cobalt	0.038		0.038	E
Copper	30.7		30.7	E

Table A-26 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR THE CONSUMPTION OF FUEL-GRADE URANIUM
(pounds of pollutants per 1,000 pounds of uranium)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5,845		5,845	E
Lead	4.87		4.87	E
Lithium	1,522		1,522	E
Magnesium	1,068		1,068	E
Manganese	566		566	E
Mercury	0.043		0.043	E
Molybdenum	0.039		0.039	E
Nickel	0.33		0.33	E
Selenium	43.4		43.4	E
Silver	3.56		3.56	E
Sodium	17,670		17,670	E
Strontium	92.6		92.6	E
Thallium	0.0067		0.0067	E
Tin	0.22		0.22	E
Titanium	0.49		0.49	E
Vanadium	0.046		0.046	E
Yttrium	0.011		0.011	E
Zinc	61.7		61.7	E
Chlorides (unspecified)	61,678		61,678	E
Chlorides (methyl chloride)	6.8E-05		6.8E-05	E
Calcium	5,538		5,538	E
Fluorine/ Fluorides	2,007		2,007	E
Nitrates	308		308	E
Nitrogen (ammonia)	108		108	E
Bromide	364		364	E
Boron	5.33		5.33	E
Organic Carbon	7.17		7.17	E
Cyanide	1.2E-04		1.2E-04	E
Hardness	16,819		16,819	E
Total Alkalinity	136		136	E
Surfactants	1.65		1.65	E
Acetone	0.017		0.017	E
Alkylated Benzenes	0.028		0.028	E
Alkylated Fluorenes	0.0016		0.0016	E
Alkylated Naphthalenes	4.6E-04		4.6E-04	E
Alkylated Phenanthrenes	1.9E-04		1.9E-04	E
Benzene	2.85		2.85	E
Cresols	0.10		0.10	E
Cymene	1.7E-04		1.7E-04	E
Dibenzofuran	3.2E-04		3.2E-04	E
Dibenzothiophene	2.6E-04		2.6E-04	E
2,4 dimethylphenol	0.048		0.048	E
Ethylbenzene	0.16		0.16	E
2-Hexanone	0.011		0.011	E
Methyl ethyl Ketone (MEK)	1.4E-04		1.4E-04	E
1-methylfluorene	1.9E-04		1.9E-04	E
2-methyl naphthalene	0.027		0.027	E
4-methyl- 2-pentanone	0.0071		0.0071	E
Naphthalene	0.031		0.031	E
Pentamethyl benzene	1.3E-04		1.3E-04	E
Phenanthrene	2.6E-04		2.6E-04	E
Toluene	2.69		2.69	E
Total Biphenyls	0.0018		0.0018	E
Total dibenzo- thiophenes	5.6E-06		5.6E-06	E
Xylenes	1.43		1.43	E
Radionuclides (unspecified)	0.22		0.22	E
Solid Waste	5,264,237		5,264,237	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-60, A-92, A-93, and A-94.

Source: Franklin Associates, A Division of ERG

Wood Wastes

The combustion of wood in boilers is mostly confined to industries where it is available as a byproduct. It is burned to obtain both heat energy and to alleviate possible solid waste disposal problems. In boilers, wood is normally burned in the form of hogged wood, sawdust, shavings, chips, sander dust, or wood trim. Heating values for wood waste range from 4,000 to 5,000 Btu per pound of fuel on a wet, as-fired basis. The moisture content of as-fired wood is typically near 50 percent, but may vary from 5 to 75 weight percent.

Bark is the major type of waste burned in pulp mills; either a mixture of wood and bark waste or wood waste alone is burned most frequently in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1,600 wood-fired boilers operating in the U.S., with a total capacity of over 30 GW (1.0 x 1011 Btu per hour).

The emission factors for this appendix are based on wet, as-fired wood waste with average properties of 50 percent (by weight) moisture and 4,500 Btu per pound higher heating value (Reference A-99).

Solid waste from the combustion of wood are proportional to the ash content of the wood. This typically varies between 0.5 and 2.2 percent by weight of dry wood. Some is released as flyash, and some remains as bottom ash. If there are controls for particulate matter, some of the flyash is collected before leaving the emissions stack.

The solid residues from the combustion process are boiler ash, clinker and slag, fly ash, and carbon char. The major components of these wastes are silica, alumina, and calcium oxides. Minor constituents include sodium, magnesium, potassium, and trace amounts of heavy metals (Reference A-98). Another source of solid wastes is impurities in wood bark (sand and dirt), which are picked up during transportation as rough logs are dragged to central loading points.

Table A-27

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF WOOD IN INDUSTRIAL BOILERS

(pounds of pollutant per 1,000 lb of wood—as fired)

	Combustion (lb/1000 lb)	Combustion (lb/MM Btu) (1)	DQI
Atmospheric Emissions			
Particulates (PM10)	2.25	0.50	C
Nitrogen Oxides	0.99	0.22	C
TNMOC (unspecified)	0.018	0.0041	C
Sulfur Oxides	0.11	0.025	C
Carbon Monoxide	2.70	0.60	C
Non-Fossil CO2	878	195	C
Aldehydes (Formaldehyde)	0.020	0.0044	E
Aldehydes (Acetaldehyde)	0.0037	8.3E-04	E
Methane	0.095	0.021	C
Chlorine	0.0036	7.9E-04	E
HCl	0.086	0.019	E
Metals (unspecified)	0.19	0.043	E
Antimony	3.6E-05	7.9E-06	E
Arsenic	9.9E-05	2.2E-05	E
Beryllium	5.0E-06	1.1E-06	E
Cadmium	1.8E-05	4.1E-06	E
Chromium (unspecified)	9.5E-05	2.1E-05	E
Cobalt	2.9E-05	6.5E-06	E
Lead	2.2E-04	4.8E-05	E
Manganese	0.0072	0.0016	E
Mercury	1.6E-05	3.5E-06	E
Nickel	1.5E-04	3.3E-05	E
Selenium	1.3E-05	2.8E-06	E
acrolein	0.018	0.0040	E
Nitrous Oxide	0.059	0.013	C
Benzene	0.019	0.0042	E
Naphthalene	4.4E-04	9.7E-05	E
Methylene Chloride	0.0013	2.9E-04	E
Carbon Tetrachloride	2.0E-04	4.5E-05	E
Phenols	2.3E-04	5.1E-05	E
dioxins (unspecified)	7.5E-06	1.7E-06	E
Waterborne Emissions			
BOD	8.75	1.94	E
Solid Waste	44.1	9.80	C

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(1) Wood "as fired" has a higher heating value of about 4,500 Btu/lb.

References: A-57, A-98, A-99, A-118, and A-119.

Source: Franklin Associates, A Division of ERG

Mobile Sources

Transportation sources such as barges, locomotives, and diesel- and gasoline-powered trucks constitute a major source of air pollution. Some of the emissions, such as carbon monoxide and hydrocarbons, are due to incomplete combustion. Other emissions, such as nitrogen oxides, are normal byproducts of combustion. Lead emissions are directly related to the addition of tetraethyl lead to the fuel as an antiknock compound. Lead emissions have been decreasing significantly due to EPA regulations requiring a phase-out of lead in fuels. The major gaseous pollutants from mobile sources are carbon monoxide, nitrogen oxides, and hydrocarbons.

Trucks. Trucks are classified into two categories. Combination trucks (or tractor-trailer trucks) are those most commonly used for transporting large quantities of material. Single-unit trucks are generally used for local delivery. Several assumptions and calculations were made based on these classifications:

1. Single-unit delivery trucks have a gross weight of 8,500 to 14,000 pounds. Combination trucks include all trucks greater than 14,000 pounds in gross weight.

2. The average fuel economy for combination trucks is 5.3 miles per gallon. The average fuel economy for single-unit trucks is 7.4 miles per gallon (Reference A-100).

3. The majority (82 percent) of combination trucks use diesel, while a smaller percentage (18 percent) use gasoline (Reference A-101). Due to highly-aggregated statistics, an accurate split between diesel and gasoline use could not be determined for single-unit trucks. It was thus assumed that 50 percent of single unit trucks use diesel and 50 percent use gasoline.

4. Accounting for empty backhauling and trucks that are not fully loaded increases fuel usage by approximately 25 percent (Reference A-90).

Air emissions for gasoline- and diesel-powered trucks were taken from the GREET transportation model (Reference A-86). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference 12). The GREET transportation model includes data for most modes of transportation, but does not have emissions data for combination or single-unit trucks that use gasoline. Data for these transportation modes was estimated from data on gasoline consumption and vehicle characteristics given in the Transportation Energy Databook (References A-89).

Locomotives. Freight locomotives use diesel fuel exclusively (Reference A-85). According to 2001 data, freight locomotives consume 2.48 gallons of diesel per ton-mile. This fuel requirement factor was calculated from the annual quantity of fuel consumed by freight locomotives and the annual ton-miles traveled by freight locomotives (Reference A-102).

Air emissions from diesel combustion in trucks were taken from the GREET transportation model (Reference A-85). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

Barges. Commercial water transport can be categorized by boundary of travel, type of fuel consumed, and type of power source. The following details were used to develop an environmental profile for residual oil-powered barges:

1. Barges are typically vessels traveling in the Great Lakes, rivers, or along a coast. Ocean freighters encompass longer travel not within the range or capability of a barge.

2. Two types of engine technologies can be used as a power source for water vessels: diesel fuel engines and steam turbines using residual oil.

3. 22 percent of barges use diesel fuel in their engines, and 78 percent use residual oil to generate steam for steam turbines (Reference A-89).

4. The fuel requirements for a barge that consumes only residual oil are 3.4 gallons per 1,000 ton-miles (Reference A-89).

5. Power usage of the engines is 50 percent of full capacity. This adjusts for emissions occurring at dockside while the engine is idling.

Air emissions from residual fuel oil combustion in barges were taken from the GREET transportation model (Reference A-85). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

Ocean Freighters. Commercial water transport can be categorized by boundary of travel, type of fuel consumed, and type of power source. The following details were used to develop an environmental profile for diesel-powered ocean freighters:

1. Barges are typically vessels traveling in the Great Lakes, rivers, or along a coast. Ocean freighters are used for long distances not within the range or capability of a barge.

2. Two types of engine technologies can be used as a power source for water vessels: diesel fuel engines and steam turbines using residual oil.

3. 10 percent of ocean freighters use diesel fuel, and 90 percent use residual fuel. (Reference A-104).

4. The fuel requirements for an ocean freighter are 1.9 gallons of fuel per 1,000 ton-miles (Reference A-104). This value is assumed to be the same for diesel and residual oil.

5. Power usage of the engines is 50 percent of full capacity. This adjusts for emissions occurring at dockside while the engine is idling.

Air emissions from diesel combustion in ocean freighters were taken from the GREET transportation model (Reference A-85). Most of the air emission data in the GREET model are derived from EPA sources, including the AP-42 emission factor documentation (Reference A-50).

Cargo Plane. The emissions from jet fuel combustion depend on the composition of the fuel, the type of engine, and the operating conditions of the engine. Jet fuel is similar to the kerosene, so this appendix assumes that jet fuel has the same composition as kerosene.

The types of jet engines currently in operation in commercial widebody jets were determined from data published by the Aviation Industry Press (Reference A-108). These data were used to develop a profile of the manufacturers and engine types that dominate the commercial widebody aircraft market. The conditions of airplane operation include takeoff and landing (TOL), cruising, and idle phases. Measured emissions for these conditions are available in the ICAO Engine Exhaust Data Bank (Reference A-107). The above data and assumptions were used to calculate the primary emissions (hydrocarbons, carbon monoxide, and nitrogen oxides) resulting from the combustion of jet fuel in widebody cargo planes.

Aviation emissions also include small amounts of sulfur oxides. No data are available for sulfur oxide emissions from jet engines. Since jet fuel contains less than 0.5 percent sulfur (Reference A-109), this module assumes that sulfur oxide emissions from aircraft are negligible. Aviation emissions also include particulates and trace amounts of metals. No data are available for particulate or metal emissions from jet engines.

Table A-28a

ENVIRONMENTAL EMISSIONS FOR TRACTOR-TRAILER GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.12		2.12	C
Particulates (PM10)	0.55	0.45	1.00	B
Nitrogen Oxides	21.3	104	125	B
Hydrocarbons (unspecified)	13.3		13.3	C
VOC (unspecified)	0.85	16.9	17.8	D
TNMOC (unspecified)	0.018		0.018	C
Sulfur Dioxide	11.9		11.9	C
Sulfur Oxides	18.3	4.52	22.8	B
Carbon Monoxide	90.0	376	467	B
Fossil CO2	2,776	18,952	21,729	B
Non-Fossil CO2	19.5		19.5	D
Aldehydes (Formaldehyde)	0.0019		0.0019	C
Aldehydes (Acetaldehyde)	1.5E-04		1.5E-04	D
Aldehydes (Propionaldehyde)	3.3E-08		3.3E-08	D
Aldehydes (unspecified)	0.28		0.28	C
Organics (unspecified)	0.0010		0.0010	D
Ammonia	0.14		0.14	D
Ammonia Chloride	1.4E-04		1.4E-04	D
Methane	29.8	2.73	32.5	B
Kerosene	2.4E-04		2.4E-04	D
Chlorine	7.9E-05		7.9E-05	D
HCl	0.22		0.22	C
HF	0.025		0.025	C
Metals (unspecified)	0.0043		0.0043	D
Mercaptan	1.8E-05		1.8E-05	D
Antimony	3.7E-06		3.7E-06	C
Arsenic	1.0E-04		1.0E-04	C
Beryllium	4.9E-06		4.9E-06	C
Cadmium	2.6E-05		2.6E-05	C
Chromium (VI)	1.3E-05		1.3E-05	C
Chromium (unspecified)	7.4E-05		7.4E-05	D
Cobalt	1.6E-04		1.6E-04	C
Copper	1.2E-06		1.2E-06	D
Lead	1.1E-04		1.1E-04	C
Magnesium	0.0018		0.0018	C
Manganese	3.1E-04		3.1E-04	C
Mercury	1.9E-05		1.9E-05	C
Nickel	0.0021		0.0021	C
Selenium	2.3E-04		2.3E-04	C
Zinc	7.9E-07		7.9E-07	D
Acetophenone	1.3E-09		1.3E-09	D
Acrolein	4.5E-04		4.5E-04	D
Nitrous Oxide	0.051	0.55	0.60	B
Benzene	0.029		0.029	D
Benzyl Chloride	6.1E-08		6.1E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	6.4E-09		6.4E-09	D
1,3 Butadiene	3.1E-06		3.1E-06	D
2-Chloroacetophenone	6.1E-10		6.1E-10	D
Chlorobenzene	1.9E-09		1.9E-09	D
2,4-Dinitrotoluene	2.4E-11		2.4E-11	D
Ethyl Chloride	3.7E-09		3.7E-09	D
Ethylbenzene	0.0034		0.0034	D
Ethylene Dibromide	1.0E-10		1.0E-10	D
Ethylene Dichloride	3.5E-09		3.5E-09	D
Hexane	5.9E-09		5.9E-09	D
Isophorone ($C_9H_{14}O$)	5.1E-08		5.1E-08	D
Methyl Bromide	1.4E-08		1.4E-08	D
Methyl Chloride	4.6E-08		4.6E-08	D
Methyl Ethyl Ketone	3.4E-08		3.4E-08	D
Methyl Hydrazine	1.5E-08		1.5E-08	D
Methyl Methacrylate	1.7E-09		1.7E-09	D
Methyl Tert Butyl Ether (MTBE)	3.1E-09		3.1E-09	D
Naphthalene	4.0E-05		4.0E-05	D
Propylene	2.1E-04		2.1E-04	D

Table A-28a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR TRACTOR-TRAILER GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.2E-09		2.2E-09	D
Toluene	0.043		0.043	D
Trichloroethane	6.4E-07		6.4E-07	D
Vinyl Acetate	6.6E-10		6.6E-10	D
Xylenes	0.025		0.025	D
Bromoform	3.4E-09		3.4E-09	D
Chloroform	5.2E-09		5.2E-09	D
Carbon Disulfide	1.1E-08		1.1E-08	D
Dimethyl Sulfate	4.2E-09		4.2E-09	D
Cumene	4.6E-10		4.6E-10	D
Cyanide	2.2E-07		2.2E-07	D
Perchloroethylene	8.8E-06		8.8E-06	D
Methylene Chloride	2.0E-04		2.0E-04	D
Carbon Tetrachloride	4.6E-06		4.6E-06	D
Phenols	9.8E-05		9.8E-05	D
Fluorides	1.5E-05		1.5E-05	D
Polyaromatic Hydrocarbons (total)	1.7E-05		1.7E-05	E
Biphenyl	2.8E-07		2.8E-07	E
Acenaphthene	8.3E-08		8.3E-08	E
Acenaphthylene	4.1E-08		4.1E-08	E
Anthracene	3.4E-08		3.4E-08	E
Benzo(a)anthracene	1.3E-08		1.3E-08	E
Benzo(a)pyrene	6.2E-09		6.2E-09	E
Benzo(b,j,k)fluroanthene	1.8E-08		1.8E-08	E
Benzo(g,h,i) perylene	4.4E-09		4.4E-09	E
Chrysene	1.6E-08		1.6E-08	E
Fluoranthene	1.2E-07		1.2E-07	E
Fluorene	1.5E-07		1.5E-07	E
Indeno(1,2,3-cd)pyrene	1.0E-08		1.0E-08	E
Naphthalene	2.1E-06		2.1E-06	E
Phenanthrene	4.4E-07		4.4E-07	E
Pyrene	5.4E-08		5.4E-08	E
5-methyl Chrysene	3.6E-09		3.6E-09	E
Dioxins (unspecified)	1.7E-07		1.7E-07	D
Furans (unspecified)	7.4E-10		7.4E-10	D
CFC12	7.5E-07		7.5E-07	D
Radionuclides (unspecified)	0.014		0.014	C
Waterborne Emissions				
Acid (unspecified)	0.0016		0.0016	E
Acid (benzoic)	0.026		0.026	E
Acid (hexanoic)	0.0053		0.0053	E
Metal (unspecified)	20.0		20.0	E
Dissolved Solids	1,129		1,129	E
Suspended Solids	67.1		67.1	E
BOD	0.64		0.64	E
COD	1.89		1.89	E
Phenol/Phenolic Compounds	0.013		0.013	E
Sulfur	0.067		0.067	E
Sulfates	2.02		2.02	E
Sulfides	0.0012		0.0012	E
Oil	0.58		0.58	E
Hydrocarbons	0.0051		0.0051	E
Ammonia	0.46		0.46	E
Ammonium	1.1E-04		1.1E-04	E
Aluminum	2.18		2.18	E
Antimony	0.0014		0.0014	E
Arsenic	0.0069		0.0069	E
Barium	29.9		29.9	E
Beryllium	3.9E-04		3.9E-04	E
Cadmium	0.0010		0.0010	E
Chromium (unspecified)	0.062		0.062	E
Cobalt	5.6E-04		5.6E-04	E
Copper	0.0071		0.0071	E

Table A-28a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR TRACTOR-TRAILER GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	4.35		4.35	E
Lead	0.015		0.015	E
Lithium	1.41		1.41	E
Magnesium	15.9		15.9	E
Manganese	0.028		0.028	E
Mercury	2.4E-05		2.4E-05	E
Molybdenum	5.8E-04		5.8E-04	E
Nickel	0.0068		0.0068	E
Selenium	3.0E-04		3.0E-04	E
Silver	0.053		0.053	E
Sodium	258		258	E
Strontium	1.38		1.38	E
Thallium	2.9E-04		2.9E-04	E
Tin	0.0055		0.0055	E
Titanium	0.021		0.021	E
Vanadium	6.9E-04		6.9E-04	E
Yttrium	1.7E-04		1.7E-04	E
Zinc	0.050		0.050	E
Chlorides (unspecified)	915		915	E
Chlorides (methyl chloride)	1.0E-06		1.0E-06	E
Calcium	81.4		81.4	E
Fluorine/ Fluorides	0.0018		0.0018	E
Nitrates	2.7E-04		2.7E-04	E
Nitrogen (ammonia)	9.5E-05		9.5E-05	E
Bromide	5.43		5.43	E
Boron	0.080		0.080	E
Organic Carbon	0.0065		0.0065	E
Cyanide	1.8E-06		1.8E-06	E
Hardness	251		251	E
Total Alkalinity	2.00		2.00	E
Surfactants	0.021		0.021	E
Acetone	2.5E-04		2.5E-04	E
Alkylated Benzenes	0.0012		0.0012	E
Alkylated Fluorenes	6.9E-05		6.9E-05	E
Alkylated Naphthalenes	2.0E-05		2.0E-05	E
Alkylated Phenanthrenes	8.1E-06		8.1E-06	E
Benzene	0.043		0.043	E
Cresols	0.0015		0.0015	E
Cymene	2.5E-06		2.5E-06	E
Dibenzofuran	4.8E-06		4.8E-06	E
Dibenzothiophene	3.9E-06		3.9E-06	E
2,4-dimethylphenol	7.1E-04		7.1E-04	E
Ethylbenzene	0.0024		0.0024	E
2-Hexanone	1.7E-04		1.7E-04	E
Methyl ethyl Ketone (MEK)	2.0E-06		2.0E-06	E
1-methylfluorene	2.9E-06		2.9E-06	E
2-methyl naphthalene	4.0E-04		4.0E-04	E
4-methyl-2-pentanone	1.1E-04		1.1E-04	E
Naphthalene	4.6E-04		4.6E-04	E
Pentamethyl benzene	1.9E-06		1.9E-06	E
Phenanthrene	7.0E-06		7.0E-06	E
Toluene	0.040		0.040	E
Total Biphenyls	7.7E-05		7.7E-05	E
Total dibenzo-thiophenes	2.4E-07		2.4E-07	E
Xylenes	0.021		0.021	E
Radionuclides (unspecified)	1.9E-07		1.9E-07	E
Solid Waste	330		330	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-28b

ENVIRONMENTAL EMISSIONS FOR TRACTOR-TRAILER DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.49		2.49	C
Particulates (PM10)	0.64	29.8	30.4	B
Nitrogen Oxides	25.0	163	188	B
Hydrocarbons (unspecified)	15.6		15.6	D
VOC (unspecified)	0.99	8.06	9.05	C
TNMOC (unspecified)	0.021		0.021	C
Sulfur Dioxide	14.0		14.0	C
Sulfur Oxides	21.5	5.39	26.9	B
Carbon Monoxide	106	38.9	145	B
Fossil CO2	3,258	24,485	27,743	B
Non-Fossil CO2	22.8		22.8	D
Aldehydes (Formaldehyde)	0.0022		0.0022	C
Aldehydes (Acetaldehyde)	1.7E-04		1.7E-04	D
Aldehydes (Propionaldehyde)	3.9E-08		3.9E-08	D
Aldehydes (unspecified)	0.32		0.32	C
Organics (unspecified)	0.0012		0.0012	D
Ammonia	0.16		0.16	D
Ammonia Chloride	1.6E-04		1.6E-04	D
Methane	34.9	0.39	35.3	B
Kerosene	2.9E-04		2.9E-04	D
Chlorine	9.3E-05		9.3E-05	D
HCl	0.25		0.25	C
HF	0.029		0.029	C
Metals (unspecified)	0.0050		0.0050	D
Mercaptan	2.1E-05		2.1E-05	D
Antimony	4.4E-06		4.4E-06	C
Arsenic	1.2E-04		1.2E-04	C
Beryllium	5.7E-06		5.7E-06	C
Cadmium	3.0E-05		3.0E-05	C
Chromium (VI)	1.5E-05		1.5E-05	C
Chromium (unspecified)	8.7E-05		8.7E-05	D
Cobalt	1.9E-04		1.9E-04	C
Copper	1.4E-06		1.4E-06	D
Lead	1.3E-04		1.3E-04	C
Magnesium	0.0021		0.0021	C
Manganese	3.7E-04		3.7E-04	C
Mercury	2.2E-05		2.2E-05	C
Nickel	0.0024		0.0024	C
Selenium	2.7E-04		2.7E-04	C
Zinc	9.3E-07		9.3E-07	D
Acetophenone	1.5E-09		1.5E-09	D
Acrolein	5.3E-04		5.3E-04	D
Nitrous Oxide	0.060	0.61	0.67	B
Benzene	0.034		0.034	D
Benzyl Chloride	7.2E-08		7.2E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09		7.5E-09	D
1,3 Butadiene	3.7E-06		3.7E-06	D
2-Chloroacetophenone	7.2E-10		7.2E-10	D
Chlorobenzene	2.3E-09		2.3E-09	D
2,4-Dinitrotoluene	2.9E-11		2.9E-11	D
Ethyl Chloride	4.3E-09		4.3E-09	D
Ethylbenzene	0.0039		0.0039	D
Ethylene Dibromide	1.2E-10		1.2E-10	D
Ethylene Dichloride	4.1E-09		4.1E-09	D
Hexane	6.9E-09		6.9E-09	D
Isophorone ($C_9H_{14}O$)	5.9E-08		5.9E-08	D
Methyl Bromide	1.6E-08		1.6E-08	D
Methyl Chloride	5.4E-08		5.4E-08	D
Methyl Ethyl Ketone	4.0E-08		4.0E-08	D
Methyl Hydrazine	1.7E-08		1.7E-08	D
Methyl Methacrylate	2.1E-09		2.1E-09	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09		3.6E-09	D
Naphthalene	4.7E-05		4.7E-05	D
Propylene	2.4E-04		2.4E-04	D

Table A-28b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR TRACTOR-TRAILER DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.6E-09		2.6E-09	D
Toluene	0.051		0.051	D
Trichloroethane	7.5E-07		7.5E-07	D
Vinyl Acetate	7.8E-10		7.8E-10	D
Xylenes	0.030		0.030	D
Bromoform	4.0E-09		4.0E-09	D
Chloroform	6.1E-09		6.1E-09	D
Carbon Disulfide	1.3E-08		1.3E-08	D
Dimethyl Sulfate	4.9E-09		4.9E-09	D
Cumene	5.4E-10		5.4E-10	D
Cyanide	2.6E-07		2.6E-07	D
Perchloroethylene	1.0E-05		1.0E-05	D
Methylene Chloride	2.3E-04		2.3E-04	D
Carbon Tetrachloride	5.4E-06		5.4E-06	D
Phenols	1.2E-04		1.2E-04	D
Fluorides	1.8E-05		1.8E-05	D
Polyaromatic Hydrocarbons (total)	2.0E-05		2.0E-05	E
Biphenyl	3.3E-07		3.3E-07	E
Acenaphthene	9.8E-08		9.8E-08	E
Acenaphthylene	4.8E-08		4.8E-08	E
Anthracene	4.0E-08		4.0E-08	E
Benzo(a)anthracene	1.5E-08		1.5E-08	E
Benzo(a)pyrene	7.3E-09		7.3E-09	E
Benzo(b,j,k)fluroanthene	2.1E-08		2.1E-08	E
Benzo(g,h,i) perylene	5.2E-09		5.2E-09	E
Chrysene	1.9E-08		1.9E-08	E
Fluoranthene	1.4E-07		1.4E-07	E
Fluorene	1.7E-07		1.7E-07	E
Indeno(1,2,3-cd)pyrene	1.2E-08		1.2E-08	E
Naphthalene	2.5E-06		2.5E-06	E
Phenanthrene	5.2E-07		5.2E-07	E
Pyrene	6.3E-08		6.3E-08	E
5-methyl Chrysene	4.2E-09		4.2E-09	E
Dioxins (unspecified)	2.0E-07		2.0E-07	D
Furans (unspecified)	8.7E-10		8.7E-10	D
CFC12	8.9E-07		8.9E-07	D
Radionuclides (unspecified)	0.016		0.016	C
Waterborne Emissions				
Acid (unspecified)	0.0018		0.0018	E
Acid (benzoic)	0.030		0.030	E
Acid (hexanoic)	0.0062		0.0062	E
Metal (unspecified)	23.4		23.4	E
Dissolved Solids	1,325		1,325	E
Suspended Solids	78.8		78.8	E
BOD	0.75		0.75	E
COD	2.22		2.22	E
Phenol/Phenolic Compounds	0.015		0.015	E
Sulfur	0.079		0.079	E
Sulfates	2.37		2.37	E
Sulfides	0.0014		0.0014	E
Oil	0.68		0.68	E
Hydrocarbons	0.0059		0.0059	E
Ammonia	0.54		0.54	E
Ammonium	1.3E-04		1.3E-04	E
Aluminum	2.56		2.56	E
Antimony	0.0016		0.0016	E
Arsenic	0.0081		0.0081	E
Barium	35.1		35.1	E
Beryllium	4.5E-04		4.5E-04	E
Cadmium	0.0012		0.0012	E
Chromium (unspecified)	0.073		0.073	E
Cobalt	6.6E-04		6.6E-04	E
Copper	0.0084		0.0084	E

Table A-28b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR TRACTOR-TRAILER DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5.11		5.11	E
Lead	0.017		0.017	E
Lithium	1.65		1.65	E
Magnesium	18.7		18.7	E
Manganese	0.032		0.032	E
Mercury	2.8E-05		2.8E-05	E
Molybdenum	6.8E-04		6.8E-04	E
Nickel	0.0080		0.0080	E
Selenium	3.5E-04		3.5E-04	E
Silver	0.062		0.062	E
Sodium	303		303	E
Strontium	1.62		1.62	E
Thallium	3.4E-04		3.4E-04	E
Tin	0.0065		0.0065	E
Titanium	0.025		0.025	E
Vanadium	8.1E-04		8.1E-04	E
Yttrium	2.0E-04		2.0E-04	E
Zinc	0.059		0.059	E
Chlorides (unspecified)	1,074		1,074	E
Chlorides (methyl chloride)	1.2E-06		1.2E-06	E
Calcium	95.5		95.5	E
Fluorine/ Fluorides	0.0021		0.0021	E
Nitrates	3.2E-04		3.2E-04	E
Nitrogen (ammonia)	1.1E-04		1.1E-04	E
Bromide	6.37		6.37	E
Boron	0.093		0.093	E
Organic Carbon	0.0076		0.0076	E
Cyanide	2.1E-06		2.1E-06	E
Hardness	294		294	E
Total Alkalinity	2.34		2.34	E
Surfactants	0.025		0.025	E
Acetone	3.0E-04		3.0E-04	E
Alkylated Benzenes	0.0014		0.0014	E
Alkylated Fluorenes	8.1E-05		8.1E-05	E
Alkylated Naphthalenes	2.3E-05		2.3E-05	E
Alkylated Phenanthrenes	9.5E-06		9.5E-06	E
Benzene	0.050		0.050	E
Cresols	0.0018		0.0018	E
Cymene	3.0E-06		3.0E-06	E
Dibenzofuran	5.7E-06		5.7E-06	E
Dibenzothiophene	4.6E-06		4.6E-06	E
2,4-dimethylphenol	8.3E-04		8.3E-04	E
Ethylbenzene	0.0028		0.0028	E
2-Hexanone	1.9E-04		1.9E-04	E
Methyl ethyl Ketone (MEK)	2.4E-06		2.4E-06	E
1-methylfluorene	3.4E-06		3.4E-06	E
2-methyl naphthalene	4.7E-04		4.7E-04	E
4-methyl-2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.4E-04		5.4E-04	E
Pentamethyl benzene	2.2E-06		2.2E-06	E
Phenanthrene	8.2E-06		8.2E-06	E
Toluene	0.047		0.047	E
Total Biphenyls	9.1E-05		9.1E-05	E
Total dibenzo-thiophenes	2.8E-07		2.8E-07	E
Xylenes	0.025		0.025	E
Radionuclides (unspecified)	2.3E-07		2.3E-07	E
Solid Waste	387		387	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-29a

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT GASOLINE POWERED TRUCKS

(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.12		2.12	C
Particulates (PM10)	0.55	0.54	1.09	B
Nitrogen Oxides	21.3	111	132	B
Hydrocarbons (unspecified)	13.3		13.3	D
VOC (unspecified)	0.85	25.3	26.2	C
TNMOC (unspecified)	0.018		0.018	C
Sulfur Dioxide	11.9		11.9	C
Sulfur Oxides	18.3	4.52	22.8	B
Carbon Monoxide	90.0	340	430	B
Fossil CO2	2,776	18,947	21,723	B
Non-Fossil CO2	19.5		19.5	D
Aldehydes (Formaldehyde)	0.0019		0.0019	C
Aldehydes (Acetaldehyde)	1.5E-04		1.5E-04	D
Aldehydes (Propionaldehyde)	3.3E-08		3.3E-08	D
Aldehydes (unspecified)	0.28		0.28	C
Organics (unspecified)	0.0010		0.0010	D
Ammonia	0.14		0.14	D
Ammonia Chloride	1.4E-04		1.4E-04	D
Methane	29.8	4.08	33.9	B
Kerosene	2.4E-04		2.4E-04	D
Chlorine	7.9E-05		7.9E-05	D
HCl	0.22		0.22	C
HF	0.025		0.025	C
Metals (unspecified)	0.0043		0.0043	D
Mercaptan	1.8E-05		1.8E-05	D
Antimony	3.7E-06		3.7E-06	C
Arsenic	1.0E-04		1.0E-04	C
Beryllium	4.9E-06		4.9E-06	C
Cadmium	2.6E-05		2.6E-05	C
Chromium (VI)	1.3E-05		1.3E-05	C
Chromium (unspecified)	7.4E-05		7.4E-05	D
Cobalt	1.6E-04		1.6E-04	C
Copper	1.2E-06		1.2E-06	D
Lead	1.1E-04		1.1E-04	C
Magnesium	0.0018		0.0018	C
Manganese	3.1E-04		3.1E-04	C
Mercury	1.9E-05		1.9E-05	C
Nickel	0.0021		0.0021	C
Selenium	2.3E-04		2.3E-04	C
Zinc	7.9E-07		7.9E-07	D
Acetophenone	1.3E-09		1.3E-09	D
Acrolein	4.5E-04		4.5E-04	D
Nitrous Oxide	0.051	0.80	0.85	B
Benzene	0.029		0.029	D
Benzyl Chloride	6.1E-08		6.1E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	6.4E-09		6.4E-09	D
1,3 Butadiene	3.1E-06		3.1E-06	D
2-Chloroacetophenone	6.1E-10		6.1E-10	D
Chlorobenzene	1.9E-09		1.9E-09	D
2,4-Dinitrotoluene	2.4E-11		2.4E-11	D
Ethyl Chloride	3.7E-09		3.7E-09	D
Ethylbenzene	0.0034		0.0034	D
Ethylene Dibromide	1.0E-10		1.0E-10	D
Ethylene Dichloride	3.5E-09		3.5E-09	D
Hexane	5.9E-09		5.9E-09	D
Isophorone ($C_9H_{14}O$)	5.1E-08		5.1E-08	D
Methyl Bromide	1.4E-08		1.4E-08	D
Methyl Chloride	4.6E-08		4.6E-08	D
Methyl Ethyl Ketone	3.4E-08		3.4E-08	D
Methyl Hydrazine	1.5E-08		1.5E-08	D
Methyl Methacrylate	1.7E-09		1.7E-09	D
Methyl Tert Butyl Ether (MTBE)	3.1E-09		3.1E-09	D
Naphthalene	4.0E-05		4.0E-05	D
Propylene	2.1E-04		2.1E-04	D

Table A-29a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.2E-09		2.2E-09	D
Toluene	0.043		0.043	D
Trichloroethane	6.4E-07		6.4E-07	D
Vinyl Acetate	6.6E-10		6.6E-10	D
Xylenes	0.025		0.025	D
Bromoform	3.4E-09		3.4E-09	D
Chloroform	5.2E-09		5.2E-09	D
Carbon Disulfide	1.1E-08		1.1E-08	D
Dimethyl Sulfate	4.2E-09		4.2E-09	D
Cumene	4.6E-10		4.6E-10	D
Cyanide	2.2E-07		2.2E-07	D
Perchloroethylene	8.8E-06		8.8E-06	D
Methylene Chloride	2.0E-04		2.0E-04	D
Carbon Tetrachloride	4.6E-06		4.6E-06	D
Phenols	9.8E-05		9.8E-05	D
Fluorides	1.5E-05		1.5E-05	D
Polyaromatic Hydrocarbons (total)	1.7E-05		1.7E-05	E
Biphenyl	2.8E-07		2.8E-07	E
Acenaphthene	8.3E-08		8.3E-08	E
Acenaphthylene	4.1E-08		4.1E-08	E
Anthracene	3.4E-08		3.4E-08	E
Benzo(a)anthracene	1.3E-08		1.3E-08	E
Benzo(a)pyrene	6.2E-09		6.2E-09	E
Benzo(b,j,k)fluroanthene	1.8E-08		1.8E-08	E
Benzo(g,h,i) perylene	4.4E-09		4.4E-09	E
Chrysene	1.6E-08		1.6E-08	E
Fluoranthene	1.2E-07		1.2E-07	E
Fluorene	1.5E-07		1.5E-07	E
Indeno(1,2,3-cd)pyrene	1.0E-08		1.0E-08	E
Naphthalene	2.1E-06		2.1E-06	E
Phenanthrene	4.4E-07		4.4E-07	E
Pyrene	5.4E-08		5.4E-08	E
5-methyl Chrysene	3.6E-09		3.6E-09	E
Dioxins (unspecified)	1.7E-07		1.7E-07	D
Furans (unspecified)	7.4E-10		7.4E-10	D
CFC12	7.5E-07		7.5E-07	D
Radionuclides (unspecified)	0.014		0.014	C
Waterborne Emissions				
Acid (unspecified)	0.0016		0.0016	E
Acid (benzoic)	0.026		0.026	E
Acid (hexanoic)	0.0053		0.0053	E
Metal (unspecified)	20.0		20.0	E
Dissolved Solids	1,129		1,129	E
Suspended Solids	67.1		67.1	E
BOD	0.64		0.64	E
COD	1.89		1.89	E
Phenol/Phenolic Compounds	0.013		0.013	E
Sulfur	0.067		0.067	E
Sulfates	2.02		2.02	E
Sulfides	0.0012		0.0012	E
Oil	0.58		0.58	E
Hydrocarbons	0.0051		0.0051	E
Ammonia	0.46		0.46	E
Ammonium	1.1E-04		1.1E-04	E
Aluminum	2.18		2.18	E
Antimony	0.0014		0.0014	E
Arsenic	0.0069		0.0069	E
Barium	29.9		29.9	E
Beryllium	3.9E-04		3.9E-04	E
Cadmium	0.0010		0.0010	E
Chromium (unspecified)	0.062		0.062	E
Cobalt	5.6E-04		5.6E-04	E
Copper	0.0071		0.0071	E

Table A-29a (Cont'd)

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	4.35		4.35	E
Lead	0.015		0.015	E
Lithium	1.41		1.41	E
Magnesium	15.9		15.9	E
Manganese	0.028		0.028	E
Mercury	2.4E-05		2.4E-05	E
Molybdenum	5.8E-04		5.8E-04	E
Nickel	0.0068		0.0068	E
Selenium	3.0E-04		3.0E-04	E
Silver	0.053		0.053	E
Sodium	258		258	E
Strontium	1.38		1.38	E
Thallium	2.9E-04		2.9E-04	E
Tin	0.0055		0.0055	E
Titanium	0.021		0.021	E
Vanadium	6.9E-04		6.9E-04	E
Yttrium	1.7E-04		1.7E-04	E
Zinc	0.050		0.050	E
Chlorides (unspecified)	915		915	E
Chlorides (methyl chloride)	1.0E-06		1.0E-06	E
Calcium	81.4		81.4	E
Fluorine/ Fluorides	0.0018		0.0018	E
Nitrates	2.7E-04		2.7E-04	E
Nitrogen (ammonia)	9.5E-05		9.5E-05	E
Bromide	5.43		5.43	E
Boron	0.080		0.080	E
Organic Carbon	0.0065		0.0065	E
Cyanide	1.8E-06		1.8E-06	E
Hardness	251		251	E
Total Alkalinity	2.00		2.00	E
Surfactants	0.021		0.021	E
Acetone	2.5E-04		2.5E-04	E
Alkylated Benzenes	0.0012		0.0012	E
Alkylated Fluorenes	6.9E-05		6.9E-05	E
Alkylated Naphthalenes	2.0E-05		2.0E-05	E
Alkylated Phenanthrenes	8.1E-06		8.1E-06	E
Benzene	0.043		0.043	E
Cresols	0.0015		0.0015	E
Cymene	2.5E-06		2.5E-06	E
Dibenzofuran	4.8E-06		4.8E-06	E
Dibenzothiophene	3.9E-06		3.9E-06	E
2,4-dimethylphenol	7.1E-04		7.1E-04	E
Ethylbenzene	0.0024		0.0024	E
2-Hexanone	1.7E-04		1.7E-04	E
Methyl ethyl Ketone (MEK)	2.0E-06		2.0E-06	E
1-methylfluorene	2.9E-06		2.9E-06	E
2-methyl naphthalene	4.0E-04		4.0E-04	E
4-methyl-2-pentanone	1.1E-04		1.1E-04	E
Naphthalene	4.6E-04		4.6E-04	E
Pentamethyl benzene	1.9E-06		1.9E-06	E
Phenanthrene	7.0E-06		7.0E-06	E
Toluene	0.040		0.040	E
Total Biphenyls	7.7E-05		7.7E-05	E
Total dibenzo-thiophenes	2.4E-07		2.4E-07	E
Xylenes	0.021		0.021	E
Radionuclides (unspecified)	1.9E-07		1.9E-07	E
Solid Waste	330		330	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-29b

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.49		2.49	C
Particulates (PM10)	0.64	3.37	4.01	B
Nitrogen Oxides	25.0	174	199	B
Hydrocarbons (unspecified)	15.6		15.6	D
VOC (unspecified)	0.99	12.0	13.0	C
TNMOC (unspecified)	0.021		0.021	C
Sulfur Dioxide	14.0		14.0	C
Sulfur Oxides	21.5	5.39	26.9	B
Carbon Monoxide	106	35.1	141	B
Fossil CO2	3,258	24,478	27,736	B
Non-Fossil CO2	22.8		22.8	D
Aldehydes (Formaldehyde)	0.0022		0.0022	C
Aldehydes (Acetaldehyde)	1.7E-04		1.7E-04	D
Aldehydes (Propionaldehyde)	3.9E-08		3.9E-08	D
Aldehydes (unspecified)	0.32		0.32	C
Organics (unspecified)	0.0012		0.0012	D
Ammonia	0.16		0.16	D
Ammonia Chloride	1.6E-04		1.6E-04	D
Methane	34.9	0.59	35.5	B
Kerosene	2.9E-04		2.9E-04	D
Chlorine	9.3E-05		9.3E-05	D
HCl	0.25		0.25	C
HF	0.029		0.029	C
Metals (unspecified)	0.0050		0.0050	D
Mercaptan	2.1E-05		2.1E-05	D
Antimony	4.4E-06		4.4E-06	C
Arsenic	1.2E-04		1.2E-04	C
Beryllium	5.7E-06		5.7E-06	C
Cadmium	3.0E-05		3.0E-05	C
Chromium (VI)	1.5E-05		1.5E-05	C
Chromium (unspecified)	8.7E-05		8.7E-05	D
Cobalt	1.9E-04		1.9E-04	C
Copper	1.4E-06		1.4E-06	D
Lead	1.3E-04		1.3E-04	C
Magnesium	0.0021		0.0021	C
Manganese	3.7E-04		3.7E-04	C
Mercury	2.2E-05		2.2E-05	C
Nickel	0.0024		0.0024	C
Selenium	2.7E-04		2.7E-04	C
Zinc	9.3E-07		9.3E-07	D
Acetophenone	1.5E-09		1.5E-09	D
Acrolein	5.3E-04		5.3E-04	D
Nitrous Oxide	0.060	0.89	0.95	B
Benzene	0.034		0.034	D
Benzyl Chloride	7.2E-08		7.2E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09		7.5E-09	D
1,3 Butadiene	3.7E-06		3.7E-06	D
2-Chloroacetophenone	7.2E-10		7.2E-10	D
Chlorobenzene	2.3E-09		2.3E-09	D
2,4-Dinitrotoluene	2.9E-11		2.9E-11	D
Ethyl Chloride	4.3E-09		4.3E-09	D
Ethylbenzene	0.0039		0.0039	D
Ethylene Dibromide	1.2E-10		1.2E-10	D
Ethylene Dichloride	4.1E-09		4.1E-09	D
Hexane	6.9E-09		6.9E-09	D
Isophorone ($C_9H_{14}O$)	5.9E-08		5.9E-08	D
Methyl Bromide	1.6E-08		1.6E-08	D
Methyl Chloride	5.4E-08		5.4E-08	D
Methyl Ethyl Ketone	4.0E-08		4.0E-08	D
Methyl Hydrazine	1.7E-08		1.7E-08	D
Methyl Methacrylate	2.1E-09		2.1E-09	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09		3.6E-09	D
Naphthalene	4.7E-05		4.7E-05	D
Propylene	2.4E-04		2.4E-04	D

Table A-29b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.6E-09		2.6E-09	D
Toluene	0.051		0.051	D
Trichloroethane	7.5E-07		7.5E-07	D
Vinyl Acetate	7.8E-10		7.8E-10	D
Xylenes	0.030		0.030	D
Bromoform	4.0E-09		4.0E-09	D
Chloroform	6.1E-09		6.1E-09	D
Carbon Disulfide	1.3E-08		1.3E-08	D
Dimethyl Sulfate	4.9E-09		4.9E-09	D
Cumene	5.4E-10		5.4E-10	D
Cyanide	2.6E-07		2.6E-07	D
Perchloroethylene	1.0E-05		1.0E-05	D
Methylene Chloride	2.3E-04		2.3E-04	D
Carbon Tetrachloride	5.4E-06		5.4E-06	D
Phenols	1.2E-04		1.2E-04	D
Fluorides	1.8E-05		1.8E-05	D
Polyaromatic Hydrocarbons (total)	2.0E-05		2.0E-05	E
Biphenyl	3.3E-07		3.3E-07	E
Acenaphthene	9.8E-08		9.8E-08	E
Acenaphthylene	4.8E-08		4.8E-08	E
Anthracene	4.0E-08		4.0E-08	E
Benzo(a)anthracene	1.5E-08		1.5E-08	E
Benzo(a)pyrene	7.3E-09		7.3E-09	E
Benzo(b,j,k)fluroanthene	2.1E-08		2.1E-08	E
Benzo(g,h,i) perylene	5.2E-09		5.2E-09	E
Chrysene	1.9E-08		1.9E-08	E
Fluoranthene	1.4E-07		1.4E-07	E
Fluorene	1.7E-07		1.7E-07	E
Indeno(1,2,3-cd)pyrene	1.2E-08		1.2E-08	E
Naphthalene	2.5E-06		2.5E-06	E
Phenanthrene	5.2E-07		5.2E-07	E
Pyrene	6.3E-08		6.3E-08	E
5-methyl Chrysene	4.2E-09		4.2E-09	E
Dioxins (unspecified)	2.0E-07		2.0E-07	D
Furans (unspecified)	8.7E-10		8.7E-10	D
CFC12	8.9E-07		8.9E-07	D
Radionuclides (unspecified)	0.016		0.016	C
Waterborne Emissions				
Acid (unspecified)	0.0018		0.0018	E
Acid (benzoic)	0.030		0.030	E
Acid (hexanoic)	0.0062		0.0062	E
Metal (unspecified)	23.4		23.4	E
Dissolved Solids	1,325		1,325	E
Suspended Solids	78.8		78.8	E
BOD	0.75		0.75	E
COD	2.22		2.22	E
Phenol/Phenolic Compounds	0.015		0.015	E
Sulfur	0.079		0.079	E
Sulfates	2.37		2.37	E
Sulfides	0.0014		0.0014	E
Oil	0.68		0.68	E
Hydrocarbons	0.0059		0.0059	E
Ammonia	0.54		0.54	E
Ammonium	1.3E-04		1.3E-04	E
Aluminum	2.56		2.56	E
Antimony	0.0016		0.0016	E
Arsenic	0.0081		0.0081	E
Barium	35.1		35.1	E
Beryllium	4.5E-04		4.5E-04	E
Cadmium	0.0012		0.0012	E
Chromium (unspecified)	0.073		0.073	E
Cobalt	6.6E-04		6.6E-04	E
Copper	0.0084		0.0084	E

Table A-29b (Cont'd)

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5.11		5.11	E
Lead	0.017		0.017	E
Lithium	1.65		1.65	E
Magnesium	18.7		18.7	E
Manganese	0.032		0.032	E
Mercury	2.8E-05		2.8E-05	E
Molybdenum	6.8E-04		6.8E-04	E
Nickel	0.0080		0.0080	E
Selenium	3.5E-04		3.5E-04	E
Silver	0.062		0.062	E
Sodium	303		303	E
Strontium	1.62		1.62	E
Thallium	3.4E-04		3.4E-04	E
Tin	0.0065		0.0065	E
Titanium	0.025		0.025	E
Vanadium	8.1E-04		8.1E-04	E
Yttrium	2.0E-04		2.0E-04	E
Zinc	0.059		0.059	E
Chlorides (unspecified)	1,074		1,074	E
Chlorides (methyl chloride)	1.2E-06		1.2E-06	E
Calcium	95.5		95.5	E
Fluorine/ Fluorides	0.0021		0.0021	E
Nitrates	3.2E-04		3.2E-04	E
Nitrogen (ammonia)	1.1E-04		1.1E-04	E
Bromide	6.37		6.37	E
Boron	0.093		0.093	E
Organic Carbon	0.0076		0.0076	E
Cyanide	2.1E-06		2.1E-06	E
Hardness	294		294	E
Total Alkalinity	2.34		2.34	E
Surfactants	0.025		0.025	E
Acetone	3.0E-04		3.0E-04	E
Alkylated Benzenes	0.0014		0.0014	E
Alkylated Fluorenes	8.1E-05		8.1E-05	E
Alkylated Naphthalenes	2.3E-05		2.3E-05	E
Alkylated Phenanthrenes	9.5E-06		9.5E-06	E
Benzene	0.050		0.050	E
Cresols	0.0018		0.0018	E
Cymene	3.0E-06		3.0E-06	E
Dibenzofuran	5.7E-06		5.7E-06	E
Dibenzothiophene	4.6E-06		4.6E-06	E
2,4-dimethylphenol	8.3E-04		8.3E-04	E
Ethylbenzene	0.0028		0.0028	E
2-Hexanone	1.9E-04		1.9E-04	E
Methyl ethyl Ketone (MEK)	2.4E-06		2.4E-06	E
1-methylfluorene	3.4E-06		3.4E-06	E
2-methyl naphthalene	4.7E-04		4.7E-04	E
4-methyl-2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.4E-04		5.4E-04	E
Pentamethyl benzene	2.2E-06		2.2E-06	E
Phenanthrene	8.2E-06		8.2E-06	E
Toluene	0.047		0.047	E
Total Biphenyls	9.1E-05		9.1E-05	E
Total dibenzo-thiophenes	2.8E-07		2.8E-07	E
Xylenes	0.025		0.025	E
Radionuclides (unspecified)	2.3E-07		2.3E-07	E
Solid Waste	387		387	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-30

ENVIRONMENTAL EMISSIONS FOR DIESEL POWERED LOCOMOTIVES

(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.49		2.49	C
Particulates (PM10)	0.64	15.9	16.6	B
Nitrogen Oxides	25.0	642	667	B
Hydrocarbons (unspecified)	15.6		15.6	D
VOC (unspecified)	0.99	23.8	24.8	C
TNMOC (unspecified)	0.021		0.021	C
Sulfur Dioxide	14.0		14.0	C
Sulfur Oxides	21.5	5.39	26.9	B
Carbon Monoxide	106	63.2	169	B
Fossil CO2	3,258	24,396	27,654	B
Non-Fossil CO2	22.8		22.8	D
Aldehydes (Formaldehyde)	0.0022		0.0022	C
Aldehydes (Acetaldehyde)	1.7E-04		1.7E-04	D
Aldehydes (Propionaldehyde)	3.9E-08		3.9E-08	D
Aldehydes (unspecified)	0.32		0.32	C
Organics (unspecified)	0.0012		0.0012	D
Ammonia	0.16		0.16	D
Ammonia Chloride	1.6E-04		1.6E-04	D
Methane	34.9	1.16	36.1	B
Kerosene	2.9E-04		2.9E-04	D
Chlorine	9.3E-05		9.3E-05	D
HCl	0.25		0.25	C
HF	0.029		0.029	C
Metals (unspecified)	0.0050		0.0050	D
Mercaptan	2.1E-05		2.1E-05	D
Antimony	4.4E-06		4.4E-06	C
Arsenic	1.2E-04		1.2E-04	C
Beryllium	5.7E-06		5.7E-06	C
Cadmium	3.0E-05		3.0E-05	C
Chromium (VI)	1.5E-05		1.5E-05	C
Chromium (unspecified)	8.7E-05		8.7E-05	D
Cobalt	1.9E-04		1.9E-04	C
Copper	1.4E-06		1.4E-06	D
Lead	1.3E-04		1.3E-04	C
Magnesium	0.0021		0.0021	C
Manganese	3.7E-04		3.7E-04	C
Mercury	2.2E-05		2.2E-05	C
Nickel	0.0024		0.0024	C
Selenium	2.7E-04		2.7E-04	C
Zinc	9.3E-07		9.3E-07	D
Acetophenone	1.5E-09		1.5E-09	D
Acrolein	5.3E-04		5.3E-04	D
Nitrous Oxide	0.060	0.61	0.67	B
Benzene	0.034		0.034	D
Benzyl Chloride	7.2E-08		7.2E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.5E-09		7.5E-09	D
1,3 Butadiene	3.7E-06		3.7E-06	D
2-Chloroacetophenone	7.2E-10		7.2E-10	D
Chlorobenzene	2.3E-09		2.3E-09	D
2,4-Dinitrotoluene	2.9E-11		2.9E-11	D
Ethyl Chloride	4.3E-09		4.3E-09	D
Ethylbenzene	0.0039		0.0039	D
Ethylene Dibromide	1.2E-10		1.2E-10	D
Ethylene Dichloride	4.1E-09		4.1E-09	D
Hexane	6.9E-09		6.9E-09	D
Isophorone ($C_9H_{14}O$)	5.9E-08		5.9E-08	D
Methyl Bromide	1.6E-08		1.6E-08	D
Methyl Chloride	5.4E-08		5.4E-08	D
Methyl Ethyl Ketone	4.0E-08		4.0E-08	D
Methyl Hydrazine	1.7E-08		1.7E-08	D
Methyl Methacrylate	2.1E-09		2.1E-09	D
Methyl Tert Butyl Ether (MTBE)	3.6E-09		3.6E-09	D
Naphthalene	4.7E-05		4.7E-05	D
Propylene	2.4E-04		2.4E-04	D

Table A-30 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR DIESEL POWERED LOCOMOTIVES
(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.6E-09		2.6E-09	D
Toluene	0.051		0.051	D
Trichloroethane	7.5E-07		7.5E-07	D
Vinyl Acetate	7.8E-10		7.8E-10	D
Xylenes	0.030		0.030	D
Bromoform	4.0E-09		4.0E-09	D
Chloroform	6.1E-09		6.1E-09	D
Carbon Disulfide	1.3E-08		1.3E-08	D
Dimethyl Sulfate	4.9E-09		4.9E-09	D
Cumene	5.4E-10		5.4E-10	D
Cyanide	2.6E-07		2.6E-07	D
Perchloroethylene	1.0E-05		1.0E-05	D
Methylene Chloride	2.3E-04		2.3E-04	D
Carbon Tetrachloride	5.4E-06		5.4E-06	D
Phenols	1.2E-04		1.2E-04	D
Fluorides	1.8E-05		1.8E-05	D
Polyaromatic Hydrocarbons (total)	2.0E-05		2.0E-05	E
Biphenyl	3.3E-07		3.3E-07	E
Acenaphthene	9.8E-08		9.8E-08	E
Acenaphthylene	4.8E-08		4.8E-08	E
Anthracene	4.0E-08		4.0E-08	E
Benzo(a)anthracene	1.5E-08		1.5E-08	E
Benzo(a)pyrene	7.3E-09		7.3E-09	E
Benzo(b,j,k)fluroanthene	2.1E-08		2.1E-08	E
Benzo(g,h,i) perylene	5.2E-09		5.2E-09	E
Chrysene	1.9E-08		1.9E-08	E
Fluoranthene	1.4E-07		1.4E-07	E
Fluorene	1.7E-07		1.7E-07	E
Indeno(1,2,3-cd)pyrene	1.2E-08		1.2E-08	E
Naphthalene	2.5E-06		2.5E-06	E
Phenanthrene	5.2E-07		5.2E-07	E
Pyrene	6.3E-08		6.3E-08	E
5-methyl Chrysene	4.2E-09		4.2E-09	E
Dioxins (unspecified)	2.0E-07		2.0E-07	D
Furans (unspecified)	8.7E-10		8.7E-10	D
CFC12	8.9E-07		8.9E-07	D
Radionuclides (unspecified)	0.016		0.016	C
Waterborne Emissions				
Acid (unspecified)	0.0018		0.0018	E
Acid (benzoic)	0.030		0.030	E
Acid (hexanoic)	0.0062		0.0062	E
Metal (unspecified)	23.4		23.4	E
Dissolved Solids	1,325		1,325	E
Suspended Solids	78.8		78.8	E
BOD	0.75		0.75	E
COD	2.22		2.22	E
Phenol/Phenolic Compounds	0.015		0.015	E
Sulfur	0.079		0.079	E
Sulfates	2.37		2.37	E
Sulfides	0.0014		0.0014	E
Oil	0.68		0.68	E
Hydrocarbons	0.0059		0.0059	E
Ammonia	0.54		0.54	E
Ammonium	1.3E-04		1.3E-04	E
Aluminum	2.56		2.56	E
Antimony	0.0016		0.0016	E
Arsenic	0.0081		0.0081	E
Barium	35.1		35.1	E
Beryllium	4.5E-04		4.5E-04	E
Cadmium	0.0012		0.0012	E
Chromium (unspecified)	0.073		0.073	E
Cobalt	6.6E-04		6.6E-04	E
Copper	0.0084		0.0084	E

Table A-30 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR DIESEL POWERED LOCOMOTIVES

(pounds of pollutants per 1,000 gallons of diesel fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	5.11		5.11	E
Lead	0.017		0.017	E
Lithium	1.65		1.65	E
Magnesium	18.7		18.7	E
Manganese	0.032		0.032	E
Mercury	2.8E-05		2.8E-05	E
Molybdenum	6.8E-04		6.8E-04	E
Nickel	0.0080		0.0080	E
Selenium	3.5E-04		3.5E-04	E
Silver	0.062		0.062	E
Sodium	303		303	E
Strontium	1.62		1.62	E
Thallium	3.4E-04		3.4E-04	E
Tin	0.0065		0.0065	E
Titanium	0.025		0.025	E
Vanadium	8.1E-04		8.1E-04	E
Yttrium	2.0E-04		2.0E-04	E
Zinc	0.059		0.059	E
Chlorides (unspecified)	1,074		1,074	E
Chlorides (methyl chloride)	1.2E-06		1.2E-06	E
Calcium	95.5		95.5	E
Fluorine/ Fluorides	0.0021		0.0021	E
Nitrates	3.2E-04		3.2E-04	E
Nitrogen (ammonia)	1.1E-04		1.1E-04	E
Bromide	6.37		6.37	E
Boron	0.093		0.093	E
Organic Carbon	0.0076		0.0076	E
Cyanide	2.1E-06		2.1E-06	E
Hardness	294		294	E
Total Alkalinity	2.34		2.34	E
Surfactants	0.025		0.025	E
Acetone	3.0E-04		3.0E-04	E
Alkylated Benzenes	0.0014		0.0014	E
Alkylated Fluorenes	8.1E-05		8.1E-05	E
Alkylated Naphthalenes	2.3E-05		2.3E-05	E
Alkylated Phenanthrenes	9.5E-06		9.5E-06	E
Benzene	0.050		0.050	E
Cresols	0.0018		0.0018	E
Cymene	3.0E-06		3.0E-06	E
Dibenzofuran	5.7E-06		5.7E-06	E
Dibenzothiophene	4.6E-06		4.6E-06	E
2,4-dimethylphenol	8.3E-04		8.3E-04	E
Ethylbenzene	0.0028		0.0028	E
2-Hexanone	1.9E-04		1.9E-04	E
Methyl ethyl Ketone (MEK)	2.4E-06		2.4E-06	E
1-methylfluorene	3.4E-06		3.4E-06	E
2-methyl naphthalene	4.7E-04		4.7E-04	E
4-methyl-2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.4E-04		5.4E-04	E
Pentamethyl benzene	2.2E-06		2.2E-06	E
Phenanthrene	8.2E-06		8.2E-06	E
Toluene	0.047		0.047	E
Total Biphenyls	9.1E-05		9.1E-05	E
Total dibenzo-thiophenes	2.8E-07		2.8E-07	E
Xylenes	0.025		0.025	E
Radionuclides (unspecified)	2.3E-07		2.3E-07	E
Solid Waste	387		387	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-31

ENVIRONMENTAL EMISSIONS FOR BARGES
(pounds of pollutants per 1,000 gallons of fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.66		2.66	C
Particulates (PM10)	0.69	8.19	8.88	B
Nitrogen Oxides	26.8	330	357	B
Hydrocarbons (unspecified)	16.7		16.7	D
VOC (unspecified)	1.06	12.2	13.3	C
TNMOC (unspecified)	0.023		0.023	C
Sulfur Dioxide	14.9		14.9	C
Sulfur Oxides	23.0	67.9	90.8	B
Carbon Monoxide	113	32.6	146	B
Fossil CO2	3,485	26,588	30,073	B
Non-Fossil CO2	24.4		24.4	D
Aldehydes (Formaldehyde)	0.0024		0.0024	C
Aldehydes (Acetaldehyde)	1.9E-04		1.9E-04	D
Aldehydes (Propionaldehyde)	4.2E-08		4.2E-08	D
Aldehydes (unspecified)	0.35		0.35	C
Organics (unspecified)	0.0013		0.0013	D
Ammonia	0.17		0.17	D
Ammonia Chloride	1.7E-04		1.7E-04	D
Methane	37.4	0.60	38.0	B
Kerosene	3.1E-04		3.1E-04	D
Chlorine	9.9E-05		9.9E-05	D
HCl	0.27		0.27	C
HF	0.031		0.031	C
Metals (unspecified)	0.0054		0.0054	D
Mercaptan	2.2E-05		2.2E-05	D
Antimony	4.7E-06		4.7E-06	C
Arsenic	1.3E-04		1.3E-04	C
Beryllium	6.1E-06		6.1E-06	C
Cadmium	3.2E-05		3.2E-05	C
Chromium (VI)	1.6E-05		1.6E-05	C
Chromium (unspecified)	9.3E-05		9.3E-05	D
Cobalt	2.0E-04		2.0E-04	C
Copper	1.5E-06		1.5E-06	D
Lead	1.4E-04		1.4E-04	C
Magnesium	0.0023		0.0023	C
Manganese	3.9E-04		3.9E-04	C
Mercury	2.4E-05		2.4E-05	C
Nickel	0.0026		0.0026	C
Selenium	2.9E-04		2.9E-04	C
Zinc	1.0E-06		1.0E-06	D
Acetophenone	1.6E-09		1.6E-09	D
Acrolein	5.7E-04		5.7E-04	D
Nitrous Oxide	0.064	0.51	0.58	B
Benzene	0.036		0.036	D
Benzyl Chloride	7.7E-08		7.7E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.0E-09		8.0E-09	D
1,3 Butadiene	3.9E-06		3.9E-06	D
2-Chloroacetophenone	7.7E-10		7.7E-10	D
Chlorobenzene	2.4E-09		2.4E-09	D
2,4-Dinitrotoluene	3.1E-11		3.1E-11	D
Ethyl Chloride	4.6E-09		4.6E-09	D
Ethylbenzene	0.0042		0.0042	D
Ethylene Dibromide	1.3E-10		1.3E-10	D
Ethylene Dichloride	4.4E-09		4.4E-09	D
Hexane	7.3E-09		7.3E-09	D
Isophorone ($C_9H_{14}O$)	6.4E-08		6.4E-08	D
Methyl Bromide	1.8E-08		1.8E-08	D
Methyl Chloride	5.8E-08		5.8E-08	D
Methyl Ethyl Ketone	4.3E-08		4.3E-08	D
Methyl Hydrazine	1.9E-08		1.9E-08	D
Methyl Methacrylate	2.2E-09		2.2E-09	D
Methyl Tert Butyl Ether (MTBE)	3.8E-09		3.8E-09	D
Naphthalene	5.1E-05		5.1E-05	D
Propylene	2.6E-04		2.6E-04	D

Table A-31 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR BARGES
(pounds of pollutants per 1,000 gallons of fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.7E-09		2.7E-09	D
Toluene	0.054		0.054	D
Trichloroethane	8.0E-07		8.0E-07	D
Vinyl Acetate	8.3E-10		8.3E-10	D
Xylenes	0.032		0.032	D
Bromoform	4.3E-09		4.3E-09	D
Chloroform	6.5E-09		6.5E-09	D
Carbon Disulfide	1.4E-08		1.4E-08	D
Dimethyl Sulfate	5.3E-09		5.3E-09	D
Cumene	5.8E-10		5.8E-10	D
Cyanide	2.7E-07		2.7E-07	D
Perchloroethylene	1.1E-05		1.1E-05	D
Methylene Chloride	2.5E-04		2.5E-04	D
Carbon Tetrachloride	5.7E-06		5.7E-06	D
Phenols	1.2E-04		1.2E-04	D
Fluorides	1.9E-05		1.9E-05	D
Polyaromatic Hydrocarbons (total)	2.1E-05		2.1E-05	E
Biphenyl	3.5E-07		3.5E-07	E
Acenaphthene	1.0E-07		1.0E-07	E
Acenaphthylene	5.1E-08		5.1E-08	E
Anthracene	4.3E-08		4.3E-08	E
Benzo(a)anthracene	1.6E-08		1.6E-08	E
Benzo(a)pyrene	7.8E-09		7.8E-09	E
Benzo(b,j,k)fluroanthene	2.3E-08		2.3E-08	E
Benzo(g,h,i) perylene	5.5E-09		5.5E-09	E
Chrysene	2.1E-08		2.1E-08	E
Fluoranthene	1.5E-07		1.5E-07	E
Fluorene	1.9E-07		1.9E-07	E
Indeno(1,2,3-cd)pyrene	1.3E-08		1.3E-08	E
Naphthalene	2.7E-06		2.7E-06	E
Phenanthrene	5.5E-07		5.5E-07	E
Pyrene	6.8E-08		6.8E-08	E
5-methyl Chrysene	4.5E-09		4.5E-09	E
Dioxins (unspecified)	2.1E-07		2.1E-07	D
Furans (unspecified)	9.3E-10		9.3E-10	D
CFC12	9.5E-07		9.5E-07	D
Radionuclides (unspecified)	0.017		0.017	C
Waterborne Emissions				
Acid (unspecified)	0.0020		0.0020	E
Acid (benzoic)	0.032		0.032	E
Acid (hexanoic)	0.0067		0.0067	E
Metal (unspecified)	25.1		25.1	E
Dissolved Solids	1,417		1,417	E
Suspended Solids	84.2		84.2	E
BOD	0.80		0.80	E
COD	2.38		2.38	E
Phenol/Phenolic Compounds	0.016		0.016	E
Sulfur	0.084		0.084	E
Sulfates	2.53		2.53	E
Sulfides	0.0015		0.0015	E
Oil	0.73		0.73	E
Hydrocarbons	0.0063		0.0063	E
Ammonia	0.58		0.58	E
Ammonium	1.4E-04		1.4E-04	E
Aluminum	2.74		2.74	E
Antimony	0.0017		0.0017	E
Arsenic	0.0087		0.0087	E
Barium	37.5		37.5	E
Beryllium	4.8E-04		4.8E-04	E
Cadmium	0.0013		0.0013	E
Chromium (unspecified)	0.078		0.078	E
Cobalt	7.0E-04		7.0E-04	E
Copper	0.0090		0.0090	E
Iron	5.46		5.46	E

Table A-31 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR BARGES
(pounds of pollutants per 1,000 gallons of fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Lead	0.018		0.018	E
Lithium	1.77		1.77	E
Magnesium	20.0		20.0	E
Manganese	0.035		0.035	E
Mercury	3.0E-05		3.0E-05	E
Molybdenum	7.3E-04		7.3E-04	E
Nickel	0.0086		0.0086	E
Selenium	3.8E-04		3.8E-04	E
Silver	0.067		0.067	E
Sodium	324		324	E
Strontium	1.73		1.73	E
Thallium	3.6E-04		3.6E-04	E
Tin	0.0070		0.0070	E
Titanium	0.026		0.026	E
Vanadium	8.6E-04		8.6E-04	E
Yttrium	2.1E-04		2.1E-04	E
Zinc	0.063		0.063	E
Chlorides (unspecified)	1,149		1,149	E
Chlorides (methyl chloride)	1.3E-06		1.3E-06	E
Calcium	102		102	E
Fluorine/ Fluorides	0.0023		0.0023	E
Nitrates	3.4E-04		3.4E-04	E
Nitrogen (ammonia)	1.2E-04		1.2E-04	E
Bromide	6.81		6.81	E
Boron	0.10		0.10	E
Organic Carbon	0.0082		0.0082	E
Cyanide	2.3E-06		2.3E-06	E
Hardness	315		315	E
Total Alkalinity	2.51		2.51	E
Surfactants	0.027		0.027	E
Acetone	3.2E-04		3.2E-04	E
Alkylated Benzenes	0.0015		0.0015	E
Alkylated Fluorenes	8.7E-05		8.7E-05	E
Alkylated Naphthalenes	2.5E-05		2.5E-05	E
Alkylated Phenanthrenes	1.0E-05		1.0E-05	E
Benzene	0.053		0.053	E
Cresols	0.0019		0.0019	E
Cymene	3.2E-06		3.2E-06	E
Dibenzofuran	6.0E-06		6.0E-06	E
Dibenzothiophene	4.9E-06		4.9E-06	E
2,4-dimethylphenol	8.9E-04		8.9E-04	E
Ethylbenzene	0.0030		0.0030	E
2-Hexanone	2.1E-04		2.1E-04	E
Methyl ethyl Ketone (MEK)	2.6E-06		2.6E-06	E
1-methylfluorene	3.6E-06		3.6E-06	E
2-methyl naphthalene	5.0E-04		5.0E-04	E
4-methyl-2-pentanone	1.3E-04		1.3E-04	E
Naphthalene	5.8E-04		5.8E-04	E
Pentamethyl benzene	2.4E-06		2.4E-06	E
Phenanthrene	8.8E-06		8.8E-06	E
Toluene	0.050		0.050	E
Total Biphenyls	9.7E-05		9.7E-05	E
Total dibenzo-thiophenes	3.0E-07		3.0E-07	E
Xylenes	0.027		0.027	E
Radionuclides (unspecified)	2.4E-07		2.4E-07	E
Solid Waste	414		414	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-32

ENVIRONMENTAL EMISSIONS FOR OCEAN FREIGHTERS
(pounds of pollutants per 1,000 gallons of fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.69	18.1	20.8	B
Particulates (PM10)	0.69		0.69	B
Nitrogen Oxides	27.1	730	757	B
Hydrocarbons (unspecified)	16.9		16.9	D
VOC (unspecified)	1.07	27.0	28.1	C
TNMOC (unspecified)	0.023		0.023	C
Sulfur Dioxide	15.1		15.1	C
Sulfur Oxides	23.2	77.5	101	B
Carbon Monoxide	114	72.0	186	B
Fossil CO2	3,519	26,802	30,322	B
Non-Fossil CO2	24.7		24.7	D
Aldehydes (Formaldehyde)	0.0024		0.0024	C
Aldehydes (Acetaldehyde)	1.9E-04		1.9E-04	D
Aldehydes (Propionaldehyde)	4.2E-08		4.2E-08	D
Aldehydes (unspecified)	0.35		0.35	C
Organics (unspecified)	0.0013		0.0013	D
Ammonia	0.17		0.17	D
Ammonia Chloride	1.7E-04		1.7E-04	D
Methane	37.7	1.32	39.1	B
Kerosene	3.1E-04		3.1E-04	D
Chlorine	1.0E-04		1.0E-04	D
HCl	0.27		0.27	C
HF	0.031		0.031	C
Metals (unspecified)	0.0054		0.0054	D
Mercaptan	2.3E-05		2.3E-05	D
Antimony	4.7E-06		4.7E-06	C
Arsenic	1.3E-04		1.3E-04	C
Beryllium	6.2E-06		6.2E-06	C
Cadmium	3.2E-05		3.2E-05	C
Chromium (VI)	1.6E-05		1.6E-05	C
Chromium (unspecified)	9.4E-05		9.4E-05	D
Cobalt	2.0E-04		2.0E-04	C
Copper	1.5E-06		1.5E-06	D
Lead	1.5E-04		1.5E-04	C
Magnesium	0.0023		0.0023	C
Manganese	4.0E-04		4.0E-04	C
Mercury	2.4E-05		2.4E-05	C
Nickel	0.0026		0.0026	C
Selenium	2.9E-04		2.9E-04	C
Zinc	1.0E-06		1.0E-06	D
Acetophenone	1.7E-09		1.7E-09	D
Acrolein	5.8E-04		5.8E-04	D
Nitrous Oxide	0.065	0.59	0.66	B
Benzene	0.037		0.037	D
Benzyl Chloride	7.8E-08		7.8E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	8.1E-09		8.1E-09	D
1,3 Butadiene	3.9E-06		3.9E-06	D
2-Chloroacetophenone	7.8E-10		7.8E-10	D
Chlorobenzene	2.4E-09		2.4E-09	D
2,4-Dinitrotoluene	3.1E-11		3.1E-11	D
Ethyl Chloride	4.7E-09		4.7E-09	D
Ethylbenzene	0.0043		0.0043	D
Ethylene Dibromide	1.3E-10		1.3E-10	D
Ethylene Dichloride	4.4E-09		4.4E-09	D
Hexane	7.4E-09		7.4E-09	D
Isophorone ($C_9H_{14}O$)	6.4E-08		6.4E-08	D
Methyl Bromide	1.8E-08		1.8E-08	D
Methyl Chloride	5.9E-08		5.9E-08	D
Methyl Ethyl Ketone	4.3E-08		4.3E-08	D
Methyl Hydrazine	1.9E-08		1.9E-08	D
Methyl Methacrylate	2.2E-09		2.2E-09	D
Methyl Tert Butyl Ether (MTBE)	3.9E-09		3.9E-09	D
Naphthalene	5.1E-05		5.1E-05	D
Propylene	2.6E-04		2.6E-04	D

Table A-32 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR OCEAN FREIGHTERS
(pounds of pollutants per 1,000 gallons of fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Styrene	2.8E-09		2.8E-09	D
Toluene	0.055		0.055	D
Trichloroethane	8.1E-07		8.1E-07	D
Vinyl Acetate	8.4E-10		8.4E-10	D
Xylenes	0.032		0.032	D
Bromoform	4.3E-09		4.3E-09	D
Chloroform	6.5E-09		6.5E-09	D
Carbon Disulfide	1.4E-08		1.4E-08	D
Dimethyl Sulfate	5.3E-09		5.3E-09	D
Cumene	5.9E-10		5.9E-10	D
Cyanide	2.8E-07		2.8E-07	D
Perchloroethylene	1.1E-05		1.1E-05	D
Methylene Chloride	2.5E-04		2.5E-04	D
Carbon Tetrachloride	5.8E-06		5.8E-06	D
Phenols	1.2E-04		1.2E-04	D
Fluorides	1.9E-05		1.9E-05	D
Polyaromatic Hydrocarbons (total)	2.1E-05		2.1E-05	E
Biphenyl	3.5E-07		3.5E-07	E
Acenaphthene	1.1E-07		1.1E-07	E
Acenaphthylene	5.2E-08		5.2E-08	E
Anthracene	4.4E-08		4.4E-08	E
Benzo(a)anthracene	1.7E-08		1.7E-08	E
Benzo(a)pyrene	7.9E-09		7.9E-09	E
Benzo(b,j,k)fluroanthene	2.3E-08		2.3E-08	E
Benzo(g,h,i) perylene	5.6E-09		5.6E-09	E
Chrysene	2.1E-08		2.1E-08	E
Fluoranthene	1.5E-07		1.5E-07	E
Fluorene	1.9E-07		1.9E-07	E
Indeno(1,2,3-cd)pyrene	1.3E-08		1.3E-08	E
Naphthalene	2.7E-06		2.7E-06	E
Phenanthrene	5.6E-07		5.6E-07	E
Pyrene	6.8E-08		6.8E-08	E
5-methyl Chrysene	4.6E-09		4.6E-09	E
Dioxins (unspecified)	2.1E-07		2.1E-07	D
Furans (unspecified)	9.4E-10		9.4E-10	D
CFC12	9.6E-07		9.6E-07	D
Radionuclides (unspecified)	0.017		0.017	C
Waterborne Emissions				
Acid (unspecified)	0.0020		0.0020	E
Acid (benzoic)	0.033		0.033	E
Acid (hexanoic)	0.0067		0.0067	E
Metal (unspecified)	25.3		25.3	E
Dissolved Solids	1,431		1,431	E
Suspended Solids	85.1		85.1	E
BOD	0.81		0.81	E
COD	2.40		2.40	E
Phenol/Phenolic Compounds	0.016		0.016	E
Sulfur	0.085		0.085	E
Sulfates	2.56		2.56	E
Sulfides	0.0015		0.0015	E
Oil	0.74		0.74	E
Hydrocarbons	0.0064		0.0064	E
Ammonia	0.59		0.59	E
Ammonium	1.4E-04		1.4E-04	E
Aluminum	2.77		2.77	E
Antimony	0.0017		0.0017	E
Arsenic	0.0088		0.0088	E
Barium	37.9		37.9	E
Beryllium	4.9E-04		4.9E-04	E
Cadmium	0.0013		0.0013	E
Chromium (unspecified)	0.078		0.078	E
Cobalt	7.1E-04		7.1E-04	E
Copper	0.0091		0.0091	E
Iron	5.52		5.52	E

Table A-32 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR OCEAN FREIGHTERS
(pounds of pollutants per 1,000 gallons of fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Lead	0.018		0.018	E
Lithium	1.78		1.78	E
Magnesium	20.2		20.2	E
Manganese	0.035		0.035	E
Mercury	3.0E-05		3.0E-05	E
Molybdenum	7.4E-04		7.4E-04	E
Nickel	0.0087		0.0087	E
Selenium	3.8E-04		3.8E-04	E
Silver	0.067		0.067	E
Sodium	327		327	E
Strontium	1.75		1.75	E
Thallium	3.6E-04		3.6E-04	E
Tin	0.0070		0.0070	E
Titanium	0.027		0.027	E
Vanadium	8.7E-04		8.7E-04	E
Yttrium	2.2E-04		2.2E-04	E
Zinc	0.064		0.064	E
Chlorides (unspecified)	1,160		1,160	E
Chlorides (methyl chloride)	1.3E-06		1.3E-06	E
Calcium	103		103	E
Fluorine/ Fluorides	0.0023		0.0023	E
Nitrates	3.4E-04		3.4E-04	E
Nitrogen (ammonia)	1.2E-04		1.2E-04	E
Bromide	6.88		6.88	E
Boron	0.10		0.10	E
Organic Carbon	0.0082		0.0082	E
Cyanide	2.3E-06		2.3E-06	E
Hardness	318		318	E
Total Alkalinity	2.53		2.53	E
Surfactants	0.027		0.027	E
Acetone	3.2E-04		3.2E-04	E
Alkylated Benzenes	0.0015		0.0015	E
Alkylated Fluorenes	8.8E-05		8.8E-05	E
Alkylated Naphthalenes	2.5E-05		2.5E-05	E
Alkylated Phenanthrenes	1.0E-05		1.0E-05	E
Benzene	0.054		0.054	E
Cresols	0.0019		0.0019	E
Cymene	3.2E-06		3.2E-06	E
Dibenzofuran	6.1E-06		6.1E-06	E
Dibenzothiophene	4.9E-06		4.9E-06	E
2,4 dimethylphenol	9.0E-04		9.0E-04	E
Ethylbenzene	0.0030		0.0030	E
2-Hexanone	2.1E-04		2.1E-04	E
Methyl ethyl Ketone (MEK)	2.6E-06		2.6E-06	E
1-methylfluorene	3.7E-06		3.7E-06	E
2-methyl naphthalene	5.1E-04		5.1E-04	E
4-methyl-2-pentanone	1.3E-04		1.3E-04	E
Naphthalene	5.9E-04		5.9E-04	E
Pentamethyl benzene	2.4E-06		2.4E-06	E
Phenanthrene	8.9E-06		8.9E-06	E
Toluene	0.051		0.051	E
Total Biphenyls	9.8E-05		9.8E-05	E
Total dibenzo-thiophenes	3.0E-07		3.0E-07	E
Xylenes	0.027		0.027	E
Radionuclides (unspecified)	2.4E-07		2.4E-07	E
Solid Waste	418		418	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74 and A-85.

Source: Franklin Associates, A Division of ERG

Table A-33

ENVIRONMENTAL EMISSIONS FOR
CARGO PLANES
(pounds of pollutants per 1,000 gallons of kerosene fuel)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates (unspecified)	2.32		2.32	C
Particulates (PM10)	0.60		0.60	D
Nitrogen Oxides	23.4	107	130	B
Hydrocarbons (unspecified)	14.6	20.8	35.3	B
VOC (unspecified)	0.93		0.93	D
TNMOC (unspecified)	0.020		0.020	C
Sulfur Dioxide	13.0		13.0	C
Sulfur Oxides	20.0		20.0	C
Carbon Monoxide	98.6	87.6	186	B
Fossil CO2	3,039	20,903	23,942	B
Non-Fossil CO2	21.3		21.3	D
Aldehydes (Formaldehyde)	0.0021		0.0021	C
Aldehydes (Acetaldehyde)	1.6E-04		1.6E-04	D
Aldehydes (Propionaldehyde)	3.6E-08		3.6E-08	D
Aldehydes (unspecified)	0.30		0.30	C
Organics (unspecified)	0.0011		0.0011	D
Ammonia	0.15		0.15	D
Ammonia Chloride	1.5E-04		1.5E-04	D
Methane	32.6		32.6	C
Kerosene	2.7E-04		2.7E-04	D
Chlorine	8.6E-05		8.6E-05	D
HCl	0.24		0.24	C
HF	0.027		0.027	C
Metals (unspecified)	0.0047		0.0047	D
Mercaptan	1.9E-05		1.9E-05	D
Antimony	4.1E-06		4.1E-06	C
Arsenic	1.1E-04		1.1E-04	C
Beryllium	5.3E-06		5.3E-06	C
Cadmium	2.8E-05		2.8E-05	C
Chromium (VI)	1.4E-05		1.4E-05	C
Chromium (unspecified)	8.1E-05		8.1E-05	D
Cobalt	1.7E-04		1.7E-04	C
Copper	1.3E-06		1.3E-06	D
Lead	1.3E-04		1.3E-04	C
Magnesium	0.0020		0.0020	C
Manganese	3.4E-04		3.4E-04	C
Mercury	2.1E-05		2.1E-05	C
Nickel	0.0022		0.0022	C
Selenium	2.5E-04		2.5E-04	C
Zinc	8.7E-07		8.7E-07	D
Acetophenone	1.4E-09		1.4E-09	D
Acrolein	5.0E-04		5.0E-04	D
Nitrous Oxide	0.056		0.056	C
Benzene	0.032		0.032	D
Benzyl Chloride	6.7E-08		6.7E-08	D
Bis(2-ethylhexyl) Phthalate (DEHP)	7.0E-09		7.0E-09	D
1,3 Butadiene	3.4E-06		3.4E-06	D
2-Chloroacetophenone	6.7E-10		6.7E-10	D
Chlorobenzene	2.1E-09		2.1E-09	D
2,4-Dinitrotoluene	2.7E-11		2.7E-11	D
Ethyl Chloride	4.0E-09		4.0E-09	D
Ethylbenzene	0.0037		0.0037	D
Ethylene Dibromide	1.1E-10		1.1E-10	D
Ethylene Dichloride	3.8E-09		3.8E-09	D
Hexane	6.4E-09		6.4E-09	D
Isophorone ($C_9H_{14}O$)	5.5E-08		5.5E-08	D
Methyl Bromide	1.5E-08		1.5E-08	D
Methyl Chloride	5.1E-08		5.1E-08	D
Methyl Ethyl Ketone	3.7E-08		3.7E-08	D
Methyl Hydrazine	1.6E-08		1.6E-08	D
Methyl Methacrylate	1.9E-09		1.9E-09	D
Methyl Tert Butyl Ether (MTBE)	3.3E-09		3.3E-09	D
Naphthalene	4.4E-05		4.4E-05	D
Propylene	2.2E-04		2.2E-04	D

Table A-33 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR
CARGO PLANES
(pounds of pollutants per 1,000 gallons of kerosene fuel)

	Precombustion (1)	**Combustion**	**Total**	**DQI**
Atmospheric Emissions				
Styrene	2.4E-09		2.4E-09	D
Toluene	0.048		0.048	D
Trichloroethane	7.0E-07		7.0E-07	D
Vinyl Acetate	7.3E-10		7.3E-10	D
Xylenes	0.028		0.028	D
Bromoform	3.7E-09		3.7E-09	D
Chloroform	5.6E-09		5.6E-09	D
Carbon Disulfide	1.2E-08		1.2E-08	D
Dimethyl Sulfate	4.6E-09		4.6E-09	D
Cumene	5.1E-10		5.1E-10	D
Cyanide	2.4E-07		2.4E-07	D
Perchloroethylene	9.6E-06		9.6E-06	D
Methylene Chloride	2.2E-04		2.2E-04	D
Carbon Tetrachloride	5.0E-06		5.0E-06	D
Phenols	1.1E-04		1.1E-04	D
Fluorides	1.7E-05		1.7E-05	D
Polyaromatic Hydrocarbons (total)	1.8E-05		1.8E-05	E
Biphenyl	3.0E-07		3.0E-07	E
Acenaphthene	9.1E-08		9.1E-08	E
Acenaphthylene	4.5E-08		4.5E-08	E
Anthracene	3.8E-08		3.8E-08	E
Benzo(a)anthracene	1.4E-08		1.4E-08	E
Benzo(a)pyrene	6.8E-09		6.8E-09	E
Benzo(b,j,k)fluroanthene	2.0E-08		2.0E-08	E
Benzo(g,h,i) perylene	4.8E-09		4.8E-09	E
Chrysene	1.8E-08		1.8E-08	E
Fluoranthene	1.3E-07		1.3E-07	E
Fluorene	1.6E-07		1.6E-07	E
Indeno(1,2,3-cd)pyrene	1.1E-08		1.1E-08	E
Naphthalene	2.3E-06		2.3E-06	E
Phenanthrene	4.8E-07		4.8E-07	E
Pyrene	5.9E-08		5.9E-08	E
5-methyl Chrysene	3.9E-09		3.9E-09	E
Dioxins (unspecified)	1.8E-07		1.8E-07	D
Furans (unspecified)	8.2E-10		8.2E-10	D
CFC12	8.3E-07		8.3E-07	D
Radionuclides (unspecified)	0.015		0.015	C
Waterborne Emissions				
Acid (unspecified)	0.0017		0.0017	E
Acid (benzoic)	0.028		0.028	E
Acid (hexanoic)	0.0058		0.0058	E
Metal (unspecified)	21.9		21.9	E
Dissolved Solids	1,236		1,236	E
Suspended Solids	73.5		73.5	E
BOD	0.70		0.70	E
COD	2.07		2.07	E
Phenol/Phenolic Compounds	0.014		0.014	E
Sulfur	0.073		0.073	E
Sulfates	2.21		2.21	E
Sulfides	0.0013		0.0013	E
Oil	0.64		0.64	E
Hydrocarbons	0.0055		0.0055	E
Ammonia	0.51		0.51	E
Ammonium	1.2E-04		1.2E-04	E
Aluminum	2.39		2.39	E
Antimony	0.0015		0.0015	E
Arsenic	0.0076		0.0076	E
Barium	32.7		32.7	E
Beryllium	4.2E-04		4.2E-04	E
Cadmium	0.0011		0.0011	E
Chromium (unspecified)	0.068		0.068	E
Cobalt	6.1E-04		6.1E-04	E
Copper	0.0078		0.0078	E

Table A-33 (Cont'd)

ENVIRONMENTAL EMISSIONS FOR
CARGO PLANES
(pounds of pollutants per 1,000 gallons of kerosene fuel)

	Precombustion (1)	Combustion	Total	DQI
Waterborne Emissions				
Iron	4.77		4.77	E
Lead	0.016		0.016	E
Lithium	1.54		1.54	E
Magnesium	17.4		17.4	E
Manganese	0.030		0.030	E
Mercury	2.6E-05		2.6E-05	E
Molybdenum	6.4E-04		6.4E-04	E
Nickel	0.0075		0.0075	E
Selenium	3.3E-04		3.3E-04	E
Silver	0.058		0.058	E
Sodium	282		282	E
Strontium	1.51		1.51	E
Thallium	3.1E-04		3.1E-04	E
Tin	0.0061		0.0061	E
Titanium	0.023		0.023	E
Vanadium	7.5E-04		7.5E-04	E
Yttrium	1.9E-04		1.9E-04	E
Zinc	0.055		0.055	E
Chlorides (unspecified)	1,002		1,002	E
Chlorides (methyl chloride)	1.1E-06		1.1E-06	E
Calcium	89.1		89.1	E
Fluorine/ Fluorides	0.0020		0.0020	E
Nitrates	3.0E-04		3.0E-04	E
Nitrogen (ammonia)	1.0E-04		1.0E-04	E
Bromide	5.94		5.94	E
Boron	0.087		0.087	E
Organic Carbon	0.0071		0.0071	E
Cyanide	2.0E-06		2.0E-06	E
Hardness	275		275	E
Total Alkalinity	2.19		2.19	E
Surfactants	0.023		0.023	E
Acetone	2.8E-04		2.8E-04	E
Alkylated Benzenes	0.0013		0.0013	E
Alkylated Fluorenes	7.6E-05		7.6E-05	E
Alkylated Naphthalenes	2.1E-05		2.1E-05	E
Alkylated Phenanthrenes	8.9E-06		8.9E-06	E
Benzene	0.047		0.047	E
Cresols	0.0016		0.0016	E
Cymene	2.8E-06		2.8E-06	E
Dibenzofuran	5.3E-06		5.3E-06	E
Dibenzothiophene	4.3E-06		4.3E-06	E
2,4 dimethylphenol	7.8E-04		7.8E-04	E
Ethylbenzene	0.0026		0.0026	E
2-Hexanone	1.8E-04		1.8E-04	E
Methyl ethyl Ketone (MEK)	2.2E-06		2.2E-06	E
1-methylfluorene	3.2E-06		3.2E-06	E
2-methyl naphthalene	4.4E-04		4.4E-04	E
4-methyl- 2-pentanone	1.2E-04		1.2E-04	E
Naphthalene	5.1E-04		5.1E-04	E
Pentamethyl benzene	2.1E-06		2.1E-06	E
Phenanthrene	7.7E-06		7.7E-06	E
Toluene	0.044		0.044	E
Total Biphenyls	8.5E-05		8.5E-05	E
Total dibenzo-thiophenes	2.6E-07		2.6E-07	E
Xylenes	0.023		0.023	E
Radionuclides (unspecified)	2.1E-07		2.1E-07	E
Solid Waste	361		361	C

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(1) Calculated from data in Tables A-1 through A-9. Includes process emissions from fuel extraction and processing steps, as well as emissions from the production and combustion of the fuels used for the extraction and processing steps.

References: A-74, A-85, A-121, and A-122.

Source: Franklin Associates, A Division of ERG

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GLOSSARY

Ash. Impurities in coal, consisting of silica, alumina, and other non-combustible matter. Ash increases the weight of coal, adds to the cost of handling, and can affect its burning characteristics.

Barrel (Petroleum). A unit of volume equal to 42 U.S. gallons.

Biological Oxygen Demand (BOD). An indication of the amount of organic material present in water or wastewater.

Biomass. The total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unit of the Earth's surface.

Bituminous Coal. A dense black coal, often with well-defined bands of bright and dull material, with a moisture content usually less than 20 percent. Often referred to as soft coal. It is the most common coal and is used primarily for generating electricity, making coke, and space heating.

Boiler. A device for generating steam for power, processing, or heating purposes or for producing hot water for heating purposes or hot water supply.

Btu (British thermal unit). A standard unit for measuring the quantity of heat energy equal to the quantity of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit.

Butane. A normally gaseous straight-chained or branched hydrocarbon (C_4H_{10}). It is extracted from natural gas or refinery gas streams. It includes isobutane and normal butane.

Coal. A black or brownish-black solid, combustible substance formed by the partial decomposition of vegetable matter without access to air. The rank of coal, which includes anthracite, bituminous coal, subbituminous coal, and lignite, is based on fixed carbon, volatile matter, and heating value. Coal rank indicates the progressive alteration, or coalification, from lignite to anthracite.

Combustion energy. The high heat value directly released when coal, fuel oil, natural gas, or wood are burned for energy consumption.

Combustion emissions. The environmental emissions directly emitted when coal, fuel oil, natural gas, or wood are burned for energy consumption.

Crude Oil. A mixture of hydrocarbons that exists in liquid phase in underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities.

Curie (Ci). The SI unit of radioactive decay. The quantity of any radioactive nuclide which undergoes $3.7x10^{10}$ disintegrations/sec.

Distillate Fuel Oil. A general classification for one of the petroleum fractions produced in conventional distillation operations. It is used primarily for space heating, on-and off-highway diesel engine fuel (including railroad engine fuel and fuel for agricultural machinery), and electric power generation. Included are products known as No. 1, No. 2, and No. 4 diesel fuels.

Fossil Fuel. Any naturally occurring organic fuel, such as petroleum, natural gas, or coal.

Fossil Fuel Steam-Electric Power Plant. An electricity generation plant in which the prime mover is a turbine rotated by high-pressure steam produced in a boiler by heat from burning fossil fuels.

Flue Gas Desulfurization Unit (Scrubber). Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Chemicals, such as lime, are used as the scrubbing media.

Fugitive Emissions. Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

Geothermal Energy. Energy from the internal heat of the earth, which may be residual heat, friction heat, or a result of radioactive decay. The heat is found in rocks and fluids at various depths and can be extracted by drilling and/or pumping.

Heat Content of a Quantity of Fuel, Gross. The total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce carbon dioxide and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat but is not counted as part of net content. Also referred to as the higher heating value. Btu conversion factors typically used by EIA represent gross heat content. Called combustion energy in this appendix.

Heat Content of a Quantity of Fuel, Net. The amount of usable heat energy released when a fuel is burned under conditions similar to those in which it is normally used. Also referred to as the lower heating value. Btu conversion factors typically used by EIA represent gross heat content.

Hydrocarbons: A subcategory of organic compounds which contain only hydrogen and carbon. These compounds may exist in either the gaseous, liquid, or solid phase, and have a molecular structure that varies from the simple to the very heavy and very complex. The category Non-Methane Hydrocarbons (NMHC) is sometimes used when methane is reported separately.

Hydroelectric Power Plant. A plant in which the turbine generators are driven by falling water.

Lease Condensate. A natural gas liquid recovered from gas well gas (associated and non-associated) in lease separators or natural gas field facilities. Lease condensate consists primarily of pentanes and heavier hydrocarbons.

Lignite. A brownish-black coal of low rank with a high content of moisture and volatile matter. Often referred to as brown coal.

Liquefied Petroleum Gases (LPG). Ethane, ethylene, propane, propylene, normal butane, butylene, isobutane, and isobutylene produced at refineries or natural gas processing plants, including plants that fractionate raw natural gas plant liquids.

Methane. A hydrocarbon gas (CH_4) that is the principal constituent of natural gas.

(**Motor) Gasoline.** A complex mixture of relatively volatile hydrocarbons, with or without small quantities of additives, that has been blended to form a fuel suitable for use in spark-ignition engines. “Motor gasoline” includes reformulated gasoline, oxygenated gasoline, and other finished gasoline.

Natural Gas. A mixture of hydrocarbons (principally methane) and small quantities of various nonhydrocarbons existing in the gaseous phase or in solution with crude oil in underground reservoirs.

Natural Gas Liquids (NGL). Those hydrocarbons in natural gas that are separated as liquids from the gas. Natural gas liquids include natural gas plant liquids (primarily ethane, propane, butane, and isobutane), and lease condensate (primarily pentanes produced from natural gas at lease separators and field facilities.)

Nitrogen oxides (NO_X). Compounds of nitrogen and oxygen produced by the burning of fossil fuels, or any other combustion process taking place in air. The two most important oxides in this category are nitrogen oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide (N_2O), however, is not included in this category and is considered separately.

Non-Methane Volatile Organic Compounds. Organic compounds, other than methane, that participate in atmospheric photochemical reactions.

Other organics. Compounds containing carbon combined with hydrogen and other elements such as oxygen, nitrogen, sulfur or others. Compounds containing only carbon and hydrogen are classified as hydrocarbons and are not included in this category.

Particulate Matter (Particulates): Small solid particles or liquid droplets suspended in the atmosphere, ranging in size from 0.005 to 500 microns.

Particulates are usually characterized as primary or secondary. Primary particulates, usually 0.1 to 20 microns in size, are those injected directly into the atmosphere by chemical or physical processes. Secondary particulates are produced as a result of chemical reactions that take place in the atmosphere. In our reports, particulates refer only to primary particulates.

Particulates reported by Franklin Associates are not limited by size range, and are sometimes called total suspended particulates (TSP). The category PM-10 refers to all particulates less than 10 microns in (aerodynamic) diameter. This classification is sometimes used when health effects are being considered, since the human nasal passages will filter and reject any particles larger than 10 microns.

Precombustion energy. The energy required for the production and processing of energy fuels, such as coal, fuel oil, natural gas, or uranium, starting with their extraction from the ground, up to the point of delivery to the customer.

Precombustion fuel-related emissions. The environmental emissions due to the combustion of fuels used in the production and processing of the primary fuels; coal, fuel oil, natural gas, and uranium.

Precombustion process emissions. The environmental emissions due to the production and processing of the primary fuels; coal, fuel oil, natural gas, and uranium, that are process rather than fuel-related emissions.

Petroleum. A generic term applied to oil and oil products in all forms, such as crude oil, lease condensate, unfinished oils, petroleum products, natural gas plant liquids, and nonhydrocarbon compounds blended into finished petroleum products.

Plant Condensate. One of the natural gas liquids (NGLs), mostly pentanes and heavier hydrocarbons, recovered and separated as liquids at gas inlet separators or scrubbers in processing plants.

Processing Plant (natural gas). A surface installation designed to separate and recover natural gas liquids from a stream of produced natural gas through the process of condensation, absorption, refrigeration, or other methods, and to control the quality of natural gas marketed or returned to oil or gas reservoirs for pressure maintenance, repressuring, or cycling.

Refinery (petroleum). An installation that manufactures finished petroleum products from crude oil, unfinished oils, natural gas liquids, other hydrocarbons, and alcohol.

Residual Fuel Oil. The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Included are No. 5, No. 6, and Navy Special. It is used for commercial and industrial heating, electricity generation, and to power ships.

Subbituminous Coal. A dull, black coal of rank intermediate between lignite and bituminous coal.

Sulfur oxides (SO_X). Compounds of sulfur and oxygen, such as sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Total Dissolved Solids (TDS). The TDS in water consists of inorganic salts, minute organic particles, and dissolved materials. IN natural waters, salts are chemical compounds composed of anions such as carbonates, chlorides, sulfates, and nitrates, and cations such as potassium, magnesium, calcium, and sodium.

Total Suspended Solids (TSS). TSS gives a measure of the turbidity of the water. Suspended solids cause the water to be milky or muddy looking due to the light scattering from very small particles in the water.

Volatile Organic Compounds (VOCs). Organic compounds that participate in atmospheric chemical reactions.

Uranium. A heavy naturally radioactive metallic element (atomic number 92). Its two principally occurring isotopes are ^{235}U and ^{238}U. ^{235}U is indispensable to the nuclear industry, because it is the only isotope existing in nature to any appreciable extent that is fissionable by thermal neutrons. ^{238}U is also important, because it absorbs neutrons to produce a radioactive isotope that subsequently decays to ^{239}Pu, an isotope that also is fissionable by thermal neutrons.

Uranium ore. Rock containing uranium mineralization, typically 0.05 to 0.2 percent U_3O_8.

APPENDIX B

HIGH-DENSITY POLYETHYLENE

INTRODUCTION

This appendix discusses the manufacture of high-density polyethylene (HDPE) resin. Large amounts of HDPE resin are used to manufacture blow-molded bottles, piping, film, and pails. Almost 16 billion pounds of HDPE was produced in the U.S. and Canada in 2003 (Reference B-1). The material flow for HDPE resin is shown in Figure B-1. The total unit process energy and emissions data (cradle-to-HDPE) for HDPE are displayed in Table B-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. The following processes are included in this appendix:

- Crude oil production
- Distillation, desalting, and hydrotreating
- Natural gas production
- Natural gas processing
- Olefins (Ethylene) production
- HDPE resin production

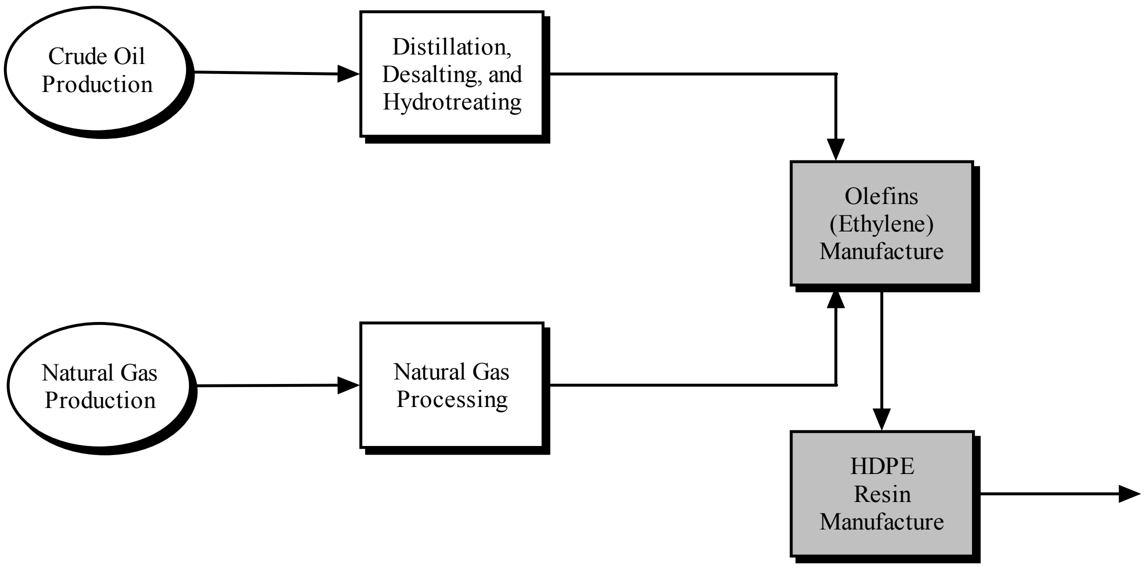


Figure B-1. Flow diagram for the manufacture of virgin high-density polyethylene (HDPE) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

Table B-1

DATA FOR THE PRODUCTION OF HIGH-DENSITY POLYETHYLENE (HDPE) RESIN

(Cradle-to-Resin)

(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	191	lb		191	kg	
Natural Gas	845	lb		845	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			19,664			45.8
Petroleum			3,722			8.66
Total Resource			23,386			54.4
Process Energy						
Electricity (grid)	160	kwh	1,699	352	kwh	3.96
Electricity (cogeneration)	130	kwh	- (2)	287	kwh	-
Natural gas	4,860	cu ft	5,444	303	cu meters	12.7
LPG	0.034	gal	3.67	0.28	liter	0.0085
Distillate oil	0.18	gal	29.1	1.53	liter	0.068
Residual oil	1.52	gal	262	12.7	liter	0.61
Gasoline	0.11	gal	16.1	0.94	liter	0.037
Diesel	0.0094	gal	1.50	0.079	liter	0.0035
Internal Offgas use (1)						
From Oil	33.3	lb	792	33.3	kg	1.84
From Natural Gas	152	lb	3,608	152	kg	8.40
Recovered Energy	11.9	thousand Btu	11.9	27.6	MJ	0.028
Total Process			11,844			27.6
Transportation Energy						
Combination truck	7.56	ton-miles		24.32	tonne-km	
Diesel	0.079	gal	12.6	0.66	liter	0.029
Rail	6.53	ton-miles		21.00	tonne-km	
Diesel	0.017	gal	2.66	0.14	liter	0.0062
Barge	15.56	ton-miles		50.08	tonne-km	
Diesel	0.013	gal	2.05	0.11	liter	0.0048
Residual oil	0.043	gal	7.35	0.36	liter	0.017
Ocean freighter	320	ton-miles		1029	tonne-km	
Diesel	0.061	gal	9.65	0.51	liter	0.022
Residual	0.55	gal	93.8	4.56	liter	0.22
Pipeline-natural gas	470	ton-miles		1512	tonne-km	
Natural gas	324	cu ft	363	20.2	cu meter	0.84
Pipeline-petroleum products	124	ton-miles		400.5	tonne-km	
Electricity	2.71	kwh	27.8	5.98	kwh	0.065
Total Transportation			519			1.21

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table B-1

DATA FOR THE PRODUCTION
OF HIGH-DENSITY POLYETHYLENE (HDPE) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)	SI units (Basis: 1,000 kg)
Environmental Emissions		
Atmospheric Emissions		
Aldehydes	0.013 lb	0.013 kg
Ammonia	0.0064 lb	0.0064 kg
Benzene	0.090 lb	0.090 kg
Carbon Dioxide (fossil)	76.9 lb	76.9 kg
Carbon Monoxide	4.22 lb	4.22 kg
Carbon Tetrachloride	3.7E-09 lb	3.7E-09 kg
Chlorine	9.9E-05 lb	9.9E-05 kg
Ethylbenzene	0.011 lb	0.011 kg
HCFC-22	9.9E-07 lb	9.9E-07 kg
Hydrocarbons (NM)	1.13 lb	1.13 kg
Hydrogen	0.0039 lb	0.0039 kg
Hydrogen Chloride	9.9E-07 lb	9.9E-07 kg
Methane	12.9 lb	12.9 kg
Nitrogen Oxides	0.13 lb	0.13 kg
Other Organics	0.011 lb	0.011 kg
Particulates (unknown)	0.10 lb	0.10 kg
PM2.5	0.012 lb	0.012 kg
PM10	0.14 lb	0.14 kg
Sulfur Oxides	23.6 lb	23.6 kg
Toluene	0.14 lb	0.14 kg
Trichloroethane	3.0E-08 lb	3.0E-08 kg
VOC	0.73 lb	0.73 kg
Xylene	0.082 lb	0.082 kg
Solid Wastes		
Landfilled	29.5 lb	29.5 kg
Burned	3.84 lb	3.84 kg
Waste-to-Energy	0.027 lb	0.027 kg
Waterborne Wastes		
1-Methylfluorene	5.1E-07 lb	5.1E-07 kg
2,4-Dimethylphenol	1.3E-04 lb	1.3E-04 kg
2-Hexanone	2.9E-05 lb	2.9E-05 kg
2-Methylnapthalene	7.2E-05 lb	7.2E-05 kg
4-Methyl-2-Pentanone	1.9E-05 lb	1.9E-05 kg
Acetone	4.5E-05 lb	4.5E-05 kg
Alkylated benzenes	7.5E-05 lb	7.5E-05 kg
Alkylated fluorenes	4.3E-06 lb	4.3E-06 kg
Alkylated naphthalenes	1.2E-06 lb	1.2E-06 kg
Alkylated phenanthrenes	5.1E-07 lb	5.1E-07 kg
Alkalinity	0.36 lb	0.36 kg
Aluminum	0.14 lb	0.14 kg
Ammonia	0.062 lb	0.062 kg
Antimony	8.5E-05 lb	8.5E-05 kg
Arsenic	0.0010 lb	0.0010 kg
Barium	2.01 lb	2.01 kg
Benzene	0.0076 lb	0.0076 kg
Benzoic acid	0.0046 lb	0.0046 kg
Beryllium	4.9E-05 lb	4.9E-05 kg
BOD	0.80 lb	0.80 kg
Boron	0.014 lb	0.014 kg
Bromide	0.97 lb	0.97 kg
Cadmium	1.5E-04 lb	1.5E-04 kg
Calcium	14.5 lb	14.5 kg
Chlorides	163 lb	163 kg
Chromium (unspecified)	0.0039 lb	0.0039 kg
Chromium (hexavalent)	1.1E-05 lb	1.1E-05 kg
Cobalt	1.0E-04 lb	1.0E-04 kg
COD	1.38 lb	1.38 kg
Copper	7.5E-04 lb	7.5E-04 kg
Cyanide	3.3E-07 lb	3.3E-07 kg
Dibenzofuran	8.6E-07 lb	8.6E-07 kg
Dibenzothiophene	7.0E-07 lb	7.0E-07 kg

Table B-1

DATA FOR THE PRODUCTION OF HIGH-DENSITY POLYETHYLENE (HDPE) RESIN
(Cradle-to-Resin)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Dissolved Solids	201	lb	201	kg
Ethylbenzene	4.4E-04	lb	4.4E-04	kg
Fluorine	2.4E-06	lb	2.4E-06	kg
Furans	1.0E-06	lb	1.0E-06	kg
Hardness	44.7	lb	44.7	kg
Hexanoic acid	9.5E-04	lb	9.5E-04	kg
Hydrocarbon	0.0010	lb	0.0010	kg
Iron	0.35	lb	0.35	kg
Lead	0.0016	lb	0.0016	kg
Lead 210	4.7E-13	lb	4.7E-13	kg
Lithium	4.02	lb	4.02	kg
Magnesium	2.84	lb	2.84	kg
Manganese	0.0046	lb	0.0046	kg
Mercury	1.5E-06	lb	1.5E-06	kg
Methylchloride	1.8E-07	lb	1.8E-07	kg
Methyl Ethyl Ketone	3.6E-07	lb	3.6E-07	kg
Molybdenum	1.0E-04	lb	1.0E-04	kg
m-Xylene	1.4E-04	lb	1.4E-04	kg
Naphthalene	8.2E-05	lb	8.2E-05	kg
n-Decane	1.3E-04	lb	1.3E-04	kg
n-Docosane	4.8E-06	lb	4.8E-06	kg
n-Dodecane	2.5E-04	lb	2.5E-04	kg
n-Eicosane	6.9E-05	lb	6.9E-05	kg
n-Hexacosane	3.0E-06	lb	3.0E-06	kg
n-Hexadecane	2.7E-04	lb	2.7E-04	kg
Nickel	8.7E-04	lb	8.7E-04	kg
n-Octadecane	6.7E-05	lb	6.7E-05	kg
n-Tetradecane	1.1E-04	lb	1.1E-04	kg
o + p-Xylene	1.0E-04	lb	1.0E-04	kg
o-Cresol	1.3E-04	lb	1.3E-04	kg
Oil and grease	0.095	lb	0.095	kg
p-Cresol	1.4E-04	lb	1.4E-04	kg
p-Cymene	4.5E-07	lb	4.5E-07	kg
Pentamethylbenzene	3.4E-07	lb	3.4E-07	kg
Phenanthrene	7.0E-07	lb	7.0E-07	kg
Phenol	0.0031	lb	0.0031	kg
Phosphorus	1.0E-04	lb	1.0E-04	kg
Process solvents	1.0E-04	lb	1.0E-04	kg
Radium 226	1.6E-10	lb	1.6E-10	kg
Radium 228	8.4E-13	lb	8.4E-13	kg
Selenium	1.7E-05	lb	1.7E-05	kg
Silver	0.0095	lb	0.0095	kg
Sodium	46.0	lb	46.0	kg
Strontium	0.25	lb	0.25	kg
Styrene	9.9E-07	lb	9.9E-07	kg
Sulfates	0.33	lb	0.33	kg
Sulfides	5.8E-05	lb	5.8E-05	kg
Sulfur	0.012	lb	0.012	kg
Surfactants	0.0044	lb	0.0044	kg
Suspended Solids	4.56	lb	4.56	kg
Thallium	1.8E-05	lb	1.8E-05	kg
Tin	5.9E-04	lb	5.9E-04	kg
Titanium	0.0013	lb	0.0013	kg
TOC	0.0010	lb	0.0010	kg
Toluene	0.0073	lb	0.0073	kg
Total biphenyls	4.8E-06	lb	4.8E-06	kg
Total dibenzothiophenes	1.5E-08	lb	1.5E-08	kg
Vanadium	1.2E-04	lb	1.2E-04	kg
Xylene (unspecified)	0.0036	lb	0.0036	kg
Yttrium	3.0E-05	lb	3.0E-05	kg
Zinc	0.0035	lb	0.0035	kg

References: Tables B-2 through B-7

Source: Franklin Associates, A Division of ERG models

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 energy to drive pumps that lift oil to the surface. Once oil is on the surface, it is separated from water and stored in tanks before being transported to a refinery. In some cases it is immediately transferred to a pipeline that 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 in order to remove the oil from the water. These separators are very efficient and leave minimal oil in the water.

According to the American Petroleum Institute, 17.9 billion barrels of brine water were produced from crude oil production in 1995 (Reference B-2). This equates to a ratio of 5.4 barrels of water per barrel of oil. The majority of this water (85 percent) is produced by onshore oil production facilities and, since such facilities are prohibited from discharging to surface water (Reference B-3), is injected into wells specifically designed for production-related waters. The remaining 15 percent of water discharges are from offshore oil production facilities and are assumed to be released to the ocean. Therefore, all waterborne wastes from crude oil production are attributable to the water released from offshore production (Reference B-4). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (Reference B-2).

Evolving technologies are reducing the amount of brine that is extracted during oil recovery and minimizing the environmental impact of discharged brine. For example, downhole separation is a technology that separates brine from oil before bringing it to the surface; the brine is injected into subsurface injection zones. The freeze-thaw evaporation (FTE) process is another technology that reduces the discharge of brine water by using a freeze crystallization process in the winter and a natural evaporation process in the summer to extract fresh water from brine water; the fresh water can be used for horticulture or agriculture applications (Reference B-5).

The second source of waste is gas produced from oil wells. The majority of this gas is recovered for sale, but some is released to the atmosphere. 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 amount of methane released from crude oil production was calculated from EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks, which has data specific to oil field emissions (Reference B-6).

The requirements for transporting crude oil from the production field to the Gulf Coast of the United States (where most petroleum refining in the United States occurs) were calculated from foreign and domestic supply data, port-to-port distance data, and domestic petroleum movement data (References B-7 and B-8). Based on 2001 foreign and domestic supply data, 62 percent of the United States crude oil supply is from foreign sources, 6 percent is from Alaska, and the remaining 32 percent is from the lower 48 states. These percentages were used to apportion transportation requirements among different transportation modes. With the exception of Canada, which transports crude oil to the United States by pipeline, foreign suppliers transport crude oil to the United States by ocean tanker. (In 2001, Saudi Arabia, Mexico, Canada, Venezuela, and Nigeria were the top five foreign suppliers of crude oil to the United States.) The transportation of crude oil from Alaska to the lower 48 states is also accomplished by ocean tanker. Domestic transportation of crude oil is accomplished by pipeline and barge.

Table B-2 shows the energy requirements and emissions for the extraction of crude oil.

Distillation, Desalting, and Hydrotreating

A petroleum refinery processes crude oil into thousands of products using physical and/or chemical processing technology. A petroleum refinery receives crude oil, which is comprised of mixtures of many hydrocarbon compounds and uses distillation processes to separate pure product streams. Because the crude oil is contaminated (to varying degrees) with compounds of sulfur, nitrogen, oxygen, and metals, cleaning operations are common in all refineries. Also, the natural hydrocarbon components that comprise crude oil are often chemically changed to yield products for which there is higher demand. These processes, such as polymerization, alkylation, reforming, and visbreaking, are used to convert light or heavy crude oil fractions into intermediate weight products, which are more easily handled and used as fuels and/or feedstocks (Reference B-18).

Table B-2

DATA FOR THE EXTRACTION OF CRUDE OIL
(page 1 of 2)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Petroleum	1,035	lb	19,538	1,035	kg	45.4
Total Resource			19,538			45.4
Process Energy						
Electricity (grid)	17.7	kwh	188	39.0	kwh	0.44
Natural gas	525	cu ft	588	32.8	cu meters	1.37
Distillate oil	0.15	gal	24.6	1.29	liter	0.057
Residual oil	0.10	gal	16.4	0.80	liter	0.038
Gasoline	0.082	gal	11.7	0.68	liter	0.027
Total Process			829			1.93
Transportation Energy						
Barge	0.37	ton-miles		1.21	tonne-km	
Diesel	3.0E-04	gal	0.048	0.0025	liter	1.1E-04
Residual oil	0.0010	gal	0.17	0.0083	liter	4.0E-04
Ocean freighter	1,472	ton-miles		4738	tonne-km	
Diesel	0.28	gal	44.4	2.33	liter	0.10
Residual	2.52	gal	432	21.0	liter	1.00
Pipeline-petroleum products	196	ton-miles		631	tonne-km	
Electricity	4.27	kwh	43.8	9.42	kwh	0.10
Total Transportation			520			1.21
Environmental Emissions						
Atmospheric Emissions						
Methane	3.53	lb		3.53	kg	
Solid Wastes						
Landfilled	26.1	lb		26.1	kg	
Waterborne Wastes						
1-Methylfluorene	4.0E-07	lb		4.0E-07	kg	
2,4-Dimethylphenol	1.0E-04	lb		1.0E-04	kg	
2-Hexanone	2.3E-05	lb		2.3E-05	kg	
2-Methylnaphthalene	5.6E-05	lb		5.6E-05	kg	
4-Methyl-2-Pentanone	1.5E-05	lb		1.5E-05	kg	
Acetone	3.6E-05	lb		3.6E-05	kg	
Alkylated benzenes	1.7E-04	lb		1.7E-04	kg	
Alkylated fluorenes	1.0E-05	lb		1.0E-05	kg	
Alkylated naphthalenes	2.9E-06	lb		2.9E-06	kg	
Alkylated phenanthrenes	1.2E-06	lb		1.2E-06	kg	
Aluminum	0.32	lb		0.32	kg	
Ammonia	0.053	lb		0.053	kg	
Antimony	2.0E-04	lb		2.0E-04	kg	
Arsenic	9.8E-04	lb		9.8E-04	kg	
Barium	4.36	lb		4.36	kg	
Benzene	0.0060	lb		0.0060	kg	
Benzoic acid	0.0036	lb		0.0036	kg	
Beryllium	5.5E-05	lb		5.5E-05	kg	
BOD	0.62	lb		0.62	kg	
Boron	0.011	lb		0.011	kg	
Bromide	0.76	lb		0.76	kg	
Cadmium	1.5E-04	lb		1.5E-04	kg	
Calcium	11.4	lb		11.4	kg	
Chlorides	128	lb		128	kg	
Chromium	0.0085	lb		0.0085	kg	
Cobalt	7.9E-05	lb		7.9E-05	kg	
COD	1.02	lb		1.02	kg	
Copper	0.0010	lb		0.0010	kg	

Table B-2

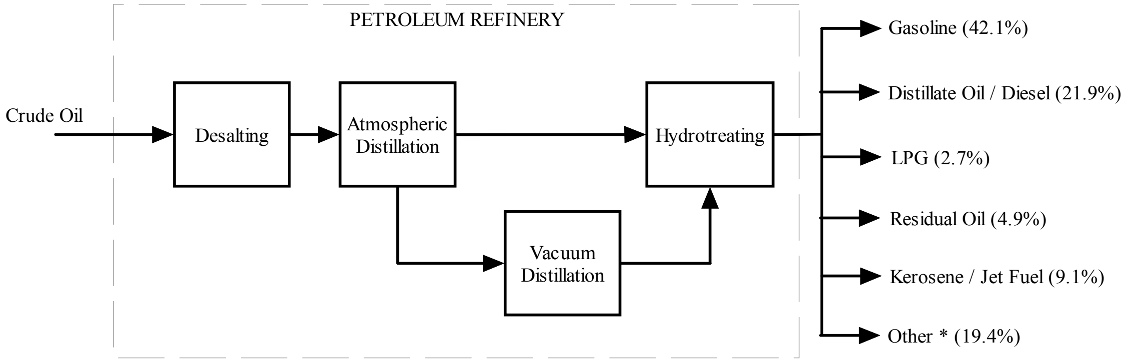
DATA FOR THE EXTRACTION OF CRUDE OIL
(page 2 of 2)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Cyanide	2.6E-07	lb	2.6E-07	kg
Dibenzofuran	6.8E-07	lb	6.8E-07	kg
Dibenzothiophene	5.5E-07	lb	5.5E-07	kg
Ethylbenzene	3.4E-04	lb	3.4E-04	kg
Fluorine	5.0E-06	lb	5.0E-06	kg
Hardness	35.2	lb	35.2	kg
Hexanoic acid	7.5E-04	lb	7.5E-04	kg
Iron	0.63	lb	0.63	kg
Lead	0.0021	lb	0.0021	kg
Lead 210	3.7E-13	lb	3.7E-13	kg
Lithium	0.0038	lb	0.0038	kg
Magnesium	2.23	lb	2.23	kg
Manganese	0.0036	lb	0.0036	kg
Mercury	3.5E-06	lb	3.5E-06	kg
Methylchloride	1.4E-07	lb	1.4E-07	kg
Methyl Ethyl Ketone	2.9E-07	lb	2.9E-07	kg
Molybdenum	8.2E-05	lb	8.2E-05	kg
m-Xylene	1.1E-04	lb	1.1E-04	kg
Naphthalene	6.5E-05	lb	6.5E-05	kg
n-Decane	1.0E-04	lb	1.0E-04	kg
n-Docosane	3.8E-06	lb	3.8E-06	kg
n-Dodecane	2.0E-04	lb	2.0E-04	kg
n-Eicosane	5.4E-05	lb	5.4E-05	kg
n-Hexacosane	2.4E-06	lb	2.4E-06	kg
n-Hexadecane	2.1E-04	lb	2.1E-04	kg
Nickel	9.8E-04	lb	9.8E-04	kg
n-Octadecane	5.3E-05	lb	5.3E-05	kg
n-Tetradecane	8.6E-05	lb	8.6E-05	kg
o + p-Xylene	7.8E-05	lb	7.8E-05	kg
o-Cresol	1.0E-04	lb	1.0E-04	kg
Oil and grease	0.072	lb	0.072	kg
p-Cresol	1.1E-04	lb	1.1E-04	kg
p-Cymene	3.6E-07	lb	3.6E-07	kg
Pentamethylbenzene	2.7E-07	lb	2.7E-07	kg
Phenanthrene	1.0E-06	lb	1.0E-06	kg
Phenol	0.0016	lb	0.0016	kg
Radium 226	1.3E-10	lb	1.3E-10	kg
Radium 228	6.6E-13	lb	6.6E-13	kg
Selenium	3.9E-05	lb	3.9E-05	kg
Silver	0.0075	lb	0.0075	kg
Sodium	36.2	lb	36.2	kg
Strontium	0.19	lb	0.19	kg
Sulfates	0.26	lb	0.26	kg
Sulfur	0.0094	lb	0.0094	kg
Surfactants	0.0030	lb	0.0030	kg
Thallium	4.2E-05	lb	4.2E-05	kg
Tin	8.0E-04	lb	8.0E-04	kg
Titanium	0.0031	lb	0.0031	kg
Toluene	0.0056	lb	0.0056	kg
Total Alkalinity	0.28	lb	0.28	kg
Total biphenyls	1.1E-05	lb	1.1E-05	kg
Total dibenzothiophenes	3.5E-08	lb	3.5E-08	kg
Total dissolved solids	158	lb	158	kg
Total suspended solids	9.77	lb	9.77	kg
Vanadium	9.7E-05	lb	9.7E-05	kg
Xylene	0.0028	lb	0.0028	kg
Yttrium	2.4E-05	lb	2.4E-05	kg
Zinc	0.0073	lb	0.0073	kg

References: B-2, B-6, and B-8 through B-17

Source: Franklin Associates, A Division of ERG

This module includes data for desalting, atmospheric distillation, vacuum distillation, and hydrotreating. These are the most energy-intensive processes of a petroleum refinery, representing over 95 percent of the total energy requirements of U.S. petroleum refineries (Reference B-19). Data for cracking, reforming, and supporting processes are not available and are not included in this module. The following figure is a simplified flow diagram of the material flows and processes included in this module.



Simplified flow diagram for petroleum refinery operations for the production of fuels.
All arrows represent material flows. The percentages of refinery products represent percent by mass of total refinery output.
* "Other" category includes still gas, petroleum coke, asphalt, and petrochemical feedstocks.

Air pollution is caused by various petroleum refining processes, including vacuum distillation, catalytic cracking, thermal cracking processes, and sulfur recovery. Fugitive emissions also contribute significantly to air emissions. Fugitive emissions include leaks from valves, seals, flanges, and drains, as well as leaks escaping from storage tanks or during transfer operations. The wastewater treatment plant for a refinery is also a source of fugitive emissions (Reference B-20).

This module expresses data on the basis 1,000 pounds of general refinery product as well as data allocated to specific refinery products. The data are allocated to specific refinery products based on the percent by mass of each product in the refinery output. The mass allocation method assigns energy requirements and environmental emissions equally to all refinery products -- equal masses of different refinery products are assigned equal energy and emissions.

Mass allocation is not the only method that can be used for assigning energy and emissions to refinery products. Heat of combustion and economic value are two additional methods for co-product allocation. Using heat of combustion of refinery products yields allocation factors similar to those derived by mass allocation, demonstrating the correlation between mass and heat of combustion. Economic allocation is complicated because market values fluctuate with supply and demand, and market data are not available for refinery products such as asphalt. This module does not apply the heat of combustion or economic allocation methods because they have no apparent advantage over mass allocation.

Co-product function expansion is yet another method for allocating environmental burdens among refinery products. Co-product function expansion is more complex than mass, heat of combustion, or economic allocation; it evaluates downstream processes and product substitutes in order to determine the percentage of total energy and emissions to assign to each refinery product. This module does not use the co-product function expansion method because it is outside the scope of this project.

There are advantages and disadvantages for each type of allocation method. Until detailed data are available for the material flows and individual processes within a refinery, life cycle practitioners will have to resort to allocation methods such as those discussed above.

The energy requirements and emissions for the refining of petroleum are found in Table B-3.

Natural Gas Production

Natural gas is a widely used energy resource, since it is a relatively clean, efficient, and versatile fuel. The major component of natural gas is methane (CH_4). Other components of natural gas include ethane, propane, butane, and other heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen, and hydrogen sulfides.

Natural gas is extracted from deep underground wells and is frequently co-produced with crude oil. Because of its gaseous nature, natural gas flows quite freely from wells which produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. An estimated 80 percent of natural gas is extracted onshore and 20 percent is extracted offshore (Reference B-12).

Atmospheric emissions from natural gas production result primarily from unflared venting. Methane and non-combustion carbon dioxide emissions from natural gas extraction are generally process related, with the largest source of these emissions from normal operations, system upsets, and routine maintenance. Waterborne wastes result from brines that occur when natural gas is produced in combination with oil. In cases where data represent both crude oil and natural gas extraction, the data module allocates environmental emissions based on the percent weight of natural gas produced. The data module also apportions environmental emissions according to the percent share of onshore and offshore extraction.

Energy data for natural gas production were calculated from fuel consumption data for the crude oil and natural gas extraction industry (Reference B-21). The energy and emissions data for the production of natural gas is displayed in Table B-4.

Table B-3

DATA FOR THE REFINING OF PETROLEUM PRODUCTS

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude Oil	1,034	lb		1,034	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	64.9	kwh	691	143	kwh	1.61
Natural gas	178	cu ft	199	11.1	cu meters	0.46
LPG	0.14	gal	14.9	1.15	liter	0.035
Residual oil	3.26	gal	560	27.2	liter	1.30
Total Process			1,465			3.41
Transportation Energy						
Combination truck	13.6	ton-miles		43.93	tonne-km	
Diesel	0.14	gal	22.8	1.20	liter	0.053
Rail	8.70	ton-miles		28.01	tonne-km	
Diesel	0.02	gal	3.4	0.18	liter	0.0080
Barge	73.7	ton-miles		237.3	tonne-km	
Diesel	0.06	gal	9.4	0.49	liter	0.022
Residual oil	0.20	gal	33.7	1.64	liter	0.078
Pipeline-petroleum products	107	ton-miles		344.7	tonne-km	
Electricity	2.335	kwh	23.92	5.15	kwh	0.056
Total Transportation			93.1			0.22
Environmental Emissions						
Atmospheric Emissions						
Aldehydes	0.042	lb		0.042	kg	
Ammonia	0.021	lb		0.021	kg	
Carbon monoxide	13.3	lb		13.3	kg	
Carbon tetrachloride	1.2E-08	lb		1.2E-08	kg	
CFC12	1.2E-07	lb		1.2E-07	kg	
Hydrocarbons (non-methane)	2.03	lb		2.03	kg	
Methane	0.071	lb		0.071	kg	
NOx	0.33	lb		0.33	kg	
Particulates (unspecified PM)	0.24	lb		0.24	kg	
SOx (unspecified)	2.35	lb		2.35	kg	
Trichloroethane	9.7E-08	lb		9.7E-08	kg	
Solid Wastes						
Landfilled	5.60	lb		5.60	kg	
Waterborne Wastes						
BOD5	0.034	lb		0.034	kg	
COD	0.23	lb		0.23	kg	
Chromium (hexavalent)	3.7E-05	lb		3.7E-05	kg	
Chromium (unspecified)	5.7E-04	lb		5.7E-04	kg	
Nitrogen (as ammonia)	0.015	lb		0.015	kg	
Oil and Grease	0.011	lb		0.011	kg	
Phenolic Compounds	2.3E-04	lb		2.3E-04	kg	
Sulfide	1.9E-04	lb		1.9E-04	kg	
Total Suspended Solids	0.028	lb		0.028	kg	

References: B-6, B-16, B-17, and B-22 through B-26

Source: Franklin Associates, A Division of ERG

Table B-4

DATA FOR THE EXTRACTION OF NATURAL GAS
(page 1 of 2)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas	1,038	lb	23,265	1,038	kg	54.1
Total Resource			23,265			54.1
Process Energy						
Electricity (grid)	17.7	kwh	188	39.0	kwh	0.44
Natural gas	525	cu ft	588	32.8	cu meters	1.37
Distillate oil	0.15	gal	24.6	1.29	liter	0.057
Residual oil	0.10	gal	16.4	0.8	liter	0.038
Gasoline	0.082	gal	11.7	0.68	liter	0.027
Total Process			829			1.93
Environmental Emissions						
Atmospheric Emissions						
Methane	11.9	lb		11.9	kg	
Carbon dioxide (fossil)	79.6	lb		79.6	kg	
Solid Wastes						
Landfilled	24.7	lb		24.7	kg	
Waterborne Wastes						
1-Methylfluorene	4.9E-07	lb		4.9E-07	kg	
2,4-Dimethylphenol	1.2E-04	lb		1.2E-04	kg	
2-Hexanone	2.8E-05	lb		2.8E-05	kg	
2-Methylnapthalene	6.8E-05	lb		6.8E-05	kg	
4-Methyl-2-Pentanone	1.8E-05	lb		1.8E-05	kg	
Acetone	4.3E-05	lb		4.3E-05	kg	
Alkylated benzenes	4.2E-05	lb		4.2E-05	kg	
Alkylated fluorenes	2.4E-06	lb		2.4E-06	kg	
Alkylated naphthalenes	6.9E-07	lb		6.9E-07	kg	
Alkylated phenanthrenes	2.9E-07	lb		2.9E-07	kg	
Aluminum	0.079	lb		0.079	kg	
Nitrogen (as ammonia)	0.053	lb		0.053	kg	
Antimony	4.8E-05	lb		4.8E-05	kg	
Arsenic	9.5E-04	lb		9.5E-04	kg	
Barium	1.22	lb		1.22	kg	
Benzene	0.0072	lb		0.0072	kg	
Benzoic acid	0.0044	lb		0.0044	kg	
Beryllium	4.3E-05	lb		4.3E-05	kg	
BOD	0.75	lb		0.75	kg	
Boron	0.013	lb		0.013	kg	
Bromide	0.92	lb		0.92	kg	
Cadmium	1.4E-04	lb		1.4E-04	kg	
Calcium	13.8	lb		13.8	kg	
Chlorides	155	lb		155	kg	
Chromium (unspecified)	0.0022	lb		0.0022	kg	
Cobalt	9.5E-05	lb		9.5E-05	kg	
COD	1.24	lb		1.24	kg	
Copper	6.1E-04	lb		6.1E-04	kg	
Cyanide	3.1E-07	lb		3.1E-07	kg	
Dibenzofuran	8.2E-07	lb		8.2E-07	kg	
Dibenzothiophene	6.6E-07	lb		6.6E-07	kg	
Ethylbenzene	4.1E-04	lb		4.1E-04	kg	
Fluorine	1.5E-06	lb		1.5E-06	kg	

Table B-4

DATA FOR THE EXTRACTION OF NATURAL GAS
(page 2 of 2)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Hardness	42.6	lb	42.6	kg
Hexanoic acid	9.0E-04	lb	9.0E-04	kg
Iron	0.25	lb	0.25	kg
Lead	0.0014	lb	0.0014	kg
Lead 210	4.5E-13	lb	4.5E-13	kg
Lithium	4.62	lb	4.62	kg
Magnesium	2.70	lb	2.70	kg
Manganese	0.0044	lb	0.0044	kg
Mercury	8.4E-07	lb	8.4E-07	kg
Methylchloride	1.7E-07	lb	1.7E-07	kg
Methyl Ethyl Ketone	3.5E-07	lb	3.5E-07	kg
Molybdenum	9.9E-05	lb	9.9E-05	kg
m-Xylene	1.3E-04	lb	1.3E-04	kg
Naphthalene	7.8E-05	lb	7.8E-05	kg
n-Decane	1.3E-04	lb	1.3E-04	kg
n-Docosane	4.6E-06	lb	4.6E-06	kg
n-Dodecane	2.4E-04	lb	2.4E-04	kg
n-Eicosane	6.5E-05	lb	6.5E-05	kg
n-Hexacosane	2.9E-06	lb	2.9E-06	kg
n-Hexadecane	2.6E-04	lb	2.6E-04	kg
Nickel	7.5E-04	lb	7.5E-04	kg
n-Octadecane	6.4E-05	lb	6.4E-05	kg
n-Tetradecane	1.0E-04	lb	1.0E-04	kg
o + p-Xylene	9.5E-05	lb	9.5E-05	kg
o-Cresol	1.2E-04	lb	1.2E-04	kg
Oil and grease	0.083	lb	0.083	kg
p-Cresol	1.3E-04	lb	1.3E-04	kg
p-Cymene	4.3E-07	lb	4.3E-07	kg
Pentamethylbenzene	3.2E-07	lb	3.2E-07	kg
Phenanthrene	5.5E-07	lb	5.5E-07	kg
Phenolic compounds	0.0019	lb	0.0019	kg
Radium 226	1.6E-10	lb	1.6E-10	kg
Radium 228	8.0E-13	lb	8.0E-13	kg
Selenium	9.5E-06	lb	9.5E-06	kg
Silver	0.0090	lb	0.0090	kg
Sodium	43.8	lb	43.8	kg
Strontium	0.23	lb	0.23	kg
Sulfates	0.32	lb	0.32	kg
Sulfur	0.011	lb	0.011	kg
Surfactants	0.0043	lb	0.0043	kg
Thallium	1.0E-05	lb	1.0E-05	kg
Tin	4.7E-04	lb	4.7E-04	kg
Titanium	7.4E-04	lb	7.4E-04	kg
Toluene	0.0068	lb	0.0068	kg
Total Alkalinity	0.35	lb	0.35	kg
Total biphenyls	2.7E-06	lb	2.7E-06	kg
Total dibenzothiophenes	8.4E-09	lb	8.4E-09	kg
Total dissolved solids	192	lb	192	kg
TSS	2.73	lb	2.73	kg
Vanadium	1.2E-04	lb	1.2E-04	kg
Xylene	0.0034	lb	0.0034	kg
Yttrium	2.9E-05	lb	2.9E-05	kg
Zinc	0.0021	lb	0.0021	kg

References: B-2, B-6, and B-8 through B-17

Source: Franklin Associates, A Division of ERG

Natural Gas Processing

Once raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG). Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the natural gas has a high hydrogen sulfide content, it is considered “sour.” Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as “sweetening.”

Atmospheric emissions result from the flaring of hydrogen sulfide (H_2S), the regeneration of glycol solutions, and fugitive emissions of methane. Hydrogen sulfide is a natural component of natural gas and is converted to sulfur dioxide (SO_2) when flared; sulfur dioxide emissions were calculated from EPA emission factors (Reference B-26) and the known hydrogen sulfide content of domestic natural gas (Reference B-27). Glycol solutions are used to dehydrate natural gas, and the regeneration of these solutions result in the release of BTEX (benzene, toluene, ethylbenzene, and xylene) as well as a variety of less toxic organics (Reference B-28). Methane emissions result from fugitive releases as well as venting (Reference B-29). Negligible particulate emissions are produced from natural gas plants, and the relatively low processing temperatures (<1,200 degrees Fahrenheit) prevent the formation of nitrogen oxides (NOx).

Natural gas is transported primarily by pipeline, but a small percentage is compressed and transported by insulated railcars and tankers (References B-30 and B-31). Transportation data were calculated from the net annual quantities of natural gas imported and exported by each state (Reference B-32).

Energy data for natural gas processing were calculated from fuel consumption data for the natural gas liquids extraction industry (Reference B-9). Table B-5 shows the energy and emissions data for processing natural gas. Sulfur was given no coproduct allocation in this process. The amount of H_2S in the sour natural gas varies widely depending on where it is extracted.

Olefins Production (Ethylene)

The primary process used for manufacturing olefins is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

Table B-5

DATA FOR THE PROCESSING OF NATURAL GAS

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Natural gas	1,028	lb		1,028	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	9.67	kwh	103	21.3	kwh	0.24
Natural gas	554	cu ft	620	34.6	cu meters	1.44
Distillate oil	0.0060	gal	0.96	0.050	liter	0.0022
Residual oil	0.0059	gal	1.02	0.050	liter	0.0024
Gasoline	0.0057	gal	0.81	0.048	liter	0.0019
Total Process			726			1.69
Transportation Energy						
Combination truck	5.00	ton-miles		16.08	tonne-km	
Diesel	0.052	gal	8.33	0.44	liter	0.019
Rail	5.00	ton-miles		16.08	tonne-km	
Diesel	0.012	gal	1.97	0.10	liter	0.0046
Pipeline-natural gas	500	ton-miles		1608	tonne-km	
Natural gas	345	cu ft	386	21.5	cu meter	0.90
Total Transportation			397			0.92
Environmental Emissions						
Atmospheric Emissions						
BTEX	0.34	lb		0.34	kg	
VOC	0.77	lb		0.77	kg	
Sulfur Oxides	24.3	lb		24.3	kg	
Methane	1.88	lb		1.88	kg	

References: B-9 through B-12, B-17, B-26 through B-31, and B-33.

Source: Franklin Associates, A Division of ERG

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is used within the hydrocracker to produce steam, while the remaining portion is exported from the hydrocracker as a coproduct, as discussed below. The offgas used within the hydrocracker is shown in Table B-6 as "Internal offgas use." This offgas is shown as a weight of natural gas and petroleum input to produce the energy, as well as the energy amount produced from those weights.

Data was collected from individual plants, and a mass allocation was used to provide an output of 1,000 pounds/kilograms of olefin product. Then a weighted average using ethylene production amounts for each plant was applied to the individual olefins plant production data collected from three leading producers (8 thermal cracking units) in North America. Transportation amounts for ethylene were calculated using a weighted average of data collected from the polyethylene producers. Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the hydrocracker, and the remaining inputs and outputs are allocated over the material hydrocracker products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{\textit{attributed to remaining hydrocracker products}} \qquad \text{(Equation 1)}$$

where
IO = Input/Output Matrix to produce all products/coproducts
M_{EO} = Mass of Exported Offgas
M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table B-6 shows the averaged energy and emissions data for the production of ethylene.

As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. (Reference B-42). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American olefins production. All data collected were individually reviewed by the data providers.

To assess the quality of the data collected for olefins, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for olefins include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for olefins is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this module represent steam cracking of natural gas and petroleum. All data submitted for olefins represent the year 2003 and U.S. and Canada production.

Table B-6

DATA FOR THE PRODUCTION OF ETHYLENE

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials (1)							
Refined Petroleum Products	186	lb			186	kg	
Processed Natural Gas	830	lb			830	kg	
Water Consumption	246	gal			2,053	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	35.7	kwh		380	78.8	kwh	0.88
Electricity (cogeneration)	30.6	kwh		209	67.4	kwh	0.49
Natural Gas	2,272	cu ft		2,545	142	cu meters	5.92
Gasoline	0.011	gal		1.56	0.091	liter	0.0036
Diesel	0.0095	gal		1.51	0.079	liter	0.0035
Internal Offgas use (2)							
From Oil	27.8	lb		852	27.8	kg	1.98
From Natural Gas	117	lb		3,593	117	kg	8.36
Recovered Energy	12.4	thousand Btu		12.4	29	MJ	0.029
Total Process				7,569			17.6
Transportation Energy							
Ethylene Products							
Pipeline-Petroleum Products	60.0	ton-miles			193.1	tonne-km	
Electricity	1.31	kwh		13.4	2.88	kwh	0.031
Environmental Emissions							
Atmospheric Emissions - Process							
Carbon Monoxide	0.0010	lb	(3)		0.0010	kg	
Chlorine	1.0E-04	lb	(3)		1.0E-04	kg	
HCFC-022	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen Chloride	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen	0.0041	lb			0.0041	kg	
Hydrocarbons (NM)	0.091	lb			0.091	kg	
Methane	0.0010	lb	(3)		0.0010	kg	
Other Organics	0.0010	lb	(3)		0.0010	kg	
Particulates (unspecified)	0.0084	lb			0.0084	kg	
Particulates (PM10)	0.10	lb	(3)		0.10	kg	
Sulfur Oxides	0.0041	lb			0.0041	kg	
VOC	0.010	lb	(3)		0.010	kg	
Atmospheric Emissions - Fuel-Related (4)							
Carbon Dioxide (fossil)	648	lb			648	kg	
Carbon Monoxide	0.39	lb			0.39	kg	
Nitrogen Oxides	0.60	lb			0.60	kg	
PM 2.5	0.0093	lb			0.0093	kg	
Sulfur Oxides	0.059	lb			0.059	kg	
Solid Wastes							
Landfilled	0.28	lb			0.28	kg	
Burned	3.62	lb			3.62	kg	
Waste-to-Energy	0.023	lb			0.023	kg	
Waterborne Wastes							
Acetone	1.0E-08	lb	(3)		1.0E-08	kg	
Benzene	1.0E-05	lb	(3)		1.0E-05	kg	
BOD	6.7E-04	lb			6.7E-04	kg	
COD	0.010	lb	(3)		0.010	kg	
Ethylbenzene	1.0E-05	lb	(3)		1.0E-05	kg	
Naphthalene	1.0E-08	lb	(3)		1.0E-08	kg	
Phenol	0.0010	lb	(3)		0.0010	kg	
Styrene	1.0E-06	lb	(3)		1.0E-06	kg	
Suspended Solids	0.0045	lb			0.0045	kg	
Toluene	1.0E-04	lb	(3)		1.0E-04	kg	
Total Organic Carbon	0.0010	lb	(3)		0.0010	kg	
Xylene	1.0E-06	lb	(3)		1.0E-06	kg	

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(1) Specific raw materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source

(3) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(4) These fuel-related emissions were provided by the plants. These take into account the combustion of the off gas, as well as the natural gas.

References: B-34, B-35, B-39, B-40, and B-41.

Source: Franklin Associates, A Division of ERG

High-density Polyethylene Resin Production

High-density polyethylene is produced through the polymerization of ethylene. Polyethylene is manufactured by a slurry, solution, or a gas phase process. The average dataset includes data for the slurry and gas phase processes, which are discussed here. Ethylene and small amounts of co-monomers are continuously fed with a catalyst into a reactor.

In the slurry process, ethylene and co-monomers come into contact with the catalyst, which is suspended in a diluent. Particulates of polyethylene are then formed. After the diluent is removed, the reactor fluff is dried and pelletized.

In the gas phase process, a transition metal catalyst is introduced into a reactor containing ethylene gas, co-monomer, and a molecular control agent. The ethylene and co-monomer react to produce a polyethylene powder. The ethylene gas is separated from the powder, which is then pelletized.

A weighted average using production amounts was calculated from the HDPE production data from five plants collected from three leading producers in North America. The energy requirements and emissions data for the production of HDPE resin is displayed in Table B-7. Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for each product.

As of 2003, there were 10 HDPE producers and 23 HDPE plants in the U.S. (Reference B-43). While data was collected from a small sample of plants, the HDPE producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American HDPE production. The average dataset was reviewed and accepted by all HDPE data providers.

To assess the quality of the data collected for HDPE, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for HDPE include direct measurements, calculations from equipment specifications, information provided by purchasing and utility records, and estimates. The technology represented by the HDPE data represents a combination of UNIPOL gas and slurry processes. All data submitted for HDPE represent the year 2003 and U.S. and Canadian production.

Table B-7

DATA FOR THE PRODUCTION OF HIGH-DENSITY POLYETHYLENE (HDPE) RESIN

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Olefins	990	lb			990	kg	
Water Consumption	179	gal			1,494	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	80.7	kwh		858	178	kwh	2.00
Electricity (cogeneration)	100	kwh		683	220	kwh	1.59
Natural gas	569	cu ft		637	35.5	cu meters	1.48
LPG	0.0045	gal		0.49	0.038	liter	0.0011
Residual oil	0.72	gal		124	6.01	liter	0.29
Total Process				2,302			5.36
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.16	lb			0.16	kg	
Methane	0.014	lb			0.014	kg	
Nitrogen Oxides	0.029	lb			0.029	kg	
Hydrocarbons (NM)	0.42	lb			0.42	kg	
Other Organics	0.010	lb	(1)		0.010	kg	
Particulates (unknown)	0.018	lb			0.018	kg	
PM2.5	0.012	lb			0.012	kg	
PM10	0.041	lb			0.041	kg	
Sulfur Oxides	4.8E-05	lb			4.8E-05	kg	
Solid Wastes							
Landfilled	0.36	lb			0.36	kg	
Burned	0.26	lb			0.26	kg	
Waste-to-Energy	0.0040	lb			0.0040	kg	
Waterborne Wastes							
Aluminum	0.0010	lb	(1)		0.0010	kg	
BOD	0.0056	lb			0.0056	kg	
COD	0.0010	lb	(1)		0.0010	kg	
Chlorides	1.0E-06	lb	(1)		1.0E-06	kg	
Chromium	1.0E-05	lb	(1)		1.0E-05	kg	
Dissolved solids	0.044	lb			0.044	kg	
Furans	1.0E-06	lb	(1)		1.0E-06	kg	
Hydrocarbons	0.0010	lb	(1)		0.0010	kg	
Oil	0.0043	lb			0.0043	kg	
Phenol/Phenolics	1.0E-05	lb	(1)		1.0E-05	kg	
Phosphorus	1.0E-04	lb	(1)		1.0E-04	kg	
Process solvents	1.0E-04	lb	(1)		1.0E-04	kg	
Suspended solids	0.052	lb			0.052	kg	
Zinc	8.5E-05	lb			8.5E-05	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

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Source: Franklin Associates, A Division of ERG

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APPENDIX C

LOW-DENSITY POLYETHYLENE

INTRODUCTION

This appendix discusses the manufacture of low-density polyethylene (LDPE) resin. LDPE is commonly used to manufacture packaging films and extrusion coatings. Approximately 8 billion pounds of LDPE was produced in the U.S. and Canada in 2003 (Reference C-1). The material flow for LDPE resin is shown in Figure C-1. The total unit process energy and emissions data (cradle-to-LDPE) for LDPE are displayed in Table C-1. An individual process table on the bases of 1,000 pounds and 1,000 kilograms is shown within this appendix. Processes that have been discussed in the previous appendix have been omitted from this appendix. The following process is included in this appendix:

- LDPE resin production

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B.

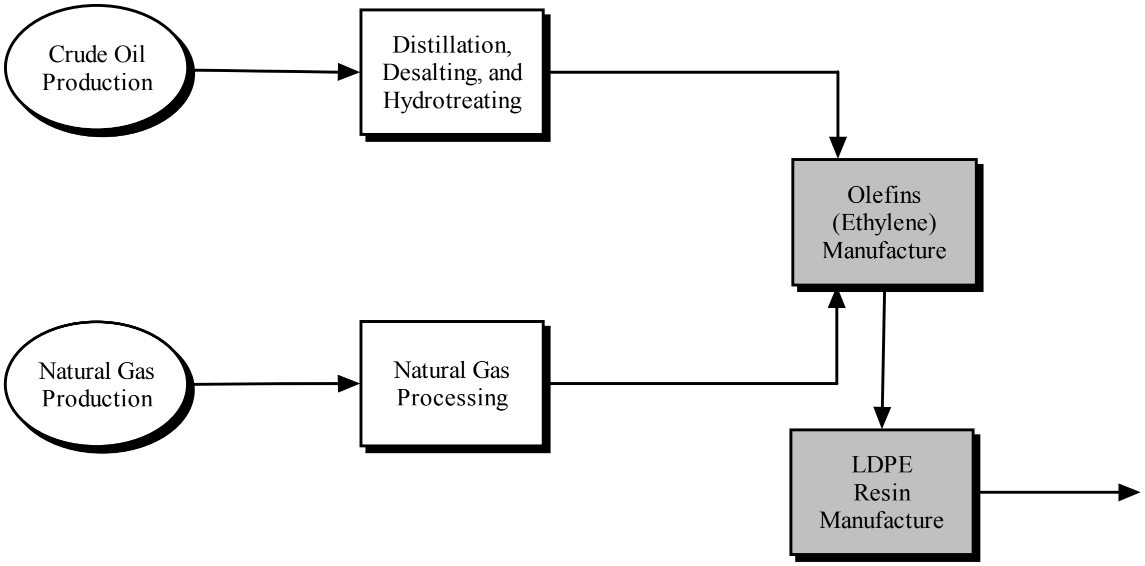

Figure C-1. Flow diagram for the manufacture of virgin low-density polyethylene (LDPE) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

Table C-1

DATA FOR THE PRODUCTION
OF LOW-DENSITY POLYETHYLENE (LDPE) RESIN
(Cradle-to-Resin)
(page 1 of 3)

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Crude oil	194	lb		194	kg	
Natural Gas	861	lb		861	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			20,021			46.6
Petroleum			3,790			8.82
Total Resource			23,811			55.4
Process Energy						
Electricity (grid)	166	kwh	1,766	366	kwh	4.11
Electricity (cogeneration)	359	kwh	- (2)	791	kwh	-
Natural gas	6,642	cu ft	7,439	415	cu meters	17.3
LPG	0.034	gal	3.65	0.28	liter	0.0085
Distillate oil	0.19	gal	29.6	1.56	liter	0.069
Residual oil	0.98	gal	168	8.17	liter	0.39
Gasoline	0.12	gal	16.4	0.96	liter	0.038
Diesel	0.010	gal	1.52	0.080	liter	0.0035
Internal Offgas use (1)						
From Oil	26.3	lb	807	26.3	kg	1.88
From Natural Gas	120	lb	3,674	120	kg	8.55
Recovered Energy	183	thousand Btu	183	426	MJ	0.43
Total Process			13,721			31.9
Transportation Energy						
Combination truck	7.69	ton-miles		24.76	tonne-km	
Diesel	0.081	gal	12.8	0.67	liter	0.030
Rail	6.65	ton-miles		21.39	tonne-km	
Diesel	0.016	gal	2.62	0.14	liter	0.0061
Barge	15.8	ton-miles		50.99	tonne-km	
Diesel	0.013	gal	2.01	0.11	liter	0.0047
Residual oil	0.042	gal	7.23	0.35	liter	0.017
Ocean freighter	326	ton-miles		1048	tonne-km	
Diesel	0.067	gal	10.7	0.56	liter	0.025
Residual	0.57	gal	98.3	4.78	liter	0.23
Pipeline-natural gas	478	ton-miles		1540	tonne-km	
Natural gas	330	cu ft	370	20.6	cu meter	0.86
Pipeline-petroleum products	127	ton-miles		407.8	tonne-km	
Electricity	2.76	kwh	29.4	6.09	kwh	0.068
Total Transportation			533			1.24

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table C-1

DATA FOR THE PRODUCTION
OF LOW-DENSITY POLYETHYLENE (LDPE) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.0090	lb	0.0090	kg
Ammonia	0.0045	lb	0.0045	kg
Benzene	0.092	lb	0.092	kg
Carbon Dioxide (fossil)	88.3	lb	88.3	kg
Carbon Monoxide	2.86	lb	2.86	kg
Carbon Tetrachloride	2.6E-09	lb	2.6E-09	kg
Chlorine	1.0E-04	lb	1.0E-04	kg
Ethylbenzene	0.011	lb	0.011	kg
HCFC-22	0.0010	lb	0.0010	kg
Hydrocarbons (NM)	1.40	lb	1.40	kg
Hydrogen	0.0040	lb	0.0040	kg
Hydrogen Chloride	1.0E-06	lb	1.0E-06	kg
Methane	14.3	lb	14.3	kg
Nitrogen Oxides	0.072	lb	0.072	kg
Nitrous Oxide	0.0010	lb	0.0010	kg
Other Organics	0.051	lb	0.051	kg
Particulates (unknown)	0.10	lb	0.10	kg
PM2.5	0.0055	lb	0.0055	kg
PM10	0.13	lb	0.13	kg
Sulfur Oxides	23.8	lb	23.8	kg
Toluene	0.14	lb	0.14	kg
Trichloroethane	2.1E-08	lb	2.1E-08	kg
VOC	0.75	lb	0.75	kg
Xylene	0.083	lb	0.083	kg
Solid Wastes				
Landfilled	31.6	lb	31.6	kg
Burned	3.89	lb	3.89	kg
Waste-to-Energy	0.024	lb	0.024	kg
Waterborne Wastes				
1-Methylfluorene	5.7E-07	lb	5.7E-07	kg
2,4-Dimethylphenol	1.4E-04	lb	1.4E-04	kg
2-Hexanone	3.3E-05	lb	3.3E-05	kg
2-Methylnapthalene	7.9E-05	lb	7.9E-05	kg
4-Methyl-2-Pentanone	2.1E-05	lb	2.1E-05	kg
Acetone	5.0E-05	lb	5.0E-05	kg
Alkylated benzenes	8.0E-05	lb	8.0E-05	kg
Alkylated fluorenes	4.6E-06	lb	4.6E-06	kg
Alkylated naphthalenes	1.3E-06	lb	1.3E-06	kg
Alkylated phenanthrenes	5.5E-07	lb	5.5E-07	kg
Alkalinity	0.40	lb	0.40	kg
Aluminum	0.15	lb	0.15	kg
Ammonia	0.067	lb	0.067	kg
Antimony	9.2E-05	lb	9.2E-05	kg
Arsenic	0.0012	lb	0.0012	kg
Barium	2.17	lb	2.17	kg
Benzene	0.0084	lb	0.0084	kg
Benzoic acid	0.0051	lb	0.0051	kg
Beryllium	5.5E-05	lb	5.5E-05	kg
BOD	0.89	lb	0.89	kg
Boron	0.016	lb	0.016	kg
Bromide	1.07	lb	1.07	kg
Cadmium	1.7E-04	lb	1.7E-04	kg
Calcium	16.1	lb	16.1	kg
CFC-011	1.0E-04	lb	1.0E-04	kg
Chlorides	181	lb	181	kg
Chromium (unspecified)	0.0041	lb	0.0041	kg
Chromium (hexavalent)	7.9E-06	lb	7.9E-06	kg
Cobalt	1.1E-04	lb	1.1E-04	kg
COD	1.60	lb	1.60	kg
Copper	8.2E-04	lb	8.2E-04	kg
Cyanide	3.6E-07	lb	3.6E-07	kg
Dibenzofuran	9.5E-07	lb	9.5E-07	kg

Table C-1

DATA FOR THE PRODUCTION
OF LOW-DENSITY POLYETHYLENE (LDPE) RESIN
(Cradle-to-Resin)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Dibenzothiophene	7.7E-07	lb	7.7E-07	kg
Dissolved Solids	224	lb	224	kg
Ethylbenzene	4.8E-04	lb	4.8E-04	kg
Fluorine	2.6E-06	lb	2.6E-06	kg
Hardness	49.7	lb	49.7	kg
Hexanoic acid	0.0011	lb	0.0011	kg
Iron	0.38	lb	0.38	kg
Isopropyl alcohol	1.0E-04	lb	1.0E-04	kg
Lead	0.0018	lb	0.0018	kg
Lead 210	5.2E-13	lb	5.2E-13	kg
Lithium	4.54	lb	4.54	kg
Magnesium	3.15	lb	3.15	kg
Manganese	0.0051	lb	0.0051	kg
Mercury	1.6E-06	lb	1.6E-06	kg
Methylchloride	2.0E-07	lb	2.0E-07	kg
Methyl Ethyl Ketone	4.0E-07	lb	4.0E-07	kg
Molybdenum	1.2E-04	lb	1.2E-04	kg
m-Xylene	1.5E-04	lb	1.5E-04	kg
Naphthalene	9.1E-05	lb	9.1E-05	kg
n-Decane	1.5E-04	lb	1.5E-04	kg
n-Docosane	5.4E-06	lb	5.4E-06	kg
n-Dodecane	2.8E-04	lb	2.8E-04	kg
n-Eicosane	7.6E-05	lb	7.6E-05	kg
n-Hexacosane	3.3E-06	lb	3.3E-06	kg
n-Hexadecane	3.0E-04	lb	3.0E-04	kg
Nickel	9.6E-04	lb	9.6E-04	kg
n-Octadecane	7.5E-05	lb	7.5E-05	kg
n-Tetradecane	1.2E-04	lb	1.2E-04	kg
o + p-Xylene	1.1E-04	lb	1.1E-04	kg
o-Cresol	1.4E-04	lb	1.4E-04	kg
Oil and grease	0.10	lb	0.10	kg
p-Cresol	1.6E-04	lb	1.6E-04	kg
p-Cymene	5.0E-07	lb	5.0E-07	kg
Pentamethylbenzene	3.8E-07	lb	3.8E-07	kg
Phenanthrene	7.7E-07	lb	7.7E-07	kg
Phenol	0.0033	lb	0.0033	kg
Phosphorus	1.0E-04	lb	1.0E-04	kg
Radium 226	1.8E-10	lb	1.8E-10	kg
Radium 228	9.3E-13	lb	9.3E-13	kg
Selenium	1.8E-05	lb	1.8E-05	kg
Silver	0.011	lb	0.011	kg
Sodium	51.1	lb	51.1	kg
Strontium	0.27	lb	0.27	kg
Styrene	1.0E-06	lb	1.0E-06	kg
Sulfates	0.37	lb	0.37	kg
Sulfides	4.1E-05	lb	4.1E-05	kg
Sulfur	0.013	lb	0.013	kg
Surfactants	0.0049	lb	0.0049	kg
Suspended Solids	4.86	lb	4.86	kg
Thallium	1.9E-05	lb	1.9E-05	kg
Tin	6.4E-04	lb	6.4E-04	kg
Titanium	0.0014	lb	0.0014	kg
TOC	0.0010	lb	0.0010	kg
Toluene	0.0081	lb	0.0081	kg
Total biphenyls	5.2E-06	lb	5.2E-06	kg
Total dibenzothiophenes	1.6E-08	lb	1.6E-08	kg
Vanadium	1.4E-04	lb	1.4E-04	kg
Xylene (unspecified)	0.0040	lb	0.0040	kg
Yttrium	3.4E-05	lb	3.4E-05	kg
Zinc	0.0037	lb	0.0037	kg

References: Tables B-2 through B-6 and C-2.

Source: Franklin Associates, A Division of ERG models

LDPE Resin Production

Low-density polyethylene (LDPE) is produced by the polymerization of ethylene in high pressure reactors (above 3,000 psi). This is the standard technology for LDPE production. The two reactor types used are autoclaves and tubular reactors. Generally, tubular reactors operate at a higher average ethylene conversion than autoclave reactors. The polymerization mechanism is either free-radical, using peroxide initiators, or ionic polymerization, using Ziegler catalyst.

Reactor effluent consists of unreacted ethylene and polymer. The pressure of the effluent mixture is reduced and the ethylene is purified and recycled back to the reactor.

A weighted average using production amounts was calculated from the LDPE production data from seven plants collected from three leading producers in North America. Table C-2 displays the energy and emissions data for the production of LDPE resin. Scrap and steam are produced as coproducts during this process. A mass basis was used to partition the credit for scrap, while the energy amount for the steam was reported separately as recovered energy.

As of 2003, there were 8 LDPE producers and 15 LDPE plants in the U.S. (Reference C-3). The LDPE data collected for this module represents a majority of North American LDPE production. The average dataset was reviewed and accepted by all LDPE data providers.

To assess the quality of the data collected for LDPE, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for LDPE include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the LDPE data represents a combination of the tubular and autoclave high-pressure reactors. All data submitted for LDPE represent the years 2002 and 2003 and production in U.S. and Canada.

Table C-2

DATA FOR THE PRODUCTION OF LOW-DENSITY POLYETHYLENE (LDPE) RESIN

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Olefins	1,008	lb			1,008	kg	
Water Consumption	499	gal			4,164	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	85.5	kwh		909	188	kwh	2.12
Electricity (cogeneration)	328	kwh		2,242	724	kwh	5.22
Natural gas	775	cu ft		868	48.4	cu meters	2.02
LPG	0.0038	gal		0.41	0.032	liter	9.6E-04
Residual oil	0.16	gal		27.4	1.33	liter	0.064
Recovered Energy	171	thousand Btu		171	398	MJ	0.40
Total Process				3,876			9.0
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.010	lb	(1)		0.010	kg	
Carbon Dioxide	10.0	lb	(1)		10.0	kg	
Chlorine	1.0E-06	lb	(1)		1.0E-06	kg	
HFC/HCFC	0.0010	lb	(1)		0.0010	kg	
Methane	0.0066	lb			0.0066	kg	
NM Hydrocarbons	0.87	lb			0.87	kg	
Nitrogen Oxides	0.0010	lb	(1)		0.0010	kg	
Nitrous Oxide	0.0010	lb	(1)		0.0010	kg	
Other Organics	0.050	lb			0.050	kg	
Particulates (unknown)	0.045	lb			0.045	kg	
PM2.5	0.0055	lb			0.0055	kg	
PM10	0.026	lb			0.026	kg	
Sulfur Oxides	1.0E-05	lb	(1)		1.0E-05	kg	
Solid Wastes							
Landfilled	0.063	lb			0.063	kg	
Burned	0.24	lb			0.24	kg	
Waterborne Wastes							
Aluminum	1.0E-04	lb	(1)		1.0E-04	kg	
BOD	0.010	lb	(1)		0.010	kg	
COD	0.10	lb	(1)		0.10	kg	
Dissolved Solids	0.0010	lb	(1)		0.0010	kg	
CFC-011	1.0E-04	lb	(1)		1.0E-04	kg	
Isopropyl Alcohol	1.0E-04	lb	(1)		1.0E-04	kg	
Oil	0.0010	lb	(1)		0.0010	kg	
Phenol/Phenolics	1.0E-06	lb	(1)		1.0E-06	kg	
Phosphorus	1.0E-04	lb	(1)		1.0E-04	kg	
Suspended Solids	0.010	lb	(1)		0.010	kg	
Zinc	1.0E-05	lb	(1)		1.0E-05	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: C-2

Source: Franklin Associates, A Division of ERG

REFERENCES

C-1. APC Plastics Industry Producers' Statistics Group, as compiled by VERIS Consulting, LLC. 2004.

C-2. Information and data collected from APC member and non-member companies producing LDPE. 2004-2005.

C-3. Chemical profile information taken from the website: http://www.the-innovation-group.com/welcome.htm.

APPENDIX D

LINEAR LOW-DENSITY POLYETHYLENE

INTRODUCTION

This appendix discusses the manufacture of linear low-density polyethylene (LLDPE) resin. LLDPE is commonly used to manufacture shrink/stretch film and trash bags. More than 11 billion pounds of LDPE was produced in the U.S. and Canada in 2003 (Reference D-1). The material flow for LLDPE resin is shown in Figure D-1. The total unit process energy and emissions data (cradle-to-LLDPE) for LLDPE are displayed in Table D-1. An individual process table on the bases of 1,000 pounds and 1,000 kilograms is shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following process is included in this appendix:

- LLDPE resin production

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B.

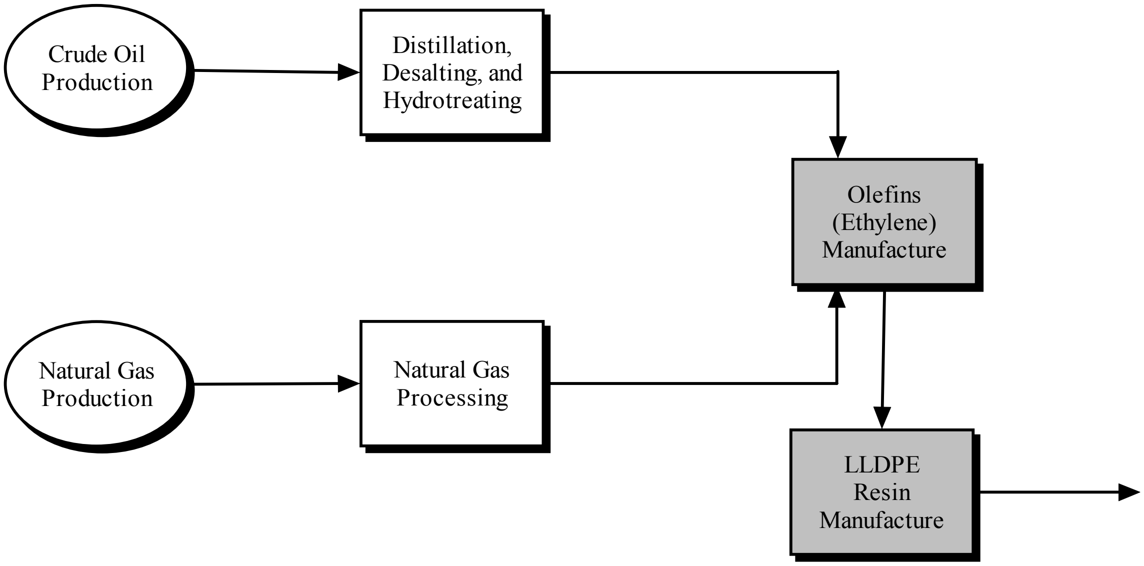

Figure D-1. Flow diagram for the manufacture of virgin linear low-density (LLDPE) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

Table D-1

DATA FOR THE PRODUCTION
OF LINEAR LOW-DENSITY POLYETHYLENE (LLDPE) RESIN
(Cradle-to-Resin)
(page 1 of 3)

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Crude oil	192	lb		192	kg	
Natural Gas	853	lb		853	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			19,849			46.2
Petroleum			3,757			8.75
Total Resource			23,606			55.0
Process Energy						
Electricity (grid)	137	kwh	1,462	303	kwh	3.40
Electricity (cogeneration)	100	kwh	- (2)	220	kwh	-
Natural gas	4,796	cu ft	5,372	299	cu meters	12.5
LPG	0.030	gal	3.21	0.25	liter	0.0075
Distillate oil	0.18	gal	29.4	1.54	liter	0.068
Residual oil	1.21	gal	208	10.1	liter	0.48
Gasoline	0.12	gal	16.4	0.96	liter	0.038
Diesel	0.010	gal	1.63	0.086	liter	0.0038
Internal Offgas use (1)						
From Oil	26.1	lb	800	26.1	kg	1.86
From Natural Gas	119	lb	3,642	119	kg	8.48
Recovered Energy	12.0	thousand Btu	12.0	27.9	MJ	0.028
Total Process			11,522			26.8
Transportation Energy						
Combination truck	7.63	ton-miles		24.55	tonne-km	
Diesel	0.080	gal	12.7	0.67	liter	0.030
Rail	6.59	ton-miles		21.20	tonne-km	
Diesel	0.016	gal	2.59	0.14	liter	0.0060
Barge	15.7	ton-miles		50.55	tonne-km	
Diesel	0.013	gal	2.00	0.10	liter	0.0046
Residual oil	0.042	gal	7.17	0.35	liter	0.017
Ocean freighter	323	ton-miles		1039	tonne-km	
Diesel	0.067	gal	10.6	0.56	liter	0.025
Residual	0.55	gal	94.7	4.61	liter	0.22
Pipeline-natural gas	474	ton-miles		1527	tonne-km	
Natural gas	327	cu ft	367	20.4	cu meter	0.85
Pipeline-petroleum products	126	ton-miles		404.3	tonne-km	
Electricity	2.74	kwh	28.0	6.04	kwh	0.065
Total Transportation			524			1.22

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table D-1

DATA FOR THE PRODUCTION OF LINEAR LOW-DENSITY POLYETHYLENE (LLDPE) RESIN

(Cradle-to-Resin)

(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.0089	lb	0.0089	kg
Aluminum Compounds	1.0E-04	lb	1.0E-04	kg
Ammonia	0.0045	lb	0.0045	kg
Benzene	0.091	lb	0.091	kg
Carbon Dioxide (fossil)	128	lb	128.4	kg
Carbon Monoxide	2.92	lb	2.92	kg
Carbon Tetrachloride	2.5E-09	lb	2.5E-09	kg
Chlorine	1.0E-04	lb	1.0E-04	kg
Ethylbenzene	0.011	lb	0.011	kg
Furans	0.0010	lb	0.0010	kg
HCFC-22	1.1E-05	lb	1.1E-05	kg
Hydrocarbons (NM)	0.88	lb	0.88	kg
Hydrogen	0.0039	lb	0.0039	kg
Hydrogen Chloride	1.0E-06	lb	1.0E-06	kg
Methane	14.2	lb	14.2	kg
Nitrogen Oxides	0.10	lb	0.10	kg
Nitrous Oxide	0.017	lb	0.017	kg
Other Organics	0.011	lb	0.011	kg
Particulates (unknown)	0.069	lb	0.069	kg
PM2.5	0.010	lb	0.010	kg
PM10	0.11	lb	0.11	kg
Sulfur Oxides	23.6	lb	23.6	kg
Toluene	0.14	lb	0.14	kg
Trichloroethane	2.1E-08	lb	2.1E-08	kg
VOC	0.74	lb	0.74	kg
Xylene	0.083	lb	0.083	kg
Solid Wastes				
Landfilled	31.6	lb	31.6	kg
Burned	3.75	lb	3.75	kg
Waste-to-Energy	0.11	lb	0.11	kg
Waterborne Wastes				
1-Methylfluorene	5.7E-07	lb	5.7E-07	kg
2,4-Dimethylphenol	1.4E-04	lb	1.4E-04	kg
2-Hexanone	3.2E-05	lb	3.2E-05	kg
2-Methylnapthalene	7.9E-05	lb	7.9E-05	kg
4-Methyl-2-Pentanone	2.1E-05	lb	2.1E-05	kg
Acetone	5.0E-05	lb	5.0E-05	kg
Alkylated benzenes	8.0E-05	lb	8.0E-05	kg
Alkylated fluorenes	4.6E-06	lb	4.6E-06	kg
Alkylated naphthalenes	1.3E-06	lb	1.3E-06	kg
Alkylated phenanthrenes	5.4E-07	lb	5.4E-07	kg
Alkalinity	0.40	lb	0.40	kg
Aluminum	0.15	lb	0.15	kg
Ammonia	0.067	lb	0.067	kg
Antimony	9.1E-05	lb	9.1E-05	kg
Arsenic	0.0011	lb	0.0011	kg
Barium	2.15	lb	2.15	kg
Benzene	0.0084	lb	0.0084	kg
Benzoic acid	0.0050	lb	0.0050	kg
Beryllium	5.4E-05	lb	5.4E-05	kg
BOD	0.87	lb	0.87	kg
Boron	0.016	lb	0.016	kg
Bromide	1.07	lb	1.07	kg
Butene	1.0E-04	lb	1.0E-04	kg
Cadmium	1.7E-04	lb	1.7E-04	kg
Calcium	16.0	lb	16.0	kg
Chlorides	180	lb	180	kg
Chromium (unspecified)	0.0041	lb	0.0041	kg
Chromium (hexavalent)	7.8E-06	lb	7.8E-06	kg
Cobalt	1.1E-04	lb	1.1E-04	kg
COD	1.50	lb	1.50	kg
Copper	8.2E-04	lb	8.2E-04	kg

Table D-1

DATA FOR THE PRODUCTION
OF LINEAR LOW-DENSITY POLYETHYLENE (LLDPE) RESIN
(Cradle-to-Resin)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Cyanide	3.6E-07	lb	3.6E-07	kg
Cyclohexane	1.0E-04	lb	1.0E-04	kg
Dibenzofuran	9.5E-07	lb	9.5E-07	kg
Dibenzothiophene	7.7E-07	lb	7.7E-07	kg
Dissolved Solids	222	lb	222	kg
Ethylbenzene	4.8E-04	lb	4.8E-04	kg
Fluorine	2.6E-06	lb	2.6E-06	kg
Hardness	49.2	lb	49.2	kg
Hexanoic acid	0.0010	lb	0.0010	kg
Iron	0.38	lb	0.38	kg
Lead	0.0018	lb	0.0018	kg
Lead 210	5.2E-13	lb	5.2E-13	kg
Lithium	4.50	lb	4.50	kg
Magnesium	3.12	lb	3.12	kg
Manganese	0.0050	lb	0.0050	kg
Mercury	1.6E-06	lb	1.6E-06	kg
Methylchloride	2.0E-07	lb	2.0E-07	kg
Methyl Ethyl Ketone	4.0E-07	lb	4.0E-07	kg
Molybdenum	1.1E-04	lb	1.1E-04	kg
m-Xylene	1.5E-04	lb	1.5E-04	kg
Naphthalene	9.0E-05	lb	9.0E-05	kg
n-Decane	1.4E-04	lb	1.4E-04	kg
n-Docosane	5.3E-06	lb	5.3E-06	kg
n-Dodecane	2.8E-04	lb	2.8E-04	kg
n-Eicosane	7.6E-05	lb	7.6E-05	kg
n-Hexacosane	3.3E-06	lb	3.3E-06	kg
n-Hexadecane	3.0E-04	lb	3.0E-04	kg
Nickel	9.5E-04	lb	9.5E-04	kg
n-Octadecane	7.4E-05	lb	7.4E-05	kg
n-Tetradecane	1.2E-04	lb	1.2E-04	kg
o + p-Xylene	1.1E-04	lb	1.1E-04	kg
o-Cresol	1.4E-04	lb	1.4E-04	kg
Oil and grease	0.10	lb	0.10	kg
p-Cresol	1.5E-04	lb	1.5E-04	kg
p-Cymene	5.0E-07	lb	5.0E-07	kg
Pentamethylbenzene	3.7E-07	lb	3.7E-07	kg
Phenanthrene	7.6E-07	lb	7.6E-07	kg
Phenol	0.0033	lb	0.0033	kg
Phosphorus	1.0E-04	lb	1.0E-04	kg
Process solvents	1.0E-04	lb	1.0E-04	kg
Radium 226	1.8E-10	lb	1.8E-10	kg
Radium 228	9.2E-13	lb	9.2E-13	kg
Selenium	1.8E-05	lb	1.8E-05	kg
Silver	0.010	lb	0.010	kg
Sodium	50.7	lb	50.7	kg
Strontium	0.27	lb	0.27	kg
Styrene	1.0E-06	lb	1.0E-06	kg
Sulfates	0.37	lb	0.37	kg
Sulfides	4.0E-05	lb	4.0E-05	kg
Sulfur	0.013	lb	0.013	kg
Surfactants	0.0048	lb	0.0048	kg
Suspended Solids	4.84	lb	4.84	kg
Thallium	1.9E-05	lb	1.9E-05	kg
Tin	6.4E-04	lb	6.4E-04	kg
Titanium	0.0014	lb	0.0014	kg
TOC	0.0010	lb	0.0010	kg
Toluene	0.0080	lb	0.0080	kg
Total biphenyls	5.1E-06	lb	5.1E-06	kg
Total dibenzothiophenes	1.6E-08	lb	1.6E-08	kg
Vanadium	1.4E-04	lb	1.4E-04	kg
Xylene (unspecified)	0.0040	lb	0.0040	kg
Yttrium	3.4E-05	lb	3.4E-05	kg
Zinc	0.0037	lb	0.0037	kg

References: Tables B-2 through B-6 and D-2.

Source: Franklin Associates, A Division of ERG models

LLDPE Resin Production

LLDPE is produced through the polymerization of ethylene. Polyethylene is most commonly manufactured by either a solution process or a gas phase process. The data in this module represent solution and gas phase technologies. Ethylene and small amounts of co-monomers are continuously fed with a catalyst into a reactor.

In the solution process, ethylene and co-monomers come into contact with the catalyst, which is suspended in a diluent. Particulates of polyethylene are then formed. After the diluent is removed, the reactor fluff is dried and pelletized.

In the gas phase process, a transition metal catalyst is introduced into a reactor containing ethylene gas, co-monomer, and a molecular control agent. The ethylene and co-monomer react to produce a polyethylene powder. The ethylene gas is separated from the powder, which is then pelletized.

A weighted average using production amounts was calculated from the LLDPE production data from five plants collected from three leading producers in North America. Table D-2 displays the energy and emissions data for the production of LLDPE resin. Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for scrap.

As of 2003, there were 11 LLDPE producers and 24 LLDPE plants in the U.S. (Reference D-3). While data was collected from a small sample of plants, the LLDPE producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American LLDPE production. The average dataset was reviewed and accepted by all LLDPE data providers.

To assess the quality of the data collected for LLDPE, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for LLDPE include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the LLDPE data represents a combination of the solution and gas phase processes. All data submitted for LLDPE represent the year 2003 and production in U.S. and Canada.

Table D-2

DATA FOR THE PRODUCTION OF LINEAR LOW-DENSITY POLYETHYLENE (LLDPE) RESIN

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
				Total Energy Thousand Btu			Total Energy GigaJoules
Raw Materials							
Olefins	999	lb			999	kg	
Water Consumption	60.0	gal			501	liter	
Energy Usage							
Process Energy							
Electricity (grid)	57.6	kwh		613	127	kwh	1.43
Electricity (cogeneration)	69.3	kwh		473	153	kwh	1.10
Natural gas	674	cu ft		755	42.1	cu meters	1.76
Residual oil	0.40	gal		68.6	3.34	liter	0.16
Gasoline	0.0010	gal		0.14	0.0083	liter	3.3E-04
Diesel	7.5E-04	gal		0.12	0.0063	liter	2.8E-04
Total Process				1,910			4.45
Environmental Emissions							
Atmospheric Emissions							
Aluminum Compounds	1.0E-04	lb	(1)		1.0E-04	kg	
Carbon Dioxide (fossil)	50.8	lb			50.8	kg	
Carbon Monoxide	0.10	lb			0.10	kg	
Furans	0.0010	lb	(1)		0.0010	kg	
HFC/HCFC	1.0E-05	lb	(1)		1.0E-05	kg	
Methane	0.0020	lb			0.0020	kg	
Nitrogen Oxides	0.030	lb			0.030	kg	
Nitrous Oxides	0.017	lb			0.017	kg	
NM Hydrocarbons	0.36	lb			0.36	kg	
Other Organics	0.010	lb	(1)		0.010	kg	
Particulates (unknown)	0.010	lb	(1)		0.010	kg	
PM2.5	0.010	lb	(1)		0.010	kg	
PM10	0.014	lb			0.014	kg	
Sulfur Oxides	1.6E-04	lb			1.6E-04	kg	
Solid Wastes							
Landfilled	0.35	lb			0.35	kg	
Burned	0.13	lb			0.13	kg	
Waste-to-Energy	0.091	lb			0.091	kg	
Waterborne Wastes							
Aluminum	0.0010	lb	(1)		0.0010	kg	
BOD	0.0010	lb	(1)		0.0010	kg	
Butene	1.0E-04	lb	(1)		1.0E-04	kg	
COD	0.010	lb	(1)		0.010	kg	
Cyclohexane	1.0E-04	lb	(1)		1.0E-04	kg	
Dissolved Solids	0.024	lb			0.024	kg	
Oil & Grease	0.0034	lb			0.0034	kg	
Phenolics	1.0E-06	lb	(1)		1.0E-06	kg	
Phosphorus	1.0E-04	lb	(1)		1.0E-04	kg	
Process Solvents	1.0E-04	lb	(1)		1.0E-04	kg	
Suspended Solids	0.034	lb			0.034	kg	
Zinc	1.0E-05	lb	(1)		1.0E-05	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: D-2

Source: Franklin Associates, A Division of ERG

REFERENCES

D-1. APC Plastics Industry Producers' Statistics Group, as compiled by VERIS Consulting, LLC. 2004.

D-2. Information and data collected from APC member and non-member companies producing LLDPE. 2004-2005.

D-3. Chemical profile information taken from the website: http://www.the-innovation-group.com/welcome.htm.

APPENDIX E

POLYPROPYLENE

INTRODUCTION

This appendix discusses the manufacture of polypropylene (PP) resin. PP is used to manufacture textiles, rigid packaging, and consumer products. More than 17 billion pounds of PP was produced in the U.S. and Canada in 2003 (Reference E-1). The material flow for PP resin is shown in Figure E-1. The total unit process energy and emissions data (cradle-to-PP) for PP are displayed in Table E-1. An individual process table on the bases of 1,000 pounds and 1,000 kilograms is shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following process is included in this appendix:

- Propylene production
- Polypropylene resin production

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, and natural gas processing are discussed in Appendix B.

Olefins Production (Propylene)

The primary process used for manufacturing olefins is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is used within the hydrocracker to produce steam, while the remaining portion is exported from the hydrocracker as a coproduct, as discussed below. The offgas used within the hydrocracker is shown in Table E-2 as "Internal offgas use." This offgas is shown as a weight of natural gas and petroleum input to produce the energy, as well as the energy amount produced from those weights.

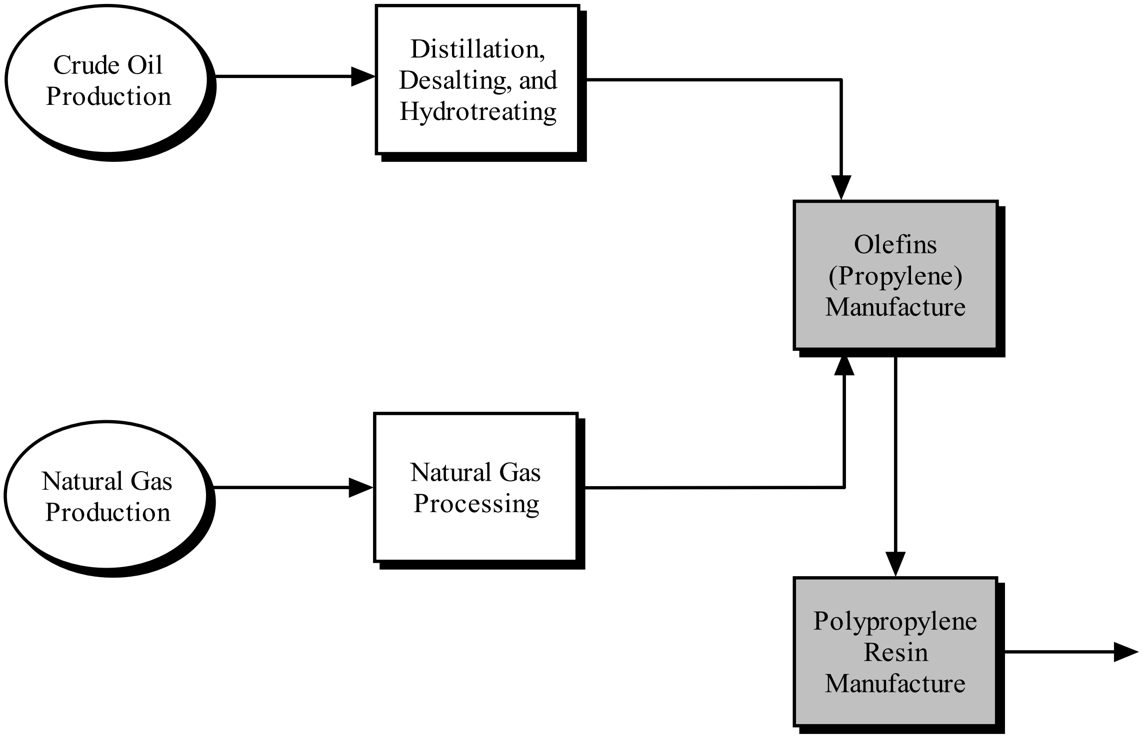

Figure E-1. Flow diagram for the manufacture of virgin polypropylene (PP) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

Data was collected from individual plants, and a mass allocation was used to provide an output of 1,000 pounds/kilograms of olefin product. Then a weighted average using propylene production amounts was applied to the individual olefins plant production data collected from three leading producers (8 thermal cracking units) in North America. Transportation amounts for propylene were calculated using a weighted average of data collected from the polypropylene producers. Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the hydrocracker, and the remaining inputs and outputs are allocated over the material hydrocracker products (Equation 1).

Table E-1

DATA FOR THE PRODUCTION OF POLYPROPYLENE (PP) RESIN (Cradle-to-Resin)

(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	373	lb		373	kg	
Natural Gas	658	lb		658	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			15,317			35.7
Petroleum			7,284			17.0
Total Resource			22,601			52.6
Process Energy						
Electricity (grid)	177	kwh	1,879	389	kwh	4.37
Electricity (cogeneration)	89.7	kwh	- (2)	198	kwh	-
Natural gas	3,792	cu ft	4,247	237	cu meters	9.89
LPG	0.060	gal	6.46	0.50	liter	0.015
Distillate oil	0.19	gal	29.8	1.56	liter	0.069
Residual oil	2.03	gal	349	17.0	liter	0.81
Gasoline	0.11	gal	15.1	0.89	liter	0.035
Diesel	0.0018	gal	0.28	0.015	liter	6.6E-04
Internal Offgas use (1)						
From Oil	66.0	lb	1,877	66.0	kg	4.37
From Natural Gas	117	lb	3,336	117	kg	7.77
Recovered Energy	2.29	thousand Btu	2.29	5.33	MJ	0.0053
Total Process			11,737			27.3
Transportation Energy						
Combination truck	9.59	ton-miles		30.86	tonne-km	
Diesel	0.10	gal	16.0	0.84	liter	0.037
Rail	7.50	ton-miles		24.13	tonne-km	
Diesel	0.019	gal	2.95	0.16	liter	0.0069
Barge	31.6	ton-miles		101.7	tonne-km	
Diesel	0.025	gal	4.01	0.21	liter	0.0093
Residual oil	0.084	gal	14.4	0.70	liter	0.034
Ocean freighter	649	ton-miles		2089	tonne-km	
Diesel	0.12	gal	19.6	1.03	liter	0.046
Residual	1.10	gal	189	9.21	liter	0.44
Pipeline-natural gas	379	ton-miles		1219	tonne-km	
Natural gas	261	cu ft	293	16.3	cu meter	0.68
Pipeline-petroleum products	152	ton-miles		487.6	tonne-km	
Electricity	3.30	kwh	33.8	7.28	kwh	0.079
Total Transportation			573			1.33

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table E-1

DATA FOR THE PRODUCTION OF POLYPROPYLENE (PP) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.018	lb	0.018	kg
Ammonia	0.0090	lb	0.0090	kg
Benzene	0.073	lb	0.073	kg
Carbon Dioxide (fossil)	81.3	lb	81.3	kg
Carbon Monoxide	5.79	lb	5.79	kg
Carbon Tetrachloride	5.1E-09	lb	5.1E-09	kg
Chlorine	1.0E-04	lb	1.0E-04	kg
Ethylbenzene	0.0091	lb	0.0091	kg
HCFC-22	1.0E-06	lb	1.0E-06	kg
Hydrocarbons (NM)	1.12	lb	1.12	kg
Hydrogen	0.0052	lb	0.0052	kg
Hydrogen Chloride	1.0E-06	lb	1.0E-06	kg
Lead	1.0E-12	lb	1.0E-12	kg
Methane	12.3	lb	12.3	kg
Nitrogen Oxides	0.15	lb	0.15	kg
Nitrous Oxide	0.0045	lb	0.0045	kg
Other Organics	0.011	lb	0.011	kg
Particulates (unknown)	0.13	lb	0.13	kg
PM2.5	1.0E-05	lb	1.0E-05	kg
PM10	0.10	lb	0.10	kg
Sulfur Oxides	19.4	lb	19.4	kg
Toluene	0.11	lb	0.11	kg
Trichloroethane	4.1E-08	lb	4.1E-08	kg
VOC	0.59	lb	0.59	kg
Xylene	0.066	lb	0.066	kg
Zinc	1.0E-06	lb	1.0E-06	kg
Solid Wastes				
Landfilled	33.6	lb	33.6	kg
Burned	7.63	lb	7.63	kg
Waste-to-Energy	0.0044	lb	0.0044	kg
Waterborne Wastes				
1-Methylfluorene	5.6E-07	lb	5.6E-07	kg
2,4-Dimethylphenol	1.4E-04	lb	1.4E-04	kg
2-Hexanone	3.2E-05	lb	3.2E-05	kg
2-Methylnapthalene	7.8E-05	lb	7.8E-05	kg
4-Methyl-2-Pentanone	2.1E-05	lb	2.1E-05	kg
Acetone	4.9E-05	lb	4.9E-05	kg
Alkylated benzenes	1.1E-04	lb	1.1E-04	kg
Alkylated fluorenes	6.4E-06	lb	6.4E-06	kg
Alkylated naphthalenes	1.8E-06	lb	1.8E-06	kg
Alkylated phenanthrenes	7.5E-07	lb	7.5E-07	kg
Alkalinity	0.39	lb	0.39	kg
Aluminum	0.20	lb	0.20	kg
Ammonia	0.071	lb	0.071	kg
Antimony	1.3E-04	lb	1.3E-04	kg
Arsenic	0.0012	lb	0.0012	kg
Barium	2.88	lb	2.88	kg
Benzene	0.0083	lb	0.0083	kg
Benzoic acid	0.0050	lb	0.0050	kg
Beryllium	5.8E-05	lb	5.8E-05	kg
BOD	0.87	lb	0.87	kg
Boron	0.015	lb	0.015	kg
Bromide	1.05	lb	1.05	kg
Cadmium	1.7E-04	lb	1.7E-04	kg
Calcium	15.8	lb	15.8	kg
Chlorides	178	lb	178	kg
Chromium (unspecified)	0.0057	lb	0.0057	kg
Chromium (hexavalent)	1.6E-05	lb	1.6E-05	kg
Cobalt	1.1E-04	lb	1.1E-04	kg
COD	1.53	lb	1.53	kg
Copper	9.2E-04	lb	9.2E-04	kg
Cyanide	3.5E-07	lb	3.5E-07	kg

Table E-1

DATA FOR THE PRODUCTION
OF POLYPROPYLENE (PP) RESIN
(Cradle-to-Resin)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Dibenzofuran	9.3E-07	lb	9.3E-07	kg
Dibenzothiophene	7.6E-07	lb	7.6E-07	kg
Dissolved Solids	219	lb	219	kg
Ethylbenzene	4.7E-04	lb	4.7E-04	kg
Fluorine	3.4E-06	lb	3.4E-06	kg
Hardness	48.7	lb	48.7	kg
Hexanoic acid	0.0010	lb	0.0010	kg
Iron	0.47	lb	0.47	kg
Lead	0.0020	lb	0.0020	kg
Lead 210	5.1E-13	lb	5.1E-13	kg
Lithium	3.60	lb	3.60	kg
Magnesium	3.09	lb	3.09	kg
Manganese	0.0050	lb	0.0050	kg
Mercury	2.2E-06	lb	2.2E-06	kg
Methylchloride	2.0E-07	lb	2.0E-07	kg
Methyl Ethyl Ketone	4.0E-07	lb	4.0E-07	kg
Molybdenum	1.1E-04	lb	1.1E-04	kg
m-Xylene	1.5E-04	lb	1.5E-04	kg
Naphthalene	8.9E-05	lb	8.9E-05	kg
n-Decane	1.4E-04	lb	1.4E-04	kg
n-Docosane	5.3E-06	lb	5.3E-06	kg
n-Dodecane	2.7E-04	lb	2.7E-04	kg
n-Eicosane	7.5E-05	lb	7.5E-05	kg
n-Hexacosane	3.3E-06	lb	3.3E-06	kg
n-Hexadecane	3.0E-04	lb	3.0E-04	kg
Nickel	0.0010	lb	0.0010	kg
n-Octadecane	7.3E-05	lb	7.3E-05	kg
n-Tetradecane	1.2E-04	lb	1.2E-04	kg
o + p-Xylene	1.1E-04	lb	1.1E-04	kg
o-Cresol	1.4E-04	lb	1.4E-04	kg
Oil and grease	0.10	lb	0.10	kg
p-Cresol	1.5E-04	lb	1.5E-04	kg
p-Cymene	4.9E-07	lb	4.9E-07	kg
Pentamethylbenzene	3.7E-07	lb	3.7E-07	kg
Phenanthrene	8.8E-07	lb	8.8E-07	kg
Phenol	0.0033	lb	0.0033	kg
Radium 226	1.8E-10	lb	1.8E-10	kg
Radium 228	9.1E-13	lb	9.1E-13	kg
Selenium	2.4E-05	lb	2.4E-05	kg
Silver	0.010	lb	0.010	kg
Sodium	50.1	lb	50.1	kg
Strontium	0.27	lb	0.27	kg
Styrene	1.0E-06	lb	1.0E-06	kg
Sulfates	0.36	lb	0.36	kg
Sulfides	8.1E-05	lb	8.1E-05	kg
Sulfur	0.013	lb	0.013	kg
Surfactants	0.0046	lb	0.0046	kg
Suspended Solids	6.47	lb	6.47	kg
Thallium	2.6E-05	lb	2.6E-05	kg
Tin	7.2E-04	lb	7.2E-04	kg
Titanium	0.0019	lb	0.0019	kg
TOC	0.0010	lb	0.0010	kg
Toluene	0.0079	lb	0.0079	kg
Total biphenyls	7.1E-06	lb	7.1E-06	kg
Total dibenzothiophenes	2.2E-08	lb	2.2E-08	kg
Vanadium	1.3E-04	lb	1.3E-04	kg
Xylene (unspecified)	0.0039	lb	0.0039	kg
Yttrium	3.3E-05	lb	3.3E-05	kg
Zinc	0.0049	lb	0.0049	kg

References: Tables B-2 through B-5, E-2 and E-3.

Source: Franklin Associates, A Division of ERG models

Table E-2

DATA FOR THE PRODUCTION OF PROPYLENE

	English units (Basis: 1,000 lb)			Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Raw Materials (1)							
Refined Petroleum Products	357	lb			357	kg	
Processed Natural Gas	643	lb			643	kg	
Water Consumption	213	gal			1,780	liter	
Energy Usage							
Process Energy							
Electricity (grid)	46.2	kwh		492	102	kwh	1.15
Electricity (cogeneration)	21.4	kwh		146	47.1	kwh	0.34
Natural Gas	1,759	cu ft		1,970	110	cu meters	4.59
Gasoline	0.0021	gal		0.29	0.017	liter	6.8E-04
Diesel	0.0018	gal		0.28	0.015	liter	6.6E-04
Internal Offgas use (2)							
From Oil	63.7	lb		1,810	63.7	kg	4.21
From Natural Gas	121	lb		3,424	121	kg	7.97
Recovered Energy	2.30	thousand Btu		2.30	5.35	MJ	0.0054
Total Process				7,840			18.3
Transportation Energy							
Propylene Products							
Pipeline-Petroleum Products	19.5	ton-miles			62.8	tonne-km	
Electricity	0.43	kwh		4.35	0.94	kwh	0.010
Environmental Emissions							
Atmospheric Emissions - Process							
Carbon Monoxide	0.0010	lb	(3)		0.0010	kg	
Chlorine	1.0E-04	lb	(3)		1.0E-04	kg	
HCFC-022	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen Chloride	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen	0.0052	lb			0.0052	kg	
Hydrocarbons (NM)	0.11	lb			0.11	kg	
Methane	0.0010	lb	(3)		0.0010	kg	
Other Organics	0.0010	lb	(3)		0.0010	kg	
Particulates (unspecified)	0.0082	lb			0.0082	kg	
Particulates (PM10)	0.10	lb	(3)		0.10	kg	
Sulfur Oxides	0.0041	lb			0.0041	kg	
VOC	0.010	lb	(3)		0.010	kg	
Atmospheric Emissions - Fuel-Related (4)							
Carbon Dioxide (fossil)	666	lb			666	kg	
Carbon Monoxide	0.30	lb			0.30	kg	
Nitrogen Oxides	0.47	lb			0.47	kg	
PM 2.5	0.009	lb			0.009	kg	
Sulfur Oxides	0.071	lb			0.071	kg	
Solid Wastes							
Landfilled	0.36	lb			0.36	kg	
Burned	5.60	lb			5.60	kg	
Waste-to-Energy	0.0044	lb			0.0044	kg	
Waterborne Wastes							
Acetone	1.0E-08	lb	(3)		1.0E-08	kg	
Benzene	1.0E-05	lb	(3)		1.0E-05	kg	
BOD	6.4E-04	lb			6.4E-04	kg	
COD	0.010	lb	(3)		0.010	kg	
Ethylbenzene	1.0E-05	lb	(3)		1.0E-05	kg	
Naphthalene	1.0E-08	lb	(3)		1.0E-08	kg	
Phenol	0.0010	lb	(3)		0.0010	kg	
Styrene	1.0E-06	lb	(3)		1.0E-06	kg	
Suspended Solids	0.0048	lb			0.0048	kg	
Toluene	1.0E-04	lb	(3)		1.0E-04	kg	
Total Organic Carbon	0.0010	lb	(3)		0.0010	kg	
Xylene	1.0E-06	lb	(3)		1.0E-06	kg	

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(1) Specific raw materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(3) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(4) These fuel-related emissions were provided by the plants. These take into account the combustion of the offgas as well as the natural gas.

References: E-3 and E-4

Source: Franklin Associates, A Division of ERG

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{\text{attributed to remaining hydrocracker products}} \qquad \text{(Equation 1)}$$

where
IO = Input/Output Matrix to produce all products/coproducts
M_{EO} = Mass of Exported Offgas
M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table E-2 shows the averaged energy and emissions data for the production of propylene.

As of 2003, there were 8 olefin-producing companies and at least 16 olefin plants producing polymer-grade propylene in the U.S. (Reference E-2). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American olefins production. All data collected were individually reviewed by the data providers.

To assess the quality of the data collected for olefins, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for olefins include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for olefins is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this module represent steam cracking of natural gas and petroleum. All data submitted for olefins represent the year 2003 and U.S. and Canada production.

Polypropylene Resin Production

Polypropylene is manufactured by the polymerization of propylene using Ziegler-Natta catalysts. Commercial processes generally use titanium trichloride in combination with aluminum diethylmonochloride. Production processes vary and include slurry, gas-phase, and solution monomer polymerization. The latter two processes employ the use of improved high-yield catalysts. The five polypropylene datasets represent the gas-phase and solution monomer polymerization processes. These processes are discussed below.

The gas-phase method of production mixes the high-yield type catalyst and propylene vapor in a fluidized bed or agitated powder bed reactor. Temperature control is accomplished by the evaporation of liquid propylene entering the reactor. Reactor temperatures of 80° to 90° Celsius and pressures of 30 to 35 atmospheres are typical. Unreacted propylene gas is recovered, compressed, purified, and returned to the propylene feed stream. The polymer is then dried and pelletized. Catalyst residues are low and catalyst removal is not part of this process. No solvent is used in the process; therefore, no solvent recovery is necessary.

The solution monomer process of manufacturing polypropylene often employs tubular reactors with a large specific-exchange surface and a high heat-exchange coefficient. The use of high-yield catalyst eliminates the need for catalyst residue and atactic removal. Unreacted propylene is recovered, and the isotactic polypropylene is dried and pelletized. As in the gas-phase process, no solvent is used.

A weighted average using production amounts was calculated from the PP production data from four plants collected from three leading producers in North America. Table E-3 displays the energy and emissions data for the production of polypropylene resin. Scrap and some alkane/alkene streams are produced as coproducts during this process. A mass basis was used to partition the credit for the coproducts.

As of 2003 there were 11 PP producers and 20 PP plants in the U.S. (Reference E-5). While data was collected from a small sample of plants, the PP producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American PP production. The average dataset was reviewed and accepted by all PP data providers.

To assess the quality of the data collected for PP, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for PP include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the PP data represents a combination of the liquid monomer and gas phase processes. All data submitted for PP represent the years 2003 and 2004 and production in U.S.

Table E-3

DATA FOR THE PRODUCTION OF POLYPROPYLENE (PP) RESIN

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Olefins	996	lb			996	kg	
Propane	5.0	lb			5.0	kg	
Water Consumption	139	gal			1,160	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	74.0	kwh		762	163	kwh	1.77
Electricity (cogeneration)	68.4	kwh		467	151	kwh	1.09
Natural gas	310	cu ft		347	19.4	cu meters	0.81
Residual oil	0.52	gal		89.2	4.34	liter	0.21
Total Process				1,665			3.88
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.12	lb			0.12	kg	
Carbon Dioxide	19.3	lb			19.3	kg	
Lead	1.0E-12	lb	(1)		1.0E-12	kg	
Methane	0.068	lb			0.068	kg	
Nitrogen Oxides	0.014	lb			0.014	kg	
Nitrous Oxides	0.0045	lb			0.0045	kg	
NM Hydrocarbons	0.15	lb			0.15	kg	
Other Organics	0.010	lb	(1)		0.010	kg	
Particulates (unknown)	0.023	lb			0.023	kg	
PM2.5	1.0E-05	lb	(1)		1.0E-05	kg	
PM10	0.0010	lb	(1)		0.0010	kg	
Sulfur Oxides	1.0E-04	lb	(1)		1.0E-04	kg	
Zinc	1.0E-06	lb	(1)		1.0E-06	kg	
Solid Wastes							
Landfilled	0.11	lb			0.11	kg	
Burned	2.06	lb			2.06	kg	
Waterborne Wastes							
BOD	0.0010	lb	(1)		0.0010	kg	
COD	0.010	lb	(1)		0.010	kg	
Dissolved solids	0.010	lb	(1)		0.010	kg	
Suspended Solids	0.020	lb			0.020	kg	
Zinc	1.0E-05	lb	(1)		1.0E-05	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: E-4

Source: Franklin Associates, A Division of ERG

REFERENCES

E-1. APC Plastics Industry Producers' Statistics Group, as compiled by VERIS Consulting, LLC. 2004.

E-2. Chemical Profile: Propylene. **Chemical Market Reporter.** October 6, 2003. Page 23.

E-3. Information and data collected from APC member and non-member companies producing olefins. 2004-2005.

E-4. Information and data collected from APC member and non-member companies producing PP. 2004-2005.

E-5. Chemical profile information taken from the website: http://www.the-innovation-group.com/welcome.htm.

APPENDIX F

POLYETHYLENE TEREPHTHALATE (PET)

INTRODUCTION

This appendix discusses the manufacture of polyethylene terephthalate (PET) resin. The leading use of PET resin is bottle production. Over 7 billion pounds of PET was produced in the U.S., Mexico, and Canada in 2003 (Reference F-1). The material flow for PET resin is shown in Figure F-1. The total unit process energy and emissions data (cradle-to-PET) for PET are displayed in Table F-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Methanol Production
- Carbon Monoxide Production
- Acetic Acid Production
- Oxygen Production
- Ethylene Oxide Production
- Ethylene Glycol Production
- Mixed Xylenes
- Paraxylene Extraction
- Crude Terephthalic Acid (TPA) Production
- Purified TPA (PTA) Production
- Dimethyl Terephthalate (DMT) Production
- PET Melt Phase Polymerization
- PET Solid Phase Polymerization

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B.

Methanol Production

Methanol is produced from light hydrocarbons using steam reforming and low-pressure synthesis. The feed gas is compressed, preheated, and desulfurized. Then, it is mixed with steam, preheated further, and fed to the catalytic reformer. The synthesis gas from the reformer, containing primarily hydrogen, carbon monoxide, and carbon dioxide, is cooled to remove condensate to the proper temperature for entry into the compressor section.

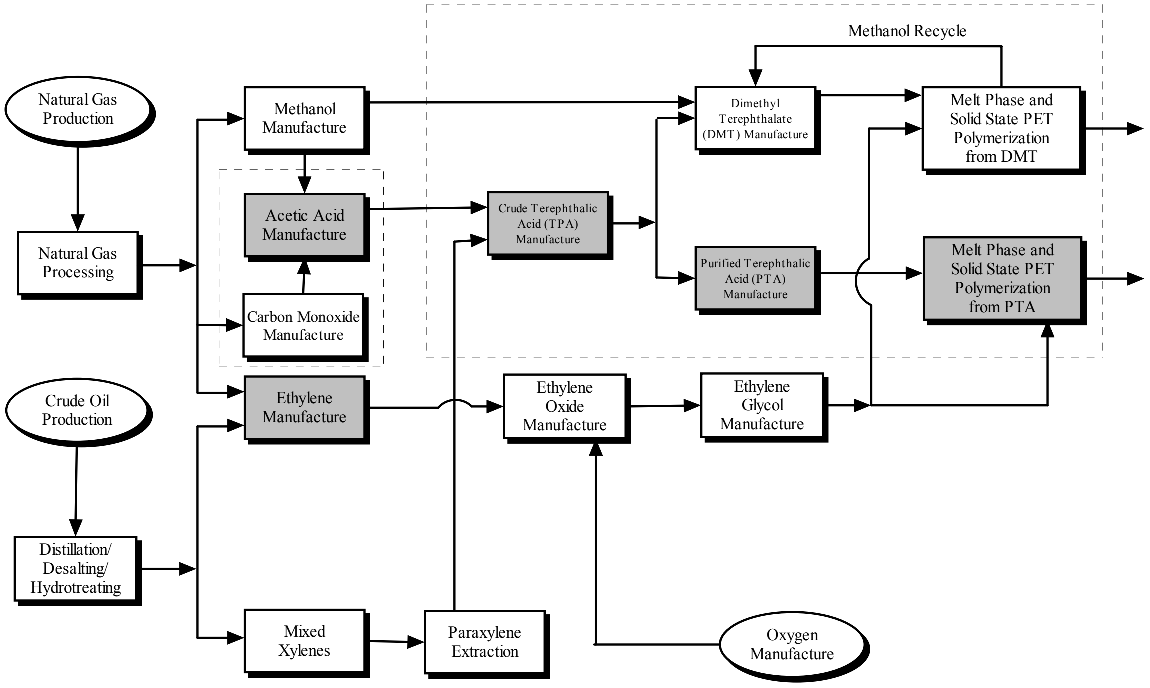

Figure F-1. Flow diagram for the manufacture of virgin polyethylene terephthalate(PET) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted rectangle are included in an aggregated dataset.

From the compressor, the pressure of the synthesis gas is raised, and the feed goes to a multi-bed inter-cooled methanol converter system. Converter effluent is sent to a cooler, and the crude methanol is removed from the gas mixture. The crude methanol is then brought to atmospheric pressure and distilled to eliminate dissolved gases and obtain the desired grade.

Table F-2 lists the energy requirements and environmental emissions for the manufacture of 1,000 pounds of methanol. Steam production is included in energy use for methanol production. The energy and carbon dioxide data for methanol are from a source outside of the United States. No energy and carbon dioxide data for the production of methanol are available for the United States. Waterborne emissions data are provided by an older U.S. source and may be overstated. The transportation energy was collected from an acetic acid producer and calculated using estimates.

Table F-1

DATA FOR THE PRODUCTION OF POLYETHYLENE TEREPHTHALATE (PET) RESIN
(Cradle-to-Resin)
(page 1 of 4)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	577	lb		577	kg	
Natural Gas	218	lb		218	kg	
Oxygen	223	lb		223	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			5,080			11.8
Petroleum			11,277			26.3
Total Resource			16,357			38.1
Process Energy						
Electricity (grid)	402	kwh	4,272	885	kwh	9.95
Electricity (cogeneration)	29.3	kwh	- (2)	64.7	kwh	-
Natural gas	6,580	cu ft	7,369	411	cu meters	17.2
LPG	0.68	gal	73.9	5.70	liter	0.17
Bit./Sbit. Coal	35.9	lb	404	35.9	kg	0.94
Distillate oil	1.66	gal	263	13.8	liter	0.61
Residual oil	9.60	gal	1,648	80.1	liter	3.84
Gasoline	0.071	gal	10.1	0.59	liter	0.024
Diesel	0.0019	gal	0.30	0.016	liter	7.0E-04
Internal Offgas use (1)						
From Oil	5.22	lb	160	5.22	kg	0.37
From Natural Gas	23.8	lb	729	23.8	kg	1.70
Recovered Energy	63.5	thousand Btu	63.5	148	MJ	0.15
Total Process			14,865			34.6
Transportation Energy						
Combination truck	8.84	ton-miles		28.46	tonne-km	
Diesel	0.093	gal	14.7	0.77	liter	0.034
Rail	507	ton-miles		1633	tonne-km	
Diesel	1.26	gal	200	10.5	liter	0.46
Barge	43.1	ton-miles		138.8	tonne-km	
Diesel	0.034	gal	5.48	0.29	liter	0.013
Residual oil	0.11	gal	19.7	0.96	liter	0.046
Ocean freighter	858	ton-miles		2760	tonne-km	
Diesel	0.16	gal	25.9	1.36	liter	0.060
Residual	1.47	gal	252	12.2	liter	0.59
Pipeline-natural gas	118	ton-miles		380.5	tonne-km	
Natural gas	81.6	cu ft	91.4	5.09	cu meter	0.21
Pipeline-petroleum products	187	ton-miles		601	tonne-km	
Electricity	4.07	kwh	41.7	8.97	kwh	0.097
Total Transportation			650			1.51

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table F-1

DATA FOR THE PRODUCTION
OF POLYETHYLENE TEREPHTHALATE (PET) RESIN
(Cradle-to-Resin)
(page 2 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Acetic Acid	0.051	lb	0.051	kg
Aldehydes	0.19	lb	0.19	kg
Ammonia	0.033	lb	0.033	kg
Bromine	0.079	lb	0.079	kg
Benzene	0.023	lb	0.023	kg
Carbon Dioxide (fossil)	296	lb	296	kg
Carbon Monoxide	13.3	lb	13.3	kg
Carbon Tetrachloride	6.8E-09	lb	6.8E-09	kg
Chlorine	2.0E-05	lb	2.0E-05	kg
Ethylbenzene	0.0028	lb	0.0028	kg
Ethylene Oxide	0.024	lb	0.024	kg
HCFC-22	2.0E-07	lb	2.0E-07	kg
Hydrocarbons (NM)	6.71	lb	6.71	kg
Hydrogen	7.9E-04	lb	7.9E-04	kg
Hydrogen Chloride	2.0E-07	lb	2.0E-07	kg
Methane	6.36	lb	6.36	kg
Methanol	0.0015	lb	0.0015	kg
Methyl Acetate	0.040	lb	0.040	kg
Nitrogen Oxides	0.24	lb	0.24	kg
Other Organics	1.11	lb	1.11	kg
Particulates (unknown)	0.29	lb	0.29	kg
PM10	0.020	lb	0.020	kg
Sulfur Oxides	7.06	lb	7.06	kg
TOC	0.081	lb	0.081	kg
Toluene	0.035	lb	0.035	kg
Trichloroethane	5.5E-08	lb	5.5E-08	kg
VOC	0.18	lb	0.18	kg
Xylene	0.062	lb	0.062	kg
Solid Wastes				
Landfilled	32.9	lb	32.9	kg
Burned	1.03	lb	1.03	kg
Waste-to-Energy	0.59	lb	0.59	kg
Waterborne Wastes				
1-Methylfluorene	3.5E-07	lb	3.5E-07	kg
2,4-Dimethylphenol	8.7E-05	lb	8.7E-05	kg
2-Hexanone	2.0E-05	lb	2.0E-05	kg
2-Methylnapthalene	4.9E-05	lb	4.9E-05	kg
4-Methyl-2-Pentanone	1.3E-05	lb	1.3E-05	kg
Acetone	3.1E-05	lb	3.1E-05	kg
Acid (unspecified)	0.036	lb	0.036	kg
Aldehydes	0.025	lb	0.025	kg
Alkylated benzenes	1.1E-04	lb	1.1E-04	kg
Alkylated fluorenes	6.5E-06	lb	6.5E-06	kg
Alkylated naphthalenes	1.8E-06	lb	1.8E-06	kg
Alkylated phenanthrenes	7.6E-07	lb	7.6E-07	kg
Alkalinity	0.25	lb	0.25	kg
Aluminum	0.20	lb	0.20	kg
Ammonia	0.16	lb	0.16	kg
Ammonium ion	0.0013	lb	0.0013	kg
Antimony	1.3E-04	lb	1.3E-04	kg
Arsenic	8.0E-04	lb	8.0E-04	kg
Barium	2.84	lb	2.84	kg
Benzene	0.0052	lb	0.0052	kg
Benzoic acid	0.0032	lb	0.0032	kg
Beryllium	4.3E-05	lb	4.3E-05	kg
BOD	1.43	lb	1.43	kg
Boron	0.0098	lb	0.0098	kg
Bromide	0.67	lb	0.67	kg

Table F-1

DATA FOR THE PRODUCTION
OF POLYETHYLENE TEREPHTHALATE (PET) RESIN
(Cradle-to-Resin)
(page 3 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Cadmium	1.2E-04	lb	1.2E-04	kg
Calcium	10.0	lb	10.0	kg
Chlorides	113	lb	113	kg
Chromium (unspecified)	0.012	lb	0.012	kg
Chromium (hexavalent)	2.1E-05	lb	2.1E-05	kg
Cobalt	6.9E-05	lb	6.9E-05	kg
COD	2.50	lb	2.50	kg
Copper	7.4E-04	lb	7.4E-04	kg
Cyanide	2.2E-07	lb	2.2E-07	kg
Dibenzofuran	5.9E-07	lb	5.9E-07	kg
Dibenzothiophene	4.8E-07	lb	4.8E-07	kg
Dissolved Solids	139	lb	139	kg
Ethylbenzene	3.0E-04	lb	3.0E-04	kg
Fluorides	5.1E-05	lb	5.1E-05	kg
Fluorine	3.3E-06	lb	3.3E-06	kg
Hardness	30.8	lb	30.8	kg
Hexanoic acid	6.5E-04	lb	6.5E-04	kg
Iron	0.43	lb	0.43	kg
Lead	0.0016	lb	0.0016	kg
Lead 210	3.2E-13	lb	3.2E-13	kg
Lithium	1.12	lb	1.12	kg
Magnesium	1.96	lb	1.96	kg
Manganese	0.0031	lb	0.0031	kg
Mercury	2.2E-06	lb	2.2E-06	kg
Metal Ion (unspecified)	4.5E-06	lb	4.5E-06	kg
Methylchloride	1.3E-07	lb	1.3E-07	kg
Methyl Ethyl Ketone	2.5E-07	lb	2.5E-07	kg
Molybdenum	7.2E-05	lb	7.2E-05	kg
m-Xylene	9.4E-05	lb	9.4E-05	kg
Naphthalene	5.7E-05	lb	5.7E-05	kg
n-Decane	9.1E-05	lb	9.1E-05	kg
n-Docosane	3.3E-06	lb	3.3E-06	kg
n-Dodecane	1.7E-04	lb	1.7E-04	kg
n-Eicosane	4.7E-05	lb	4.7E-05	kg
n-Hexacosane	2.1E-06	lb	2.1E-06	kg
n-Hexadecane	1.9E-04	lb	1.9E-04	kg
Nickel	7.5E-04	lb	7.5E-04	kg
n-Octadecane	4.6E-05	lb	4.6E-05	kg
n-Tetradecane	7.5E-05	lb	7.5E-05	kg
o + p-Xylene	6.9E-05	lb	6.9E-05	kg
o-Cresol	9.0E-05	lb	9.0E-05	kg
Oil	0.068	lb	0.068	kg
p-Cresol	9.7E-05	lb	9.7E-05	kg
p-Cymene	3.1E-07	lb	3.1E-07	kg
Pentamethylbenzene	2.3E-07	lb	2.3E-07	kg
Phenanthrene	7.2E-07	lb	7.2E-07	kg
Phenol	0.0017	lb	0.0017	kg
Phosphates	5.1E-04	lb	5.1E-04	kg
Radium 226	1.1E-10	lb	1.1E-10	kg
Radium 228	5.8E-13	lb	5.8E-13	kg
Selenium	2.5E-05	lb	2.5E-05	kg
Silver	0.0065	lb	0.0065	kg
Sodium	31.7	lb	31.7	kg
Strontium	0.17	lb	0.17	kg
Styrene	2.0E-07	lb	2.0E-07	kg
Sulfates	0.23	lb	0.23	kg
Sulfides	1.1E-04	lb	1.1E-04	kg
Sulfur	0.0083	lb	0.0083	kg
Surfactants	0.0028	lb	0.0028	kg
Suspended Solids	6.43	lb	6.43	kg

Table F-1

DATA FOR THE PRODUCTION
OF POLYETHYLENE TEREPHTHALATE (PET) RESIN
(Cradle-to-Resin)
(page 4 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Thallium	2.7E-05	lb	2.7E-05	kg
Tin	5.8E-04	lb	5.8E-04	kg
Titanium	0.0020	lb	0.0020	kg
TOC	0.044	lb	0.044	kg
Toluene	0.0050	lb	0.0050	kg
Total biphenyls	7.3E-06	lb	7.3E-06	kg
Total dibenzothiophenes	2.2E-08	lb	2.2E-08	kg
Vanadium	8.5E-05	lb	8.5E-05	kg
Xylene (unspecified)	0.0025	lb	0.0025	kg
Yttrium	2.1E-05	lb	2.1E-05	kg
Zinc	0.013	lb	0.013	kg

References: Tables B-2 through B-6 and F-2 through F-8.

Source: Franklin Associates, A Division of ERG models

Carbon Monoxide Production

The raw materials necessary for the production of carbon monoxide are the gases resulting from steam reformation, as in the production of synthesis gas for ammonia manufacture, or from partial combustion f hydrocarbons. The feed gas must be stripped of carbon dioxide by scrubbing with ethanolamine solution and then passed through a molecular sieve to remove traces of carbon dioxide and water. Carbon monoxide and unconverted methane are condensed from the gas mixture and separated by lowering the pressure to remove entrained gases. The methane is recycled and the carbon monoxide comes out as a product after evaporation, warming, and compression.

The energy requirements and environmental emissions for the production of carbon monoxide using steam reformation are included in the production of acetic acid (Table F-3). The energy and emissions data for carbon monoxide are from secondary sources and estimates. The transportation energy was collected from an acetic acid producer and calculated using estimates.

Table F-2

DATA FOR THE PRODUCTION OF METHANOL

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Natural Gas	620	lb		620	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	2.4	kwh	25	5.4	kwh	0.06
Natural gas	15,973	cu ft	17,890	997	cu meters	41.6
Total Process			17,915			41.7
Transportation Energy						
Barge	25.0	ton-miles		80.5	tonne-km	
Diesel	0.020	gal	3.2	0.17	liter	0.007
Residual oil	0.067	gal	11.4	0.55	liter	0.027
Pipeline-natural gas	0.50	ton-miles		1.61	tonne-km	
Natural gas	0.35	cu ft	0.4	0.022	cu meter	9.0E-04
Total Transportation			15.0			0.035
Environmental Emissions						
Atmospheric Emissions						
Hydrocarbons	5.0	lb		5.0	kg	
Carbon Dioxide	529.7	lb		529.7	kg	
Solid Wastes						
Landfilled	0.50	lb		0.50	kg	
Waterborne Wastes						
BOD	0.058	lb		0.058	kg	
Suspended solids	0.088	lb		0.088	kg	

References: F-2 through F-5, F-7 and F-22.

Source: Franklin Associates, A Division of ERG

Acetic Acid Production

Several methods are used for producing acetic acid. Some methods used in the United States include liquid phase oxidation of butane or LPG and the oxidation of acetaldehyde. Most commercial production of virgin synthetic acetic acid is made by reacting carbon monoxide with methanol. Recovered acetic acid represents an additional major supply (Reference F-2).

Table F-3 shows the energy and emissions data for producing acetic acid. Mixed acid and offgas are produced as coproducts during this process. A mass basis was used to partition the credit for the acid. When the offgas is exported from the process, it carries with it the allocated share of the inputs and outputs for its production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the process, and the remaining inputs and outputs are allocated over the material products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{attributed\ to\ remaining\ products} \qquad \text{(Equation 1)}$$

where
IO = Input/Output Matrix to produce all products/coproducts
M_{EO} = Mass of Exported Offgas
M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported offgas, since both the inputs and outputs for the exported fuel have been removed from the data set.

The data in Table F-3 represents the production of acetic acid by the carbonylation of methanol. As only 2 confidential datasets were available, the carbon monoxide dataset is included within the acetic acid data. One of these datasets was collected for this project and represents 2003 data in the U.S., while the other U.S. dataset comes from 1994. As no production amounts were available for either datasets, an arithmetic average was used to weight the data. The 2003 data were collected from direct measurements and engineering estimates.

Oxygen Production

Oxygen is manufactured by cryogenic separation of air. This technique is essentially one of liquefying air, then collecting the oxygen by fractionation. The oxygen is produced in the form of a liquid, which boils at 184° Celsius below zero at normal atmospheric pressure, so it must be kept under stringent conditions of temperature and pressure for handling. Most oxygen plants are located quite close to their point of consumption and use pipelines to minimize transportation difficulties, although there is a small amount of long distance hauling in insulated rail cars.

The energy data for producing oxygen is displayed in Table F-4. This energy data is primary data collected from 3 producers representing air separation for the years 1990 through 1993.

Table F-3

DATA FOR THE PRODUCTION OF ACETIC ACID
(Includes acetic acid and carbon monoxide data)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Methanol	539	lb		539	kg	
Natural Gas products	325	lb		325	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	65.7	kwh	676	145	kwh	1.57
Electricity (cogeneration)	0.93	kwh	6.35	2.05	kwh	0.015
Natural gas	3,581	cu ft	4,011	224	cu meters	9.34
Total Process			4,693			10.9
Transportation Energy						
Rail	475	ton-miles		1,529	tonne-km	
Diesel	1.18	gal	187	9.83	liter	0.44
Pipeline-natural gas	0.26	ton-miles		0.83	tonne-km	
Natural gas	0.18	cu ft	0.20	0.011	cu meter	0.0005
Total Transportation			187.3			0.44
Environmental Emissions						
Atmospheric Emissions						
Carbon Monoxide	3.97	lb		3.97	kg	
Carbon Dioxide	1.76	lb		1.76	kg	
TOC	2.17	lb		2.17	kg	
Methanol	0.040	lb		0.040	kg	
Ammonia	0.57	lb		0.57	kg	
Solid Wastes						
Landfilled	0.56	lb		0.56	kg	
Waterborne Wastes						
Acid (unspecified)	0.96	lb		0.96	kg	
Ammonia	0.052	lb		0.052	kg	

References: F-2, F-4, and F-6 through F-10.

Source: Franklin Associates, A Division of ERG

Table F-4

DATA FOR THE PRODUCTION OF OXYGEN

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	62.6	kwh	644	138	kwh	1.50
Total Process			644			1.50
Transportation Energy						
Pipeline-natural gas	0.50	ton-miles		1.61	tonne-km	
Natural gas	0.35	cu ft	0.39	0.022	cu meter	9.0E-04
Total Transportation			0.39			9.0E-04

References: F-4 and F-11

Source: Franklin Associates, A Division of ERG

Ethylene Oxide Production

The primary production method for ethylene oxide is the direct oxidation of ethylene using air or oxygen. The predominant feed for commercial oxidation processes is oxygen rather than air. The reaction is catalyzed by silver and is exothermic. Oil or boiling water is used to absorb the heat in a multitubular reactor and produce steam that is used in other parts of the process.

A disadvantage to the oxidation process is the conversion of ethylene to carbon dioxide and water, which is released to the environment. Excess ethylene is added to prevent additional oxidation of the ethylene oxide that would increase the production of carbon dioxide. This creates typical conversion rates for ethylene to ethylene oxide of only 10 to 20 percent per pass. Approximately 20 to 25 percent of the ethylene is broken down to carbon dioxide and water.

The energy requirements and environmental emissions for the production of ethylene oxide are shown in Table F-5. These data are a straight average of 6 ethylene oxide producers in the U.S. and Europe from 1990 through 1992. This average data was sent to a Plastics Division of the American Chemistry Council (ACC) member company that produces ethylene oxide for review. The company agreed that the energy and emissions are acceptable for 2005; however, new raw material estimates were provided by the Plastics Division of the American Chemistry Council (ACC) member company.

Ethylene Glycol Production

Ethylene glycol is produced by the hydration of ethylene oxide. The production process is generally close to the process unit for ethylene oxide. Ethylene oxide is very hazardous to handle and transport. In this case, crude oxide solution is used as feed to the glycol unit. Using crude solution avoids a refining step but still provides an adequate feed.

An excess amount of water is added to the reactor feed to reduce the amount of diethylene glycol and triethylene glycol. These glycols are produced from the reaction of monoethylene glycol with ethylene oxide. The hydration reaction can be uncatalyzed or catalyzed with an acid. An uncatalyzed reaction is much slower, but acid removal from the glycol is required if a catalyst is used.

Almost all the ethylene oxide is reacted. This glycol/water mixture is sent through an evaporator to concentrate the solution and recover the water. The water is recycled back to be used to prepare the ethylene oxide feed. High purity ethylene glycol is obtained from the concentrated glycol solution by vacuum distillation.

The energy and emissions data for ethylene glycol production is from a confidential source and is not shown to protect its confidentiality (Reference F-14).

Table F-5

DATA FOR THE PRODUCTION OF ETHYLENE OXIDE

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Ethylene	788	lb		788	kg	
Oxygen	880	lb		880	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	101	kwh	1,041	223	kwh	2.42
Natural gas	1,618	cu ft	1,812	101	cu meters	4.22
Total Process			2,854			6.64
Transportation Energy						
Used in PET						
Pipeline-petroleum products	1.00	ton-miles		3.22	tonne-km	
Electricity	0.022	kwh	0.22	0.048	kwh	5.2E-04
Total Transportation			0.22			5.2E-04
Used in polyether polyol for flexible foam PUR						
Rail	12.40	ton-miles		39.90	tonne-km	
Diesel	0.031	gal	4.88	0.26	liter	0.011
Pipeline-petroleum products	0.31	ton-miles		1.00	tonne-km	
Electricity	0.0068	kwh	0.069	0.015	kwh	1.6E-04
Total Transportation			4.95			0.012
Environmental Emissions						
Atmospheric Emissions						
Aldehydes	0.28	lb		0.28	kg	
Carbon Monoxide	3.0E-04	lb		3.0E-04	kg	
Carbon Dioxide	591	lb		591	kg	
Ethylene Oxides	0.10	lb		0.095	kg	
Hydrocarbons	18.1	lb		18.1	kg	
Methane	3.05	lb		3.05	kg	
Nitrogen Oxides	0.0014	lb		0.0014	kg	
Other Organics	0.68	lb		0.68	kg	
Sulfur Oxides	3.0E-04	lb		3.0E-04	kg	
Solid Wastes	16.8	lb		16.8	kg	
Waterborne Wastes						
Aldehydes	0.10	lb		0.10	kg	
Ammonia	5.0E-05	lb		5.0E-05	kg	
BOD	2.23	lb		2.23	kg	
Chromium	0.025	lb		0.025	kg	
COD	2.82	lb		2.82	kg	
Fluorides	0.0002	lb		2.0E-04	kg	
Zinc	0.010	lb		0.010	kg	

References: F-2, F-4, F-12, and F-13.

Source: Franklin Associates, A Division of ERG

Mixed Xylenes

The reforming processes are used to convert paraffinic hydrocarbon streams into aromatic compounds such as benzene, toluene, and xylene. Catalytic reforming has virtually replaced thermal reforming operations. Catalytic reforming has many advantages over thermal reforming including the following:

1. Greater production of aromatics
2. More olefin isomerization
3. More selective reforming and fewer end products
4. Operated at a low pressure, hence comparatively lower cost.

Catalysts such as platinum, alumina, or silica-alumina and chromium on alumina are used.

Table F-6 displays the energy and emissions data for the production of mixed xylenes. Total energy data for mixed xylenes were provided for this analysis by a confidential source. The mix of fuels shown in Table F-6 was calculated using statistics from a U.S. Department of Energy report (Reference F-16). No environmental emissions data were available.

Table F-6

DATA FOR THE PRODUCTION OF MIXED XYLENES FROM NAPHTHA

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Naphtha	1,000	lb		1,000	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	16.1	kwh	166	35.5	kwh	0.39
Natural gas	667	cu ft	747	41.6	cu meters	1.74
LPG	0.25	gal	27.0	2.09	liter	0.063
Bit./Sbit. Coal	7.02	lb	78.8	7.02	kg	0.18
Total Process			1,019			2.37

References: F-4, F-15, and F-16.

Source: Franklin Associates, A Division of ERG

Paraxylene Extraction

Reformate feedstock rich in xylenes is fractionated to obtain a stream rich in the para-isomer. Further purification is accomplished by heat exchange and refrigeration. The solid paraxylene crystals are separated from the feedstock by centrifugation.

Table F-7 displays the energy requirements for the production of paraxylene. Total energy data for paraxylene were provided for this analysis by a confidential source. The mix of fuels shown in Table F-7 was calculated using statistics from a U.S. Department of Energy report (Reference F-16). No environmental emissions data were available.

Table F-7

DATA FOR THE EXTRACTION OF PARAXYLENE

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Mixed Xylenes	1,000	lb		1,000	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	59.0	kwh	607	130	kwh	1.41
Natural gas	2,445	cu ft	2,738	153	cu meters	6.37
LPG	0.91	gal	98.4	7.59	liter	0.23
Bit./Sbit. Coal	25.7	lb	289	25.7	kg	0.67
Total Process			3,733			8.69
Transportation Energy						
Rail	650	ton-miles		2092	tonne-km	
Diesel	1.61	gal	256	13.5	liter	0.60
Total Transportation			256			0.60

References:F-2, F-4, F-16, and F-17.

Source: Franklin Associates, A Division of ERG

Crude Terephthalic Acid (TPA) Production

Crude terephthalic acid is manufactured primarily by the oxidation of paraxylene in the liquid phase. Liquid paraxylene, acetic acid, and a catalyst, such as manganese or cobalt bromides, are combined as the liquid feed to the oxidizers. The temperature of this exothermic reaction is maintained at about 200° C. The pressure may range from 300 to 400 psi.

Reactor effluents are continuously removed from the reactor and routed to a series of crystallizers, where they are cooled by flashing the liquids. The partially oxidized impurities are more soluble in acetic acid and tend to remain in solution, while crude TPA crystallizes from the liquor.

The slurry from the crystallizers is sent to solid/liquid separators, where crude TPA is recovered in the solids. The liquid portion is distilled and acetic acid, methyl acetate, and water are recovered overhead. Acetic acid is removed from the solution and recycled back to the oxidizer.

Purified Terephthalic Acid (PTA) Production

There are two primary methods of crude TPA purification. The first, described here, is by direct production of fiber-grade TPA or purified terephthalic acid (PTA).

In the production of fiber-grade TPA from crude TPA, the crude acid is dissolved under pressure in water at 225 to 275° C. The solution is hydrogenated in the presence of a catalyst to convert some troublesome intermediates of reaction. The solution is then cooled, causing PTA to crystallize out.

Dimethyl Terephthalate (DMT) Production

The other primary method of crude TPA purification is by conversion of crude TPA to dimethyl terephthalate (DMT). DMT now makes up no more than 15 percent of the precursor s used for PET production within North America.

The common method for the production of DMT consists of four major steps: oxidation, esterification, distillation, and crystallization. A mixture of p-xylene and crude PTA is oxidized with air in the presence of a heavy metal catalyst. The acid mixture resulting from the oxidation is esterified with methanol to produce a mixture of esters. The crude ester mixture is distilled to remove all the heavy boilers and residue produced; the lighter esters are recycled to the oxidation section. The raw DMT is then sent to the crystallization section for removal of DMT isomers and aromatic aldehydes. Some byproducts are recovered, and usable materials are recycled (Reference F-21).

PET Melt Phase Polymerization

PET resin is manufactured by the esterification of PTA with ethylene glycol and loss of water, or by the trans-esterification of DMT with ethylene glycol and loss of methanol. Both reactions occur at 100 to 150° C in the presence of a catalyst. Bis (2-hydroxyethyl) terephthalate is produced as an intermediate. This intermediate then undergoes polycondensation under vacuum at 10 to 20° C above the melting point of PET (246° C). Ethylene glycol is distilled over, and PET resin with an I.V. (intrinsic viscosity) of 0.60 to 0.65 is produced. The resulting resin is cooled and pelletized.

PET Solid State Polymerization

The final step in PET resin manufacture is a solid state polymerization process. This step raises the temperature of the solid pellets to just below the melting point in the presence of a driving force to further the polymerization. Solid stating increases the final I.V. from 0.72 to 1.04. It also produces a polymer with low acetaldehyde content.

Table F-8 shows the combined energy usage and environmental emissions for the melt phase and the solid state polymerization steps for production of PET from both PTA and DMT. Scrap and heat are produced as coproducts during this process. A mass basis was used to partition the credit for scrap, while the energy amount for the steam was reported separately as recovered energy.

The data in this table includes an aggregation of TPA, PTA, DMT, and PET production. New data was collected for PTA (including TPA) and PET production. A weighted average using production amounts was calculated from the PTA production data from two plants collected from two leading producers in North America. A weighted average using production amounts was also calculated from the PET production data from two plants collected from two leading producers in North America. Data from primary sources in the early 1990's was used for DMT and PET from DMT production. The two PET technologies were weighted accordingly at 15 percent PET from DMT and 85 percent PET from PTA.

As of 2003 there were 16 PET producers and 29 PET plants in the U.S. (Reference F-2). As of 2001 there were 4 TPA/PTA producers and 6 TPA/PTA plants in the U.S. (Reference F-2). While data was collected from a small sample of plants, the PTA and PET producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American TPA/PTA and PET production. The average TPA/PTA and PET datasets were reviewed and accepted respectively by each TPA/PTA and PET data provider.

To assess the quality of the data collected for TPA/PTA, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for TPA/PTA include direct measurements, information provided by purchasing and utility records, and estimates. All data submitted for TPA/PTA represent the years 2001, 2003, and 2004 and production in the U.S.

To assess the quality of the data collected for PET from PTA, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for PET include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the PET data is the esterification of PTA with ethylene glycol. All data submitted for PET represent the years 2001, 2003, and 2004 and production in the U.S.

Table F-8

DATA FOR THE PRODUCTION OF
PET RESIN (1)
(Includes PET resin, PTA, DMT, and TPA)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials (2)						
Paraxylene	521	lb		521	kg	
Ethylene glycol	322	lb		322	kg	
Acetic acid	37.2	lb		37.2	kg	
Methanol	35.2	lb		35.2	kg	
Water Consumption	64.4	gal		537	liter	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	253	kwh	2,691	558	kwh	6.27
Electricity (cogeneration)	23.2	kwh	158	51.1	kwh	0.37
Natural gas	1,530	cu ft	1,714	95.5	cu meters	3.99
Bit./Sbit. Coal	18.4	lb	207	18.4	kg	0.48
Distillate oil	1.40	gal	222	11.7	liter	0.52
Residual oil	3.21	gal	551	26.8	liter	1.28
Recovered energy	61.2	thousand Btu	61.2	142	MJ	0.14
Total Process			5,482			12.8
Environmental Emissions						
Atmospheric Emissions						
Acetic Acid	0.051	lb		0.051	kg	
Aldehydes	0.094	lb		0.094	kg	
Bromine	0.079	lb		0.079	kg	
Carbon Dioxide	72.4	lb		72.4	kg	
Carbon Monoxide	5.68	lb		5.680	kg	
Methane	0.16	lb		0.16	kg	
Methyl Acetate	0.040	lb		0.040	kg	
NM Hydrocarbons	0.28	lb		0.280	kg	
Nitrogen Oxides	0.052	lb		0.05	kg	
Other Organics	0.94	lb		0.94	kg	
Particulates (unknown)	0.15	lb		0.15	kg	
Xylene	0.041	lb		0.041	kg	
Solid Wastes						
Landfilled	4.19	lb		4.19	kg	
Burned	0.31	lb		0.31	kg	
Waste-to-Energy	0.59	lb		0.59	kg	
Waterborne Wastes						
Aluminum	9.7E-07	lb		9.7E-07	kg	
Ammonia	0.11	lb		0.11	kg	
Ammonium ion	0.0013	lb		0.0013	kg	
Antimony	9.7E-07	lb		9.7E-07	kg	
BOD	0.30	lb		0.30	kg	
COD	0.76	lb		0.76	kg	
Dissolved solids	0.030	lb		0.030	kg	
Iron	9.7E-07	lb		9.7E-07	kg	
Metal ion	4.5E-06	lb		4.5E-06	kg	
Phenol	3.6E-06	lb		3.6E-06	kg	
Phosphates	5.1E-04	lb		5.1E-04	kg	
Suspended solids	0.054	lb		0.054	kg	
TOC	0.044	lb		0.044	kg	
Zinc	0.0055	lb		0.0055	kg	

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(1) PET dataset represents 15 percent from DMT technology and 85 percent from PTA technology.

(2) Methanol is produced as a coproduct of PET production from DMT. This coproduct is sent to the DMT production facilities. Due to the boundaries for this table, the recycled methanol amount is not included in the methanol raw materials.

References: F-10 and F-18 through F-20.

Source: Franklin Associates, A Division of ERG

REFERENCES

F-1. APC Plastics Industry Producers' Statistics Group, as compiled by VERIS Consulting, LLC. 2004.

F-2. Chemical profile information taken from the website: http://www.the-innovation-group.com/welcome.htm.

F-3. Estimates made by SPI contacts. 1991.

F-4. Franklin Associates estimate.

F-5. **Water Pollution Abatement Technology: Capabilities and Cost, Organic Chemicals Industry.** National Commission on Water Quality Report No. 75/03, June, 1975.

F-6. Data compiled by Franklin Associates, Ltd., based on contact with confidential Acetic Acid source. 1994.

F-7. Information and data collected from an APC member company producing Acetic Acid. 2004-2005.

F-8. **Hydrocarbon Processing.** Gas Processes 2002. May, 2002.

F-9. **Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources.** Fifth Edition. U.S. Environmental Protection Agency. July 1995.

F-10. Information and data collected from APC member and non-member companies producing Terephthalic Acid. 2004-2005.

F-11. Data compiled by Franklin Associates, Ltd., based on contact with confidential Oxygen sources in Europe. 1990-1993.

F-12. Data compiled by Franklin Associates, Ltd., based on contact with confidential Ethylene Oxide sources. 1990-1992.

F-13. Estimates from an APC member company producing Ethylene Oxide. 2005.

F-14. Data compiled by Franklin Associates, Ltd., based on contact with confidential Ethylene Glycol source. 1993.

F-15. Information and data collected from an APC member company producing mixed xylenes. 2004-2005.

F-16. **Energy and Environmental Profile of the U.S. Chemical Industry.** Prepared by Energetics Inc. for the U.S. Department of Energy. May, 2000.

F-17. Information and data collected from an APC member companies producing paraxylenes. 2004-2005.

F-18. Data compiled by Franklin Associates, Ltd., based on contact with confidential DMT sources. 1988-1992.

F-19. Data compiled by Franklin Associates, Ltd., based on contact with confidential PET sources using DMT technology. 1992-1993.

F-20. Information and data collected from APC member and non-member companies producing PET using PTA technology. 2004-2005.

F-21. Information taken from the website: http://www.gtchouston.com/technologie/otech-dmt.htm.

F-22 Methanex Corporation Environmental Excellence Report 2005-2007, p. 7. Information available at the website: www.methanex.com/environment/documents/2008_Environmental_Report.pdf.

APPENDIX G

GENERAL PURPOSE POLYSTYRENE (GPPS)

INTRODUCTION

This appendix discusses the manufacture of general purpose polystyrene (GPPS) resin. Examples of GPPS end-uses include food packaging, compact disc cases, and toys. Almost 6.5 billion pounds of polystyrene were produced in the U.S. and Canada in 2003 (Reference G-1). The material flow for GPPS resin is shown in Figure G-1. The total unit process energy and emissions data (cradle-to-GPPS) for GPPS are displayed in Table G-1. No fuel-related energy or emissions are included in Table G-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Olefins Production (Pygas)
- Benzene Production
- Ethylbenzene/Styrene Production
- Mineral Oil Production
- GPPS Resin

Crude oil production, distillation, desalting and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B.

Olefins Production (Pygas)

The primary process used for manufacturing olefins (including pyrolysis gasoline or pygas) is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is used within the hydrocracker to produce steam, while the remaining portion is exported from the hydrocracker as a coproduct, as discussed below. The offgas used within the hydrocracker is shown in Table G-2 as “Internal offgas use.” This offgas is shown as a weight of natural gas and petroleum input to produce the energy, as well as the energy amount produced from those weights.

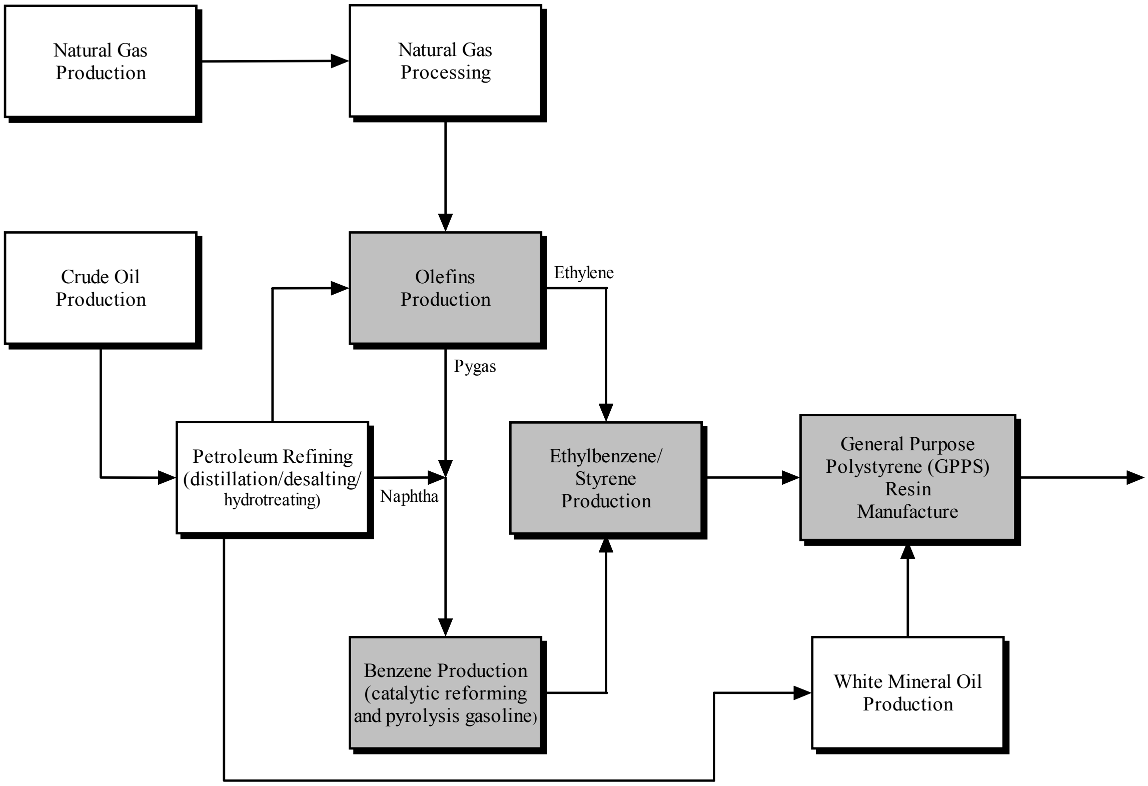

Figure G-1. Flow diagram for the production of general purpose polystyrene resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

Data was collected from individual plants, and a mass allocation was used to provide an output of 1,000 pounds/kilograms of olefin product. Then a weighted average using pygas production amounts was applied to the individual olefins plant production data collected from three leading producers (8 thermal cracking units) in North America. Transportation energy for pygas was estimated using location and capacity information (References G-19 and G-20). Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the hydrocracker, and the remaining inputs and outputs are allocated over the material hydrocracker products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{\text{attributed to remaining hydrocracker products}} \qquad \text{(Equation 1)}$$

where

IO = Input/Output Matrix to produce all products/coproducts

M_{EO} = Mass of Exported Offgas

M_{Total} = Mass of all Products and Coproducts (including fuels)

Table G-1

DATA FOR THE PRODUCTION
OF GENERAL PURPOSE POLYSTYRENE (GPPS) RESIN
(Cradle-to-Resin)
(page 1 of 3)

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Crude oil	712	lb		712	kg	
Natural Gas	407	lb		407	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			9,474			22.1
Petroleum			13,911			32.4
Total Resource			23,385			54.4
Process Energy						
Electricity (grid)	231	kwh	2,453	508	kwh	5.71
Electricity (cogeneration)	17.5	kwh	- (2)	38.5	kwh	-
Natural gas	9,876	cu ft	11,062	617	cu meters	25.8
LPG	0.10	gal	11.3	0.87	liter	0.026
Distillate oil	0.50	gal	79.7	4.19	liter	0.19
Residual oil	5.58	gal	958	46.6	liter	2.23
Gasoline	0.11	gal	15.4	0.90	liter	0.036
Diesel	0.0033	gal	0.52	0.027	liter	0.0012
Internal Offgas use (1)						
From Oil	39.9	lb	1,105	39.9	kg	2.57
From Natural Gas	79.3	lb	2,269	79.3	kg	5.28
Recovered Energy	4.17	thousand Btu	4.17	9.69	MJ	0.0097
Total Process			17,949			41.8
Transportation Energy						
Combination truck	88.4	ton-miles		284.5	tonne-km	
Diesel	0.93	gal	147	7.75	liter	0.34
Rail	142	ton-miles		456.8	tonne-km	
Diesel	0.35	gal	55.9	2.94	liter	0.13
Barge	425	ton-miles		1368	tonne-km	
Diesel	0.34	gal	54.0	2.84	liter	0.13
Residual oil	1.13	gal	194	9.43	liter	0.45
Ocean freighter	1,187	ton-miles		3819	tonne-km	
Diesel	0.23	gal	35.8	1.88	liter	0.083
Residual	2.03	gal	348	16.9	liter	0.81
Pipeline-natural gas	238	ton-miles		765	tonne-km	
Natural gas	164	cu ft	184	10.2	cu meter	0.43
Pipeline-petroleum products	244	ton-miles		785	tonne-km	
Electricity	5.32	kwh	54.5	11.7	kwh	0.13
Total Transportation			1,074			2.50

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table G-1

DATA FOR THE PRODUCTION
OF GENERAL PURPOSE POLYSTYRENE (GPPS) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.031	lb	0.031	kg
Ammonia	0.015	lb	0.015	kg
Benzene	0.046	lb	0.046	kg
Carbon Dioxide (fossil)	335	lb	335	kg
Carbon Monoxide	9.99	lb	9.99	kg
Carbon Tetrachloride	8.7E-09	lb	8.7E-09	kg
Chlorine	1.3E-04	lb	1.3E-04	kg
Ethylbenzene	0.0057	lb	0.0057	kg
HCFC-22	0.0010	lb	0.0010	kg
Hydrocarbons (NM)	1.67	lb	1.67	kg
Hydrogen	0.0026	lb	0.0026	kg
Hydrogen Chloride	5.5E-07	lb	5.5E-07	kg
Methane	9.42	lb	9.42	kg
Methyl Ethyl Ketone	2.6E-04	lb	2.6E-04	kg
Nitrogen Oxides	0.43	lb	0.43	kg
Other Organics	0.011	lb	0.011	kg
Particulates (unknown)	0.23	lb	0.23	kg
PM2.5	0.0078	lb	0.0078	kg
PM10	0.056	lb	0.056	kg
Sulfur Oxides	13.6	lb	13.6	kg
Toluene	0.071	lb	0.071	kg
Trichloroethane	7.1E-08	lb	7.1E-08	kg
VOC	0.38	lb	0.38	kg
Xylene	0.041	lb	0.041	kg
Solid Wastes				
Landfilled	38.6	lb	38.6	kg
Burned	3.43	lb	3.43	kg
Waste-to-Energy	1.55	lb	1.55	kg
Waterborne Wastes				
1-Methylfluorene	5.4E-07	lb	5.4E-07	kg
2,4-Dimethylphenol	1.3E-04	lb	1.3E-04	kg
2-Hexanone	3.1E-05	lb	3.1E-05	kg
2-Methylnapthalene	7.6E-05	lb	7.6E-05	kg
4-Methyl-2-Pentanone	2.0E-05	lb	2.0E-05	kg
Acetone	4.8E-05	lb	4.8E-05	kg
Alkylated benzenes	1.5E-04	lb	1.5E-04	kg
Alkylated fluorenes	8.8E-06	lb	8.8E-06	kg
Alkylated naphthalenes	2.5E-06	lb	2.5E-06	kg
Alkylated phenanthrenes	1.0E-06	lb	1.0E-06	kg
Alkalinity	0.38	lb	0.38	kg
Aluminum	0.28	lb	0.28	kg
Ammonia	0.077	lb	0.077	kg
Antimony	1.7E-04	lb	1.7E-04	kg
Arsenic	0.0012	lb	0.0012	kg
Barium	3.89	lb	3.89	kg
Benzene	0.0080	lb	0.0080	kg
Benzoic acid	0.0048	lb	0.0048	kg
Beryllium	6.3E-05	lb	6.3E-05	kg
BOD	1.22	lb	1.22	kg
Boron	0.015	lb	0.015	kg
Bromide	1.02	lb	1.02	kg
Cadmium	1.8E-04	lb	1.8E-04	kg
Calcium	15.4	lb	15.4	kg
Chlorides	173	lb	173	kg
Chromium (unspecified)	0.0079	lb	0.0079	kg
Chromium (hexavalent)	2.7E-05	lb	2.7E-05	kg
Cobalt	1.1E-04	lb	1.1E-04	kg
COD	2.39	lb	2.39	kg
Copper	0.0011	lb	0.0011	kg
Cyanide	1.3E-06	lb	1.3E-06	kg

Table G-1

DATA FOR THE PRODUCTION OF GENERAL PURPOSE POLYSTYRENE (GPPS) RESIN

(Cradle-to-Resin)

(page 3 of 3)

	English units (Basis: 1,000 lb)	SI units (Basis: 1,000 kg)
Dibenzofuran	9.1E-07 lb	9.1E-07 kg
Dibenzothiophene	7.4E-07 lb	7.4E-07 kg
Dissolved Solids	214 lb	214 kg
Ethylbenzene	0.0015 lb	0.0015 kg
Fluorine	4.5E-06 lb	4.5E-06 kg
Hardness	47.3 lb	47.3 kg
Hexanoic acid	0.0010 lb	0.0010 kg
Hydrocarbons	1.0E-05 lb	1.0E-05 kg
Iron	0.60 lb	0.60 kg
Lead	0.0023 lb	0.0023 kg
Lead 210	5.0E-13 lb	5.0E-13 kg
Lithium	2.26 lb	2.26 kg
Magnesium	3.00 lb	3.00 kg
Manganese	0.0048 lb	0.0048 kg
Mercury	3.0E-06 lb	3.0E-06 kg
Methylchloride	1.9E-07 lb	1.9E-07 kg
Methyl Ethyl Ketone	3.8E-07 lb	3.8E-07 kg
Molybdenum	1.1E-04 lb	1.1E-04 kg
m-Xylene	1.4E-04 lb	1.4E-04 kg
Naphthalene	8.7E-05 lb	8.7E-05 kg
n-Decane	1.4E-04 lb	1.4E-04 kg
n-Docosane	5.1E-06 lb	5.1E-06 kg
n-Dodecane	2.6E-04 lb	2.6E-04 kg
n-Eicosane	7.3E-05 lb	7.3E-05 kg
n-Hexacosane	3.2E-06 lb	3.2E-06 kg
n-Hexadecane	2.9E-04 lb	2.9E-04 kg
Nickel	0.0011 lb	0.0011 kg
n-Octadecane	7.1E-05 lb	7.1E-05 kg
n-Tetradecane	1.2E-04 lb	1.2E-04 kg
o + p-Xylene	1.1E-04 lb	1.1E-04 kg
o-Cresol	1.4E-04 lb	1.4E-04 kg
Oil	0.12 lb	0.12 kg
p-Cresol	1.5E-04 lb	1.5E-04 kg
p-Cymene	4.8E-07 lb	4.8E-07 kg
Pentamethylbenzene	3.6E-07 lb	3.6E-07 kg
Phenanthrene	1.0E-06 lb	1.0E-06 kg
Phenol/Phenolic cmpds	0.0029 lb	0.0029 kg
Phosphates	0.0010 lb	0.0010 kg
Radium 226	1.7E-10 lb	1.7E-10 kg
Radium 228	8.8E-13 lb	8.8E-13 kg
Selenium	3.4E-05 lb	3.4E-05 kg
Silver	0.010 lb	0.010 kg
Sodium	48.7 lb	48.7 kg
Strontium	0.26 lb	0.26 kg
Styrene	0.0010 lb	0.0010 kg
Sulfates	0.35 lb	0.35 kg
Sulfides	9.2E-04 lb	9.2E-04 kg
Sulfur	0.013 lb	0.013 kg
Surfactants	0.0043 lb	0.0043 kg
Suspended Solids	8.72 lb	8.72 kg
Thallium	3.7E-05 lb	3.7E-05 kg
Tin	8.3E-04 lb	8.3E-04 kg
Titanium	0.0027 lb	0.0027 kg
TOC	5.6E-04 lb	5.6E-04 kg
Toluene	0.0076 lb	0.0076 kg
Total biphenyls	9.9E-06 lb	9.9E-06 kg
Total dibenzothiophenes	3.0E-08 lb	3.0E-08 kg
Vanadium	1.3E-04 lb	1.3E-04 kg
Xylene (unspecified)	0.0038 lb	0.0038 kg
Yttrium	3.2E-05 lb	3.2E-05 kg
Zinc	0.0066 lb	0.0066 kg

References: Tables B-2 through B-6 and G-2 through G-6.

Source: Franklin Associates, A Division of ERG models

Table G-2

DATA FOR THE PRODUCTION OF PYGAS

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials (1)							
Refined Petroleum Products	419	lb			419	kg	
Processed Natural Gas	584	lb			584	kg	
Water Consumption	150	gal			1,251	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	52.6	kwh		560	116	kwh	1.30
Electricity (cogeneration)	19.2	kwh		131	42.3	kwh	0.31
Natural Gas	1,544	cu ft		1,730	96.4	cu meters	4.03
Gasoline	0.0022	gal		0.31	0.018	liter	7.3E-04
Diesel	0.0019	gal		0.30	0.016	liter	7.1E-04
Internal Offgas use (2)							
From Oil	74.2	lb		2,103	74.2	kg	4.90
From Natural Gas	105	lb		2,961	105	kg	6.89
Recovered Energy	2.50	thousand Btu		2.50	5.82	MJ	0.0058
Total Process				7,482			17.4
Transportation Energy							
Rail	115	ton-miles			370.1	tonne-km	
Diesel	0.29	gal		45.3	2.38	liter	0.11
Pipeline-Petroleum Products	1.55	ton-miles			4.99	tonne-km	
Electricity	0.034	kwh		0.35	0.074	kwh	8.0E-04
Total Transportation				45.6			0.11
Environmental Emissions							
Atmospheric Emissions - Process							
Carbon Monoxide	0.0010	lb	(3)		0.0010	kg	
Chlorine	1.0E-04	lb	(3)		1.0E-04	kg	
HCFC-022	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen Chloride	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen	0.0052	lb			0.0052	kg	
Hydrocarbons (NM)	0.11	lb			0.11	kg	
Methane	0.0010	lb	(3)		0.0010	kg	
Other Organics	0.0010	lb	(3)		0.0010	kg	
Particulates (unspecified)	0.010	lb			0.010	kg	
Particulates (PM10)	0.10	lb	(3)		0.10	kg	
Sulfur Oxides	0.0044	lb			0.0044	kg	
VOC	0.010	lb	(3)		0.010	kg	
Atmospheric Emissions - Fuel-Related (4)							
Carbon Dioxide (fossil)	661	lb			661	kg	
Carbon Monoxide	0.29	lb			0.29	kg	
Nitrogen Oxides	0.43	lb			0.43	kg	
PM 2.5	0.009	lb			0.009	kg	
Sulfur Oxides	0.068	lb			0.068	kg	
Solid Wastes							
Landfilled	0.36	lb			0.36	kg	
Burned	6.89	lb			6.89	kg	
Waste-to-Energy	0.0047	lb			0.0047	kg	
Waterborne Wastes							
Acetone	1.0E-08	lb	(3)		1.0E-08	kg	
Benzene	1.0E-05	lb	(3)		1.0E-05	kg	
BOD	3.5E-04	lb			3.5E-04	kg	
COD	0.010	lb	(3)		0.010	kg	
Ethylbenzene	1.0E-05	lb	(3)		1.0E-05	kg	
Naphthalene	1.0E-08	lb	(3)		1.0E-08	kg	
Phenol	0.0010	lb	(3)		0.0010	kg	
Styrene	1.0E-06	lb	(3)		1.0E-06	kg	
Suspended Solids	0.0028	lb			0.0028	kg	
Toluene	1.0E-04	lb	(3)		1.0E-04	kg	
Total Organic Carbon	0.0010	lb	(3)		0.0010	kg	
Xylene	1.0E-06	lb	(3)		1.0E-06	kg	

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(1) Specific raw materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(3) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(4) These fuel-related emissions were provided by the plants. These take into account the combustion of the offgas as well as the natural gas.

References: G-5, G-6, and G-19 through G-21.

Source: Franklin Associates, A Division of ERG

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table G-2 shows the averaged energy and emissions data for the production of pyrolysis gasoline.

As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. (Reference G-20). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American olefins production. All data collected were individually reviewed by the data providers.

To assess the quality of the data collected for olefins, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for olefins include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for olefins is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this module represent steam cracking of natural gas and petroleum. All data submitted for olefins represent the year 2003 and U.S. and Canada production.

Benzene Production

Benzene is the most widely used aromatic petrochemical raw material. The two major sources of benzene are catalytic reformate and pyrolysis gasoline (Reference G-2). Additional benzene is produced by the dealkylation of the toluene.

In the reforming process, naphtha is fed through a catalyst bed at elevated temperatures and pressures. The most common type of reforming process is platforming, in which a platinum-containing catalyst is used. Products obtained from the platforming process include aromatic compounds (benzene, toluene, xylene), hydrogen, light gas, and liquefied petroleum gas. The aromatics content of the reformate varies and is normally less than 45 percent. The reformate from the platforming process undergoes solvent extraction and fractional distillation to produce pure benzene, toluene, and other coproducts.

Pyrolysis gasoline is a byproduct of the steam cracking of hydrocarbons for the production of ethylene and propylene. Raw pyrolysis gas is composed of a mixture of C_5 to C_8 hydrocarbons, including several aromatic compounds. To separate the aromatics from the resulting mixture, a very polar solvent (commonly an alcohol) is used to dissolve the aromatic components. The aromatics can then be separated from the solvent using fractional distillation. The solvent is recovered and re-used.

Table G-3 represents the energy requirements and environmental emissions for producing benzene. Only catalytic reforming and pyrolysis gasoline are considered as the source of benzene in this analysis. These sources account for 70 percent of the world production of benzene (Reference G-3). It is estimated that one-third of this production is

Table G-3

DATA FOR THE PRODUCTION OF BENZENE

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Naphtha	667	lb			667	kg	
Pygas from Hydrocracker	335	lb			335	kg	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	7.22	kwh		74.3	15.9	kwh	0.17
Electricity (cogeneration)	4.35	kwh		29.7	9.59	kwh	0.069
Natural gas	631	cu ft		707	39.4	cu meters	1.65
Distillate oil	0.40	gal		63.5	3.34	liter	0.15
Residual oil	3.87	gal		664	32.3	liter	1.55
Internal Offgas use (1)							
From Oil	16.0	lb		401	16.0	kg	0.93
From Natural Gas	22.1	lb		553	22.1	kg	1.29
Total Process				2,492			3.23
Transportation Energy							
Barge	57.5	ton-miles			92.5	ton-miles	
Diesel	0.046	gal		7.30	0.074	gal	11.8
Residual oil	0.15	gal		26.2	0.25	gal	42.2
Pipeline-petroleum products	0.50	ton-miles			0.80	tonne-km	
Electricity	0.011	kwh		0.11	0.024	kwh	2.6E-04
Total Transportation				33.7			54.0
Environmental Emissions							
Atmospheric Emissions							
Chlorine	1.0E-04	lb	(2)		1.0E-04	kg	
Carbon Dioxide	45.2	lb			45.2	kg	
Carbon Monoxide	0.010	lb	(2)		0.010	kg	
NM Hydrocarbons	0.010	lb	(2)		0.010	kg	
Nitrogen Oxides	0.062	lb			0.062	kg	
Hydrogen	1.0E-06	lb	(2)		1.0E-06	kg	
Particulates (unknown)	0.019	lb			0.019	kg	
PM2.5	0.010	lb	(2)		0.010	kg	
PM10	0.0010	lb	(2)		0.0010	kg	
Sulfur Oxides	0.44	lb			0.44	kg	
Solid Wastes							
Landfilled	0.43	lb			0.43	kg	
Burned	0.051	lb			0.051	kg	
Waterborne Wastes							
Benzene	1.0E-06	lb	(2)		1.0E-06	kg	
BOD	0.47	lb			0.47	kg	
COD	1.08	lb			1.08	kg	
Dissolved solids	0.11	lb			0.11	kg	
Oil	0.018	lb			0.018	kg	
Sulfides	0.0010	lb	(2)		0.0010	kg	
Suspended Solids	0.0010	lb	(2)		0.0010	kg	
TOC	1.0E-05	lb	(2)		1.0E-05	kg	

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(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: G-5 through G-9

Source: Franklin Associates, A Division of ERG

from pyrolysis gasoline and two-thirds are produced from catalytic reforming (Reference G-4). The collected datasets were weighted using these fractions.

Numerous aromatic coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the aromatics separation process, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs, and the remaining inputs and outputs are allocated over the material aromatics products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{\text{attributed to remaining aromatics products}} \qquad \text{(Equation 1)}$$

where

IO = Input/Output Matrix to produce all products/coproducts

M_{EO} = Mass of Exported Offgas

M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table G-3 shows the averaged energy and emissions data for the production of benzene.

As of 2002 there were 22 benzene producers and 38 benzene plants in the U.S. for the three standard technologies (Reference G-19). The benzene data collected for this module represent 1 producer and 1 plant in the U.S. While data was collected from a small sample of plants, the benzene producer who provided data for this module verified that the characteristics of their plant is representative of the extraction of benzene from pyrolysis gasoline for North American benzene production. The average dataset was reviewed and accepted by the benzene data provider.

One of the three datasets was collected for this project and represents 2003 data, while the other two datasets comes from 1992. The 2003 data were collected from direct measurements and engineering estimates. The collection methods for the 1992 data are unknown.

Ethylbenzene/Styrene Production

The production of styrene monomer is accomplished through a series of processes. The first is the production of ethylbenzene by the alkylation of benzene with ethylene. In this process, benzene initially passes through a drying column. From the drying column, the benzene and ethylene are mixed in a reactor with a suitable catalyst. This reaction is exothermic and occurs at relatively low pressures and temperatures. Unreacted benzene is removed and recycled back to the process. The ethylbenzene is then separated from the solution. The heavy bottoms, tars, and vent gases are burned while the solution is recycled back to the reactor.

Styrene is produced by dehydrogenation of ethylbenzene. The ethylbenzene is mixed with steam, then allowed to come in contact with a catalyst in a reactor. This reaction is carried out at high temperature under vacuum. The heat is recovered from this reaction, and the hydrocarbon solution is sent to a series of fractionation units. The first separation removes the small amount (4 to 6 percent) of toluene and benzene produced by cracking. This toluene/benzene stream is typically sent back to the benzene plant. The second separation removes unreacted ethylbenzene and recycles it back into the system. Purified styrene monomer is recovered in the third and final phase. Bottoms or tar residue is removed from this third phase (Reference G-10).

Table G-4 displays the energy requirements and environmental emissions for the production of styrene including the production of ethylbenzene. Two of the three ethylbenzene/styrene datasets were collected for this project and represents 2002-2003 data, while the other dataset comes from 1993. The 2003 data were collected from direct measurements, purchasing/utility records, and engineering estimates. The collection methods for the 1993 data are unknown. Various coproduct streams are produced during this process. A mass basis was used to partition the credit for these coproducts.

As of 2001 there were 8 styrene producers and 8 styrene plants in the U.S. (Reference G-5). The styrene data collected for this module represent 2 producers and 2 plants in the U.S. While data was collected from a small sample of plants, the styrene producers who provided data for this module verified that the characteristics of their plants are representative of North American styrene production. The average dataset was reviewed and accepted by the styrene data providers.

Mineral Oil Production

Mineral oils are mixtures of highly refined paraffinic and naphthenic liquid hydrocarbons and have boiling points greater than 200° Celsius (Reference G-14). The initial distillation of crude oil is used to remove lighter petroleum fractions, such as gasoline and naphtha, and the remaining fractions consist of raw materials for fuel oil, coke, lubrication grease, and asphalts. This residue is processed through a vacuum distillation column to isolate the raw materials for lubricating oil production.

Lubricating oil production includes hydrotreating, deasphalting, and dewaxing processes that eliminate components such as multiple-ring aromatics, asphalt-like compounds, and straight-chain paraffins. The extensive refining requirements for mineral oil production result in high energy requirements in comparison to other refinery products. However, mineral oil (and other components of the lubricating oil category) represent less than one percent of total refinery output; thus, while they are energy intensive, they represent a small share of total refinery energy.

Table G-4

**DATA FOR THE PRODUCTION
OF ETHYLBENZENE/STYRENE**

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Ethylene	293	lb			293	kg	
Benzene	783	lb			783	kg	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	74.2	kwh		764	164	kwh	1.78
Electricity (cogeneration)	0.10	kwh		0.68	0.22	kwh	0.0016
Natural gas	6,835	cu ft		7,655	427	cu meters	17.8
Total Process				8,419			19.6
Transportation Energy							
To Polystyrene product							
Combination truck	75.5	ton-miles			243	tonne-km	
Diesel	0.79	gal		126	6.61	liter	0.29
Rail	103	ton-miles			330	tonne-km	
Diesel	0.25	gal		40.4	2.12	liter	0.094
Barge	326	ton-miles			1049	tonne-km	
Diesel	0.26	gal		41.4	2.18	liter	0.096
Residual oil	0.87	gal		149	7.24	liter	0.35
Ocean freighter	78.0	ton-miles			251	tonne-km	
Diesel	0.015	gal		2.35	0.12	liter	0.0055
Residual	0.13	gal		22.9	1.11	liter	0.053
Total Transportation				382			0.89
To ABS product							
Rail	59.2	ton-miles			190.5	tonne-km	
Diesel	0.15	gal		23.3	1.23	liter	0.054
Barge	398	ton-miles			1281	tonne-km	
Diesel	0.32	gal		50.6	2.66	liter	0.12
Residual oil	1.06	gal		182	8.83	liter	0.42
Ocean freighter	62.7	ton-miles			202	tonne-km	
Diesel	0.012	gal		1.89	0.10	liter	0.0044
Residual	0.11	gal		18.4	0.89	liter	0.043
Total Transportation				276			0.64
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.27	lb			0.27	kg	
Carbon Dioxide	261	lb			261	kg	
NM Hydrocarbons	0.010	lb	(1)		0.010	kg	
Nitrogen Oxides	0.10	lb	(1)		0.10	kg	
Particulates (unknown)	0.010	lb	(1)		0.010	kg	
Sulfur Oxides	1.0E-04	lb	(1)		1.0E-04	kg	
VOC	0.0093	lb			0.0093	kg	
Solid Wastes							
Landfilled	1.61	lb			1.61	kg	
Burned	0.44	lb			0.44	kg	
Waterborne Wastes							
Ethylbenzene	0.0010	lb	(1)		0.0010	kg	
Styrene	0.0010	lb	(1)		0.0010	kg	
Suspended Solids	0.010	lb	(1)		0.010	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: G-11 through G-13

Source: Franklin Associates, A Division of ERG

Mineral oil is used in plastics, such as polystyrene, to improve and control the melt flow rate of the finished polymer (Reference G-14). The energy and environmental burdens in Table G-5 apply to the production of mineral oil.

General Purpose Polystyrene (GPPS) Resin Production

General-purpose polystyrene (GPPS) is produced by dispensing styrene in water in a reactor and polymerizing in the presence of initiators and suspending agents. Mass polymerization is the most common polymerization process for GPPS in the United States.

Mass polymerization, also known as bulk polymerization, is one of the simplest methods of polymerization. It is often used in the polymerization of step-growth polymers. During step-growth polymerization, the functional sites of monomers react, liberate a small molecule such as water, and repeat the reaction to produce longer and longer polymer chains. Mass polymerization does not suspend the reactants in a solution such as water or organic solvents. The absence of a reaction solution makes heat control difficult and, if not monitored carefully, a mass polymerization reaction can progress too rapidly and overheating or hot spots can occur in the reaction vessel. However, since water or organic solvents are not used, there is a lower chance for contamination of the product (References G-2 and G-17).

After the reactor and contents are cooled, the beads are dewatered and dried. The wastewater is sent to an effluent treatment facility. The dried beads are screened into different sizes and the GPPS resin is packed into containers for shipment to molders.

Data for the production of GPPS resin using mass polymerization were provided by four leading producers (6 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). The energy requirements and environmental emissions for the production of GPPS resin are shown in Table G-6. Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for scrap.

As of 2002 there were 12 PS producers and 24 PS plants in the U.S. (Reference G-5). These plants produce all types of polystyrene; it is unknown how many produce GPPS. While data was collected from a small sample of plants, the GPPS producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American GPPS production. The average dataset was reviewed and accepted by all GPPS data providers.

To assess the quality of the data collected for GPPS, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for GPPS include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the GPPS data represents polymerization by mass suspension. All data submitted for GPPS ranges from 2000 through 2003 and represents U.S. production.

Table G-5

DATA FOR THE PRODUCTION OF MINERAL OIL FROM REFINED OIL

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Refined oil	1,000	lb		1,000	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	188	kwh	1,935	414	kwh	4.50
Natural gas	1,195	cu ft	1,338	74.6	cu meters	3.12
LPG	0.93	gal	101	7.76	liter	0.23
Residual oil	21.8	gal	3,741	182	liter	8.71
Total Process			7,115			16.6
Transportation Energy						
Combination truck	275	ton-miles		885	tonne-km	
Diesel	2.89	gal	459	24.1	liter	1.07
Rail	275	ton-miles		885	tonne-km	
Diesel	0.68	gal	108	5.69	liter	0.25
Total Transportation			567			1.32
Environmental Emissions						
Atmospheric Emissions						
Methylethylketone (MEK)	0.10	lb		0.10	kg	
VOC	0.10	lb		0.10	kg	
Waterborne Wastes.						
Chromium (total)	0.0010	lb		0.0010	kg	
Chromium (Hexavalent)	8.7E-05	lb		8.7E-05	kg	
Phenolic Compounds	9.0E-04	lb		9.0E-04	kg	

References: G-6, G-8, and G-15

Source: Franklin Associates, A Division of ERG

Table G-6

DATA FOR THE PRODUCTION OF GENERAL PURPOSE POLYSTYRENE (GPPS)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Styrene	999	lb			999	kg	
Mineral oil	2.57	lb			2.57	kg	
Water Consumption	32.6	gal			272	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	52.2	kwh		537	115	kwh	1.25
Natural gas	321	cu ft		360	20.0	cu meter	0.84
Total Process				897			2.09
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.019	lb			0.019	kg	
HCFC-022	0.0010	lb	(1)		0.0010	kg	
Hydrocarbons (NM)	0.12	lb			0.12	kg	
Nitrogen Oxides	0.043	lb			0.043	kg	
Other Organics	0.010	lb	(1)		0.010	kg	
Particulates (unknown)	0.024	lb			0.024	kg	
Sulfur Oxides	3.3E-04	lb			3.3E-04	kg	
Solid Wastes							
Landfilled	0.63	lb			0.63	kg	
Burned	0.017	lb			0.017	kg	
Waste-to-Energy	1.54	lb			1.54	kg	
Waterborne Wastes							
Ammonia	1.0E-04	lb	(1)		5.0E-04	kg	
BOD	1.0E-04	lb	(1)		1.0E-04	kg	
Chromium	1.0E-05	lb	(1)		5.0E-05	kg	
Cyanide	1.0E-06	lb	(1)		1.0E-06	kg	
Dissolved solids	1.00	lb	(1)		1.00	kg	
Hydrocarbons	1.0E-05	lb	(1)		1.0E-05	kg	
Iron	1.0E-05	lb	(1)		1.0E-05	kg	
Lead	1.0E-05	lb	(1)		5.0E-05	kg	
Nickel	1.0E-05	lb	(1)		5.0E-05	kg	
Oil	1.0E-04	lb	(1)		1.0E-04	kg	
Phenol	1.0E-06	lb	(1)		1.0E-06	kg	
Phosphates	0.0010	lb	(1)		0.0010	kg	
Suspended Solids	1.0E-04	lb	(1)		5.0E-04	kg	
Zinc	1.5E-05	lb			5.0E-05	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: G-13 and G-18

Source: Franklin Associates, A Division of ERG

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APPENDIX H

HIGH-IMPACT POLYSTYRENE (HIPS)

INTRODUCTION

This appendix discusses the manufacture of high-impact polystyrene (HIPS) resin. Examples of HIPS end-uses are flatware and medical products. Almost 6.5 billion pounds of polystyrene in general were produced in the U.S. and Canada in 2003 (Reference H-1). The material flow for HIPS resin is shown in Figure H-1. The total unit process energy and emissions data (cradle-to-HIPS) for HIPS are displayed in Table H-1. No fuel-related energy or emissions are included in Table H-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Butadiene Production
- Polybutadiene Production
- HIPS Resin

Crude oil production, distillation, desalting and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B. Mixed xylenes production is discussed in Appendix F. Pygas production, benzene production, and ethylbenzene/styrene production are discussed in Appendix G.

Butadiene Production

Commercial routes to production of butadiene are dehydrogenation of n-butane and n-butenes, and formation as a by-product during the manufacture of olefins. As of 2002, almost all butadiene is produced as an ethylene steam-cracking coproduct (Reference H-2).

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

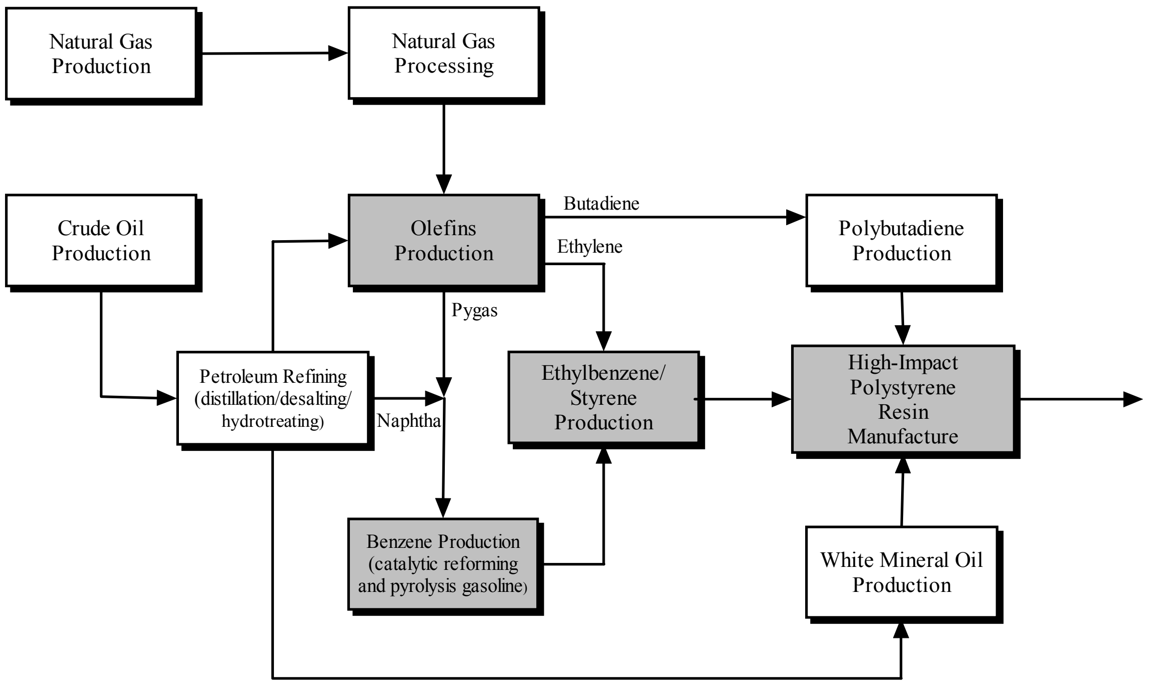

Figure H-1. Flow diagram for the production of high-impact polystyrene resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this APC analysis.

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is used within the hydrocracker to produce steam, while the remaining portion is exported from the hydrocracker as a coproduct, as discussed below. The offgas used within the hydrocracker is shown in Table H-2 as “Internal offgas use.” This offgas is shown as a weight of natural gas and petroleum input to produce the energy, as well as the energy amount produced from those weights.

Data was collected from individual plants, and a mass allocation was used to provide an output of 1,000 pounds/kilograms of olefin product. Then a weighted average using butadiene production amounts was applied to the individual olefins plant production data collected from three leading producers (3 thermal cracking units) in North America. Transportation amounts for butadiene were estimated (References H-2 and H-4). Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the hydrocracker, and the remaining inputs and outputs are allocated over the material hydrocracker products (Equation 1).

Table H-1

DATA FOR THE PRODUCTION
OF HIGH-IMPACT POLYSTYRENE (HIPS) RESIN
(Cradle-to-Resin)
(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	707	lb		707	kg	
Natural Gas	425	lb		425	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			9,883			23.0
Petroleum			13,823			32.2
Total Resource			23,706			55.2
Process Energy						
Electricity (grid)	235	kwh	2,500	518	kwh	5.82
Electricity (cogeneration)	24.0	kwh	- (2)	52.9	kwh	-
Natural gas	9,692	cu ft	10,856	605	cu meters	25.3
LPG	0.12	gal	12.8	0.99	liter	0.030
Distillate oil	0.49	gal	77.1	4.05	liter	0.18
Residual oil	5.72	gal	982	47.8	liter	2.29
Gasoline	0.11	gal	15.7	0.92	liter	0.036
Diesel	0.0033	gal	0.52	0.027	liter	0.0012
Internal Offgas use (1)						
From Oil	42.7	lb	1,184	42.7	kg	2.76
From Natural Gas	83.9	lb	2,390	83.9	kg	5.56
Recovered Energy	4.14	thousand Btu	4.14	9.63	MJ	0.0096
Total Process			18,014			41.9
Transportation Energy						
Combination truck	123	ton-miles		395.8	tonne-km	
Diesel	1.29	gal	205	10.8	liter	0.48
Rail	146	ton-miles		470.0	tonne-km	
Diesel	0.36	gal	57.5	3.02	liter	0.13
Barge	430	ton-miles		1383	tonne-km	
Diesel	0.34	gal	54.6	2.87	liter	0.13
Residual oil	1.14	gal	196	9.54	liter	0.46
Ocean freighter	1,180	ton-miles		3796	tonne-km	
Diesel	0.22	gal	35.6	1.87	liter	0.083
Residual	2.02	gal	346	16.8	liter	0.81
Pipeline-natural gas	249	ton-miles		800	tonne-km	
Natural gas	172	cu ft	192	10.7	cu meter	0.45
Pipeline-petroleum products	245	ton-miles		789	tonne-km	
Electricity	5.35	kwh	54.8	11.8	kwh	0.13
Total Transportation			1,142			2.66

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table H-1

DATA FOR THE PRODUCTION
OF HIGH-IMPACT POLYSTYRENE (HIPS) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)		**SI units (Basis: 1,000 kg)**	
Environmental Emissions				
Atmospheric Emissions				
Acid Mist (unknown)	1.0E-06	lb	1.0E-06	kg
Aldehydes	1.0E-06	lb	1.0E-06	kg
Ammonia	0.015	lb	0.015	kg
Benzene	0.048	lb	0.048	kg
Carbon Dioxide (fossil)	318	lb	318	kg
Carbon Monoxide	9.94	lb	9.94	kg
Carbon Tetrachloride	8.7E-09	lb	8.7E-09	kg
Chlorine	1.3E-04	lb	1.3E-04	kg
Ethylbenzene	0.0060	lb	0.0060	kg
HCFC-22	0.0010	lb	0.0010	kg
Hydrocarbons (NM)	2.41	lb	2.41	kg
Hydrogen	0.0024	lb	0.0024	kg
Hydrogen Chloride	5.2E-07	lb	5.2E-07	kg
Methane	9.72	lb	9.72	kg
Methyl Ethyl Ketone	0.0018	lb	0.0018	kg
Nitrogen Oxides	0.42	lb	0.42	kg
Other Organics	0.010	lb	0.010	kg
Particulates (unknown)	0.22	lb	0.22	kg
PM2.5	0.0073	lb	0.0073	kg
PM10	0.069	lb	0.069	kg
Sulfur Oxides	14.1	lb	14.1	kg
Toluene	0.075	lb	0.075	kg
Trichloroethane	7.1E-08	lb	7.1E-08	kg
VOC	0.40	lb	0.40	kg
Xylene	0.043	lb	0.043	kg
Solid Wastes				
Landfilled	41.5	lb	41.5	kg
Burned	3.72	lb	3.72	kg
Waste-to-Energy	1.15	lb	1.15	kg
Waterborne Wastes				
1-Methylfluorene	5.5E-07	lb	5.5E-07	kg
2,4-Dimethylphenol	1.4E-04	lb	1.4E-04	kg
2-Hexanone	3.2E-05	lb	3.2E-05	kg
2-Methylnapthalene	7.7E-05	lb	7.7E-05	kg
4-Methyl-2-Pentanone	2.0E-05	lb	2.0E-05	kg
Acetone	4.9E-05	lb	4.9E-05	kg
Alkylated benzenes	1.5E-04	lb	1.5E-04	kg
Alkylated fluorenes	8.9E-06	lb	8.9E-06	kg
Alkylated naphthalenes	2.5E-06	lb	2.5E-06	kg
Alkylated phenanthrenes	1.0E-06	lb	1.0E-06	kg
Alkalinity	0.39	lb	0.39	kg
Aluminum	0.28	lb	0.28	kg
Ammonia	0.078	lb	0.078	kg
Antimony	1.7E-04	lb	1.7E-04	kg
Arsenic	0.0012	lb	0.0012	kg
Barium	3.91	lb	3.91	kg
Benzene	0.0082	lb	0.0082	kg
Benzoic acid	0.0049	lb	0.0049	kg
Beryllium	6.3E-05	lb	6.3E-05	kg
BOD	1.24	lb	1.24	kg
Boron	0.015	lb	0.015	kg
Bromide	1.04	lb	1.04	kg
Cadmium	1.8E-04	lb	1.8E-04	kg
Calcium	15.6	lb	15.6	kg
Chlorides	176	lb	176	kg
Chromium (unspecified)	0.0079	lb	0.0079	kg
Chromium (hexavalent)	2.8E-05	lb	2.8E-05	kg
Cobalt	1.1E-04	lb	1.1E-04	kg
COD	2.42	lb	2.42	kg
Copper	0.0011	lb	0.0011	kg
Cyanide	1.4E-06	lb	1.4E-06	kg

Table H-1

**DATA FOR THE PRODUCTION
OF HIGH-IMPACT POLYSTYRENE (HIPS) RESIN
(Cradle-to-Resin)
(page 3 of 3)**

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Dibenzofuran	9.3E-07	lb	9.3E-07	kg
Dibenzothiophene	7.5E-07	lb	7.5E-07	kg
Dissolved Solids	220	lb	220	kg
Ethylbenzene	0.0014	lb	0.0014	kg
Fluorine	4.5E-06	lb	4.5E-06	kg
Hardness	48.2	lb	48.2	kg
Hexanoic acid	0.0010	lb	0.0010	kg
Iron	0.60	lb	0.60	kg
Lead	0.0023	lb	0.0023	kg
Lead 210	5.1E-13	lb	5.1E-13	kg
Lithium	2.36	lb	2.36	kg
Magnesium	3.06	lb	3.06	kg
Manganese	0.0049	lb	0.0049	kg
Mercury	3.1E-06	lb	3.1E-06	kg
Methylchloride	2.0E-07	lb	2.0E-07	kg
Methyl Ethyl Ketone	3.9E-07	lb	3.9E-07	kg
Molybdenum	1.1E-04	lb	1.1E-04	kg
m-Xylene	1.5E-04	lb	1.5E-04	kg
Naphthalene	8.9E-05	lb	8.9E-05	kg
n-Decane	1.4E-04	lb	1.4E-04	kg
n-Docosane	5.2E-06	lb	5.2E-06	kg
n-Dodecane	2.7E-04	lb	2.7E-04	kg
n-Eicosane	7.4E-05	lb	7.4E-05	kg
n-Hexacosane	3.3E-06	lb	3.3E-06	kg
n-Hexadecane	2.9E-04	lb	2.9E-04	kg
Nickel	0.0011	lb	0.0011	kg
n-Octadecane	7.3E-05	lb	7.3E-05	kg
n-Tetradecane	1.2E-04	lb	1.2E-04	kg
o + p-Xylene	1.1E-04	lb	1.1E-04	kg
o-Cresol	1.4E-04	lb	1.4E-04	kg
Oil and grease	0.12	lb	0.12	kg
p-Cresol	1.5E-04	lb	1.5E-04	kg
p-Cymene	4.9E-07	lb	4.9E-07	kg
Pentamethylbenzene	3.6E-07	lb	3.6E-07	kg
Phenanthrene	1.0E-06	lb	1.0E-06	kg
Phenol	0.0029	lb	0.0029	kg
Phosphates	0.0010	lb	0.0010	kg
Radium 226	1.8E-10	lb	1.8E-10	kg
Radium 228	9.0E-13	lb	9.0E-13	kg
Selenium	3.4E-05	lb	3.4E-05	kg
Silver	0.010	lb	0.010	kg
Sodium	49.6	lb	49.6	kg
Strontium	0.27	lb	0.27	kg
Styrene	9.4E-04	lb	9.4E-04	kg
Sulfates	0.36	lb	0.36	kg
Sulfides	8.7E-04	lb	8.7E-04	kg
Sulfur	0.013	lb	0.013	kg
Surfactants	0.0044	lb	0.0044	kg
Suspended Solids	8.88	lb	8.88	kg
Thallium	3.7E-05	lb	3.7E-05	kg
Tin	8.4E-04	lb	8.4E-04	kg
Titanium	0.0027	lb	0.0027	kg
TOC	5.9E-04	lb	5.9E-04	kg
Toluene	0.0078	lb	0.0078	kg
Total biphenyls	9.9E-06	lb	9.9E-06	kg
Total dibenzothiophenes	3.1E-08	lb	3.1E-08	kg
Vanadium	1.3E-04	lb	1.3E-04	kg
Xylene (unspecified)	0.0039	lb	0.0039	kg
Yttrium	3.3E-05	lb	3.3E-05	kg
Zinc	0.067	lb	0.067	kg

References: Tables B-2 through B-5, G-2, G-3, G-4, H-2, H-3, and H-4

Source: Franklin Associates, A Division of ERG models

$$[IO] \times \left(1 - \frac{M_{EO}}{M_{Total}}\right) = [IO]_{attributed\ to\ remaining\ hydrocracker\ products} \quad \text{(Equation 1)}$$

where
IO = Input/Output Matrix to produce all products/coproducts
M_{EO} = Mass of Exported Offgas
M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table H-2 shows the averaged energy and emissions data for the production of butadiene as a coproduct of olefins.

As of 2002, there were 7 butadiene producers and at least 11 butadiene plants in the U.S. (Reference H-2). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American butadiene production. All data collected were individually reviewed by the data providers.

To assess the quality of the data collected for butadiene, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for butadiene include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for butadiene is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this module represent steam cracking of natural gas and petroleum. All data submitted for butadiene represent the year 2003 and U.S. and Canada production.

Polybutadiene Production

Polybutadiene is manufactured by solution polymerization using Ziegler-Natta catalysts. The butadiene is treated to remove inhibitors and oxygen. It is then mixed with a solvent and passed through a drying column. The purified feed is fed to the reactors containing various modifiers and catalysts. The reactor effluent is sent to blend tanks for the addition of antioxidants and is then sent to dryers. The energy requirements and environmental emissions for the production of polybutadiene are shown in Table H-3. These data are from primary and secondary sources from the 1970s and were sent to a producer for review.

Table H-2

DATA FOR THE PRODUCTION OF BUTADIENE

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials (1)							
Refined Petroleum Products	360	lb			360	kg	
Processed Natural Gas	648	lb			648	kg	
Water Consumption	216	gal			1,802	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	123	kwh		1,310	271	kwh	3.05
Electricity (cogeneration)	14.0	kwh		95.8	30.9	kwh	0.22
Natural Gas	1,212	cu ft		1,357	75.6	cu meters	3.16
Gasoline	0.0032	gal		0.45	0.027	liter	0.0011
Diesel	0.0028	gal		0.44	0.023	liter	0.0010
Internal Offgas use (2)							
From Oil	84.6	lb		2,324	84.6	kg	5.41
From Natural Gas	146	lb		4,025	146	kg	9.37
Recovered Energy	3.61	thousand Btu		3.61	8.39	MJ	0.0084
Total Process				9,109			21.2
Transportation Energy							
Combination Truck	95.0	ton-miles			305.7	tonne-km	
Diesel	1.00	gal		158	8.32	liter	0.37
Rail	95.0	ton-miles			305.7	tonne-km	
Diesel	0.24	gal		37.4	1.97	liter	0.087
Pipeline-Petroleum Products	45.0	ton-miles			144.8	tonne-km	
Electricity	0.98	kwh		10.0	2.16	kwh	0.023
Total Transportation				206			0.48
Environmental Emissions							
Atmospheric Emissions - Process							
Carbon Monoxide	0.0010	lb	(3)		0.0010	kg	
HCFC-022	1.0E-06	lb	(3)		1.0E-06	kg	
Hydrogen	1.0E-04	lb	(3)		1.0E-04	kg	
Hydrocarbons (NM)	0.010	lb	(3)		0.010	kg	
Methane	0.0010	lb	(3)		0.0010	kg	
Other Organics	0.0010	lb	(3)		0.0010	kg	
Particulates (unspecified)	1.0E-04	lb	(3)		1.0E-04	kg	
Particulates (PM10)	0.10	lb	(3)		0.10	kg	
Sulfur Oxides	0.0010	lb	(3)		0.0010	kg	
VOC	0.010	lb	(3)		0.010	kg	
Atmospheric Emissions - Fuel-Related (4)							
Carbon Dioxide (fossil)	997	lb			997	kg	
Carbon Monoxide	0.083	lb			0.083	kg	
Nitrogen Oxides	0.53	lb			0.53	kg	
Sulfur Oxides	0.19	lb			0.19	kg	
Solid Wastes							
Landfilled	0.042	lb			0.042	kg	
Burned	7.50	lb			7.50	kg	
Waste-to-Energy	0.0068	lb			0.0068	kg	
Waterborne Wastes							
Acetone	1.0E-08	lb	(3)		1.0E-08	kg	
Benzene	1.0E-05	lb	(3)		1.0E-05	kg	
BOD	0.010	lb	(3)		0.010	kg	
COD	0.010	lb	(3)		0.010	kg	
Ethylbenzene	1.0E-05	lb	(3)		1.0E-05	kg	
Naphthalene	1.0E-08	lb	(3)		1.0E-08	kg	
Phenol	0.0010	lb	(3)		0.0010	kg	
Styrene	1.0E-06	lb	(3)		1.0E-06	kg	
Suspended Solids	0.010	lb	(3)		0.010	kg	
Toluene	1.0E-04	lb	(3)		1.0E-04	kg	
Total Organic Carbon	0.0010	lb	(3)		0.0010	kg	
Xylene	1.0E-06	lb	(3)		1.0E-06	kg	

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(1) Specific raw materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(3) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(4) These fuel-related emissions were provided by the plants. These take into account the combustion of the offgas as well as the natural gas.

References: H-2 through H-5

Source: Franklin Associates, A Division of ERG

Table H-3

DATA FOR THE PRODUCTION OF POLYBUTADIENE

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Butadiene	1,015	lb		1,015	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Natural gas	2,330	cu ft	2,610	145	cu meters	6.08
Total Process			2,610			6.08
Transportation Energy						
To HIPS product						
Combination truck	450	ton-miles		1,448	tonne-km	
Diesel	4.73	gal	750	39.4	liter	1.75
Rail	30.0	ton-miles		96.5	tonne-km	
Diesel	0.074	gal	11.8	0.62	liter	0.028
Barge	440	ton-miles		1,416	ton-miles	
Diesel	0.35	gal	55.9	2.94	liter	0.13
Residual oil	1.17	gal	201	9.77	liter	0.47
Total Transportation			1,019			2.37
To ABS product						
Combination truck	223	ton-miles		718	tonne-km	
Diesel	2.34	gal	372	19.5	liter	0.87
Rail	143	ton-miles		460	tonne-km	
Diesel	0.35	gal	56.3	2.96	liter	0.13
Ocean freighter	803	ton-miles		2,584	tonne-km	
Diesel	0.15	gal	24.2	1.27	liter	0.056
Residual	1.37	gal	236	11.5	liter	0.55
Total Transportation			688			1.60
Environmental Emissions						
Atmospheric Emissions						
Hydrocarbons	13.0	lb		13.0	kg	
Solid Wastes						
Landfilled	0.10	lb		0.10	kg	
Waterborne Wastes						
BOD	0.41	lb		0.41	kg	
COD	0.83	lb		0.83	kg	
Oil	0.070	lb		0.070	kg	
Suspended Solids	1.25	lb		1.25	kg	

References: H-6 through H-9

Source: Franklin Associates, A Division of ERG

High-impact Polystyrene (HIPS) Resin

High-impact polystyrene (HIPS) resin can be produced by suspension, mass, or solution polymerization. The North American producers that provided data in this analysis use mass polymerization. HIPS is produced by the polymerization of styrene in the presence of rubber, commonly polybutadiene. The rubber is dissolved within the styrene monomer before it is sent to prepolymerization, where the stabilizers, retardants and other additives are added. Production of these stabilizers, retardants, and additives are not included in this analysis. The types and quantities of these are determined by the end-use application of the HIPS resin; this is a "generic" analysis.

Mass polymerization, also known as bulk polymerization, is one of the simplest methods of polymerization. It is often used in the polymerization of step-growth polymers. During step-growth polymerization, the functional sites of monomers react, liberate a small molecule such as water, and repeat the reaction to produce longer and longer polymer chains. Mass polymerization does not suspend the reactants in a solution such as water or organic solvents. The absence of a reaction solution makes heat control difficult and, if not monitored carefully, a mass polymerization reaction can progress too rapidly and overheating or hot spots can occur in the reaction vessel. However, since water or organic solvents are not used, there is a lower chance for contamination of the product (References H-10 and H-11).

Data for the production of HIPS resin were provided by four leading producers (6 plants) in North America. Table H-4 gives the energy requirements and emissions for the production of high-impact polystyrene resin. Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for scrap.

As of 2002 there were 12 PS producers and 24 PS plants in the U.S. (Reference H-2). These plants produce all types of polystyrene; it is unknown how many produce HIPS. While data was collected from a small sample of plants, the HIPS producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American HIPS production. The average dataset was reviewed and accepted by all HIPS data providers.

To assess the quality of the data collected for HIPS, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for HIPS include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the HIPS data represents polymerization by mass suspension. All data submitted for HIPS ranges from 2000 through 2003 and represents U.S. production.

Table H-4

DATA FOR THE PRODUCTION OF HIGH-IMPACT POLYSTYRENE (HIPS)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Styrene	936	lb			936	kg	
Mineral oil	18.1	lb			18.1	kg	
Polybutadiene	64.0	lb			64.0	kg	
Water Consumption	28.0	gal			234	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	51.8	kwh		533	114	kwh	1.24
Electricity (cogeneration)	6.71	kwh		45.8	14.8	kwh	0.11
Natural gas	354	cu ft		396	22.1	cu meter	0.92
Total Process				975			2.27
Environmental Emissions							
Atmospheric Emissions							
Acid Mist	1.0E-06	lb	(1)		1.0E-06	kg	
Carbon Monoxide	0.011	lb			0.011	kg	
HCFCs	0.0010	lb	(1)		0.0010	kg	
Methane	0.0010	lb	(1)		0.0010	kg	
NM Hydrocarbons	0.028	lb			0.028	kg	
Nitrogen Oxides	0.038	lb			0.038	kg	
Other Organics	0.0094	lb			0.0094	kg	
Particulates (unknown)	0.016	lb			0.016	kg	
Particulates (PM10)	0.010	lb	(1)		0.010	kg	
Sulfur Oxides	1.0E-04	lb	(1)		1.0E-04	kg	
Solid Wastes							
Landfilled	3.13	lb			3.13	kg	
Burned	0.039	lb			0.039	kg	
Waste-to-Energy	1.14	lb			1.14	kg	
Waterborne Wastes							
Ammonia	1.E-04	lb	(1)		1.0E-04	kg	
BOD	1.E-04	lb	(1)		1.0E-04	kg	
Chromium	1.E-05	lb	(1)		1.0E-05	kg	
Cyanide	1.E-06	lb	(1)		1.0E-06	kg	
Dissolved solids	2.49	lb			2.49	kg	
Iron	1.E-05	lb	(1)		1.0E-05	kg	
Lead	1.E-05	lb	(1)		1.0E-05	kg	
Nickel	1.E-05	lb	(1)		1.0E-05	kg	
Oil	1.E-04	lb	(1)		1.0E-04	kg	
Phenol	1.E-06	lb	(1)		1.0E-06	kg	
Phosphates	0.0010	lb	(1)		0.0010	kg	
Suspended Solids	0.029	lb			0.029	kg	
Zinc	0.060	lb			0.060	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

References: H-6

Source: Franklin Associates, A Division of ERG

REFERENCES

H-1. APC Plastics Industry Producers' Statistics Group, as compiled by VERIS Consulting, LLC. 2004.

H-2. Chemical Profile: Butadiene. **Chemical Market Reporter.** March 18, 2002. Page 35.

H-3. Information and data collected from APC member and non-member companies producing olefins. 2004-2005.

H-4. Distances calculated using the websites: http://www.indo.com/distance/ and http://www.mapquest.com/.

H-5. Franklin Associates estimate.

H-6. Information and data collected from APC member and non-member companies producing HIPS resin. 2001-2003.

H-7. Texas Air Control Board, 1970 Emissions Data, Self-reporting System, Nonpublished data.

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APPENDIX I

POLYVINYL CHLORIDE (PVC)

INTRODUCTION

This appendix discusses the manufacture of polyvinyl chloride (PVC) resin. Over half of the PVC produced is used to manufacture pipe and siding. Almost 15 billion pounds of PVC was produced in the U.S. and Canada in 2003 (Reference I-1). The material flow for PVC resin is shown in Figure I-1. The total unit process energy and emissions data (cradle-to-PVC) for PVC are displayed in Table I-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Salt Mining
- Sodium Hydroxide or Chlorine Production
- Hydrochloric Acid Production
- Ethylene Dichloride (EDC) Production
- Vinyl Chloride Monomer (VCM) Production
- PVC Resin

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B.

No fillers, additives, or plasticizers are included in this analysis; therefore, no compounding process is included.

Salt Mining

Salt (sodium chloride) is an abundant, inexpensive commodity used mostly by the chlor-alkali and other chemical industries. The various technologies used include underground mining of rock salt, solution mining of salt brine, vacuum pan salt, and solar salt. Vacuum pan salt and solar salt represent a small portion of U.S. production and are thus not included in this data module. This data module represents a mix of underground mining and solution mining techniques.

Approximately 95 percent of salt-based chlorine and caustic facilities use brine salt. In solution mining, pressurized fresh water is introduced to the bedded salt through an injection well. The brine is then pumped to the surface for treatment.

Approximately 5 percent of salt-based chlorine and caustic facilities use rock salt. Rock salt mining uses the room and pillar method. The room and pillar method excavates a series of rectangular sections, leaving columns of undisturbed salt in order to support the mine roof. After rock salt is crushed in the mine, it is transported by conveyor belts to the surface. On the surface, the rock salt is screened and prepared for shipment.

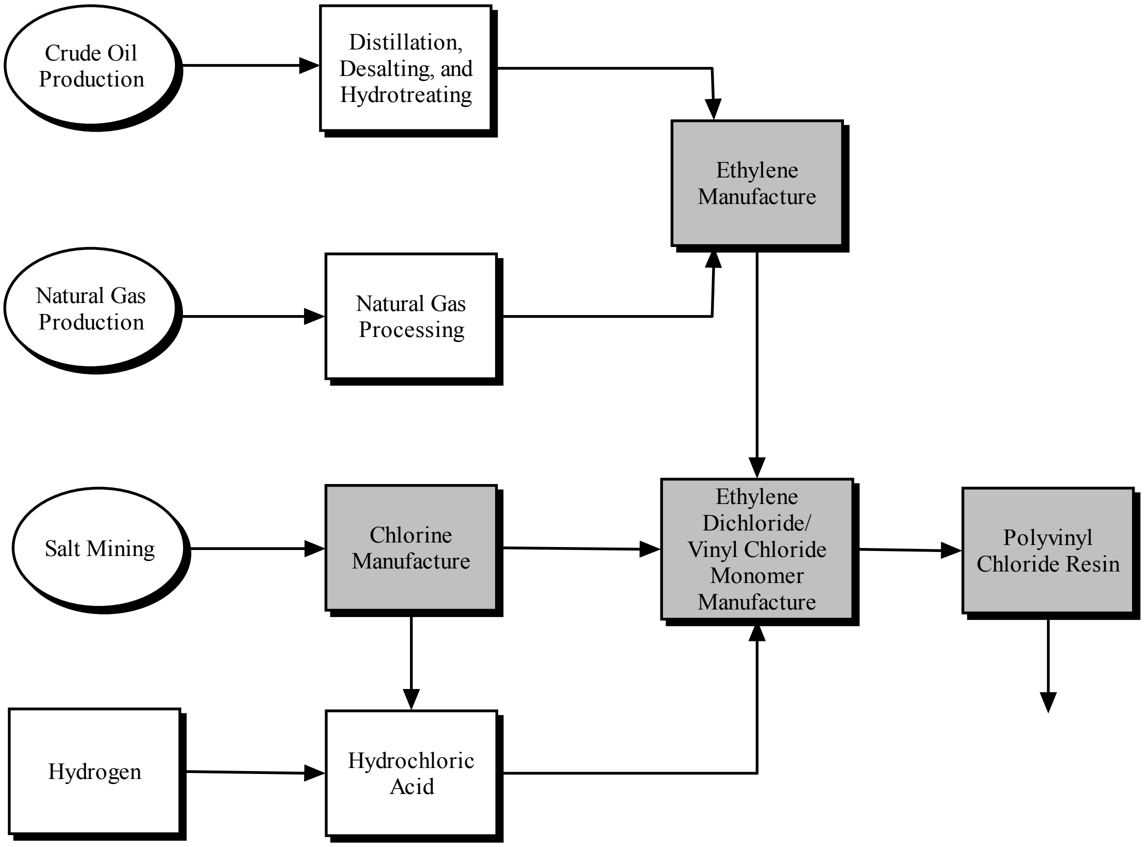

Figure I-1. Flow diagram for the manufacture of polyvinyl chloride (PVC) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

No data are available for the energy requirements of the solution mining of salt brine in the U.S. Energy data for the mining/extracting and purification of the salt in this analysis come from the Eco-profile of purified brine commissioned by PlasticsEurope. The transportation data was estimated from chlorine data collected from a confidential source.

Table I-1

DATA FOR THE PRODUCTION
OF POLYVINYL CHLORIDE (PVC) RESIN
(Cradle-to-Resin)
(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	87.2	lb		87.2	kg	
Natural Gas	387	lb		387	kg	
Salt	552	lb		552	kg	
Oxygen	144	lb		144	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			9,002			21.0
Petroleum			1,704			3.97
Total Resource			10,706			24.9
Process Energy						
Electricity (grid)	381	kwh	4,050	839	kwh	9.43
Electricity (cogeneration)	241	kwh	- (2)	532	kwh	-
Natural gas	6,952	cu ft	7,786	434	cu meters	18.1
LPG	0.013	gal	1.46	0.11	liter	0.0034
Bit./Sbit. Coal	22.3	lb	250	22.3	kg	0.58
Distillate oil	0.75	gal	119	6.27	liter	0.28
Residual oil	0.41	gal	69.5	3.38	liter	0.16
Gasoline	0.052	gal	7.37	0.43	liter	0.017
Diesel	0.0043	gal	0.68	0.036	liter	0.0016
Internal Offgas use (1)						
From Oil	11.8	lb	363	11.8	kg	0.84
From Natural Gas	53.9	lb	1,652	53.9	kg	3.85
Recovered Energy	5.44	thousand Btu	5.44	12.7	MJ	0.013
Total Process			14,294			33.3
Transportation Energy			13598.91079			
Combination truck	18.7	ton-miles		60.10	tonne-km	
Diesel	0.20	gal	31.1	1.64	liter	0.072
Rail	132	ton-miles		425.0	tonne-km	
Diesel	0.33	gal	52.0	2.73	liter	0.12
Barge	7.81	ton-miles		25.15	tonne-km	
Diesel	0.0063	gal	0.99	0.052	liter	0.0023
Residual oil	0.021	gal	3.57	0.17	liter	0.0083
Ocean freighter	146	ton-miles		471.1	tonne-km	
Diesel	0.028	gal	4.42	0.23	liter	0.010
Residual	0.25	gal	43.0	2.09	liter	0.10
Pipeline-natural gas	217	ton-miles		697	tonne-km	
Natural gas	150	cu ft	167	9.33	cu meter	0.39
Pipeline-petroleum products	123	ton-miles		395.4	tonne-km	
Electricity	2.68	kwh	27.4	5.90	kwh	0.064
Total Transportation			13929			0.77

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.0040	lb	0.0040	kg
Ammonia	0.0020	lb	0.0020	kg
Benzene	0.041	lb	0.041	kg
Carbon Dioxide (fossil)	72.6	lb	72.6	kg
Carbon Monoxide	1.29	lb	1.29	kg
Carbon Tetrachloride	1.18E-04	lb	1.2E-04	kg
Chlorine	0.17	lb	0.174	kg

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table I-1

DATA FOR THE PRODUCTION OF POLYVINYL CHLORIDE (PVC) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)	SI units (Basis: 1,000 kg)
Environmental Emissions		
Atmospheric Emissions		
Dioxins (1)	1.1E-10 lb	1.1E-10 kg
Ethylbenzene	0.0052 lb	0.0052 kg
HCFC-22	0.0010 lb	0.0010 kg
HCFC-123	5.6E-05 lb	5.6E-05 kg
HFC-134a	5.6E-05 lb	5.6E-05 kg
Hydrocarbons (NM)	0.24 lb	0.24 kg
Hydrogen	0.0018 lb	0.0018 kg
Hydrogen Chloride	0.0029 lb	0.0029 kg
Lead	6.8E-09 lb	6.8E-09 kg
Mercury	1.6E-05 lb	1.6E-05 kg
Methane	6.43 lb	6.43 kg
Nitrogen Oxides	0.066 lb	0.066 kg
Odorous Sulfur	0.028 lb	0.028 kg
Other Organics	0.046 lb	0.046 kg
Particulates (unknown)	0.13 lb	0.13 kg
PM2.5	0.0011 lb	0.0011 kg
PM10	0.059 lb	0.059 kg
Propylene Oxide	9.2E-05 lb	0.000 kg
Sulfur Oxides	10.7 lb	10.7 kg
Toluene	0.065 lb	0.065 kg
Trichloroethane	9.3E-09 lb	9.3E-09 kg
Vinyl Chloride (2)	0.039 lb	0.039 kg
VOC	0.34 lb	0.34 kg
Xylene	0.037 lb	0.037 kg
Solid Wastes		
Landfilled	16.0 lb	16.0 kg
Burned	5.84 lb	5.84 kg
Waste-to-Energy	21.7 lb	21.7 kg
Waterborne Wastes		
1-Methylfluorene	2.6E-07 lb	2.6E-07 kg
2,4-Dimethylphenol	6.3E-05 lb	6.3E-05 kg
2-Hexanone	1.5E-05 lb	1.5E-05 kg
2-Methylnapthalene	3.6E-05 lb	3.6E-05 kg
4-Methyl-2-Pentanone	9.5E-06 lb	9.5E-06 kg
Acetone	2.3E-05 lb	2.3E-05 kg
Alkylated benzenes	3.6E-05 lb	3.6E-05 kg
Alkylated fluorenes	2.1E-06 lb	2.1E-06 kg
Alkylated naphthalenes	5.9E-07 lb	5.9E-07 kg
Alkylated phenanthrenes	2.5E-07 lb	2.5E-07 kg
Alkalinity	0.18 lb	0.18 kg
Aluminum	0.067 lb	0.067 kg
Ammonia	0.031 lb	0.031 kg
Antimony	4.1E-05 lb	4.1E-05 kg
Arsenic	5.2E-04 lb	5.2E-04 kg
Barium	0.98 lb	0.98 kg
Benzene	0.0038 lb	0.0038 kg
Benzoic acid	0.0023 lb	0.0023 kg
Beryllium	2.5E-05 lb	2.5E-05 kg
BOD	0.58 lb	0.58 kg
Boron	0.0071 lb	0.0071 kg
Bromide	0.48 lb	0.48 kg
Cadmium	7.6E-05 lb	7.6E-05 kg
Calcium	7.25 lb	7.25 kg
Chlorides	81.5 lb	81.5 kg
Chromium (unspecified)	0.0020 lb	0.0020 kg
Chromium (hexavalent)	3.6E-06 lb	3.6E-06 kg
Cobalt	5.0E-05 lb	5.0E-05 kg
COD	0.74 lb	0.74 kg
Copper	3.7E-04 lb	3.7E-04 kg
Cyanide	1.2E-06 lb	1.2E-06 kg
Dibenzofuran	4.3E-07 lb	4.3E-07 kg
Dibenzothiophene	3.5E-07 lb	3.5E-07 kg

Table I-1

DATA FOR THE PRODUCTION
OF POLYVINYL CHLORIDE (PVC) RESIN
(Cradle-to-Resin)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Iron	0.17	lb	0.17	kg
Lead	8.1E-04	lb	8.1E-04	kg
Lead 210	2.3E-13	lb	2.3E-13	kg
Lithium	2.04	lb	2.04	kg
Magnesium	1.42	lb	1.42	kg
Manganese	0.0023	lb	0.0023	kg
Mercury	8.4E-07	lb	8.4E-07	kg
Methyl chloride	9.1E-08	lb	9.1E-08	kg
Methyl Ethyl Ketone	1.8E-07	lb	1.8E-07	kg
Molybdenum	5.2E-05	lb	5.2E-05	kg
m-Xylene	6.8E-05	lb	6.8E-05	kg
Naphthalene	4.1E-05	lb	4.1E-05	kg
n-Decane	6.6E-05	lb	6.6E-05	kg
n-Docosane	2.4E-06	lb	2.4E-06	kg
n-Dodecane	1.2E-04	lb	1.2E-04	kg
n-Eicosane	3.4E-05	lb	3.4E-05	kg
n-Hexacosane	1.5E-06	lb	1.5E-06	kg
n-Hexadecane	1.4E-04	lb	1.4E-04	kg
Nickel	4.3E-04	lb	4.3E-04	kg
Nitrates	0.010	lb	0.010	kg
n-Octadecane	3.4E-05	lb	3.4E-05	kg
n-Tetradecane	5.5E-05	lb	5.5E-05	kg
o + p-Xylene	5.0E-05	lb	5.0E-05	kg
o-Cresol	6.5E-05	lb	6.5E-05	kg
Oil and grease	0.046	lb	0.046	kg
p-Cresol	7.0E-05	lb	7.0E-05	kg
p-Cymene	2.3E-07	lb	2.3E-07	kg
Pentamethylbenzene	1.7E-07	lb	1.7E-07	kg
Phenanthrene	3.4E-07	lb	3.4E-07	kg
Phenol	0.0016	lb	0.0016	kg
Radium 226	8.2E-11	lb	8.2E-11	kg
Radium 228	4.2E-13	lb	4.2E-13	kg
Selenium	8.1E-06	lb	8.1E-06	kg
Silver	0.0047	lb	0.0047	kg
Sodium	23.0	lb	23.0	kg
Strontium	0.12	lb	0.12	kg
Styrene	4.5E-07	lb	4.5E-07	kg
Sulfates	0.17	lb	0.17	kg
Sulfides	2.3E-05	lb	2.3E-05	kg
Sulfur	0.0060	lb	0.0060	kg
Surfactants	0.0022	lb	0.0022	kg
Suspended Solids	2.39	lb	2.39	kg
Thallium	8.7E-06	lb	8.7E-06	kg
Tin	2.9E-04	lb	2.9E-04	kg
Titanium	6.3E-04	lb	6.3E-04	kg
TOC	4.5E-04	lb	4.5E-04	kg
Toluene	0.0036	lb	0.0036	kg
Total biphenyls	2.3E-06	lb	2.3E-06	kg
Total dibenzothiophenes	7.2E-09	lb	7.2E-09	kg
Vanadium	6.1E-05	lb	6.1E-05	kg
Vinyl Chloride (2)	0.0010	lb	0.0010	kg
Xylene (unspecified)	0.0018	lb	0.0018	kg
Yttrium	1.5E-05	lb	1.5E-05	kg
Zinc	0.0018	lb	0.0018	kg

Note: No additives or plasticizers are included in this data.

(1) This emission was provided by the Vinyl Institute based on 2003 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. The values are based on TM 17 congeners. If these amounts were converted to toxic equivalents, the TEQ would be 200 to 300 times lower.

(2) This vinyl chloride emission was provided by the Vinyl Institute, based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average.

References: Tables B-2 through B-6 and I-2 through I-5.

Source: Franklin Associates, A Division of ERG models

No U.S. data are available for air emissions from salt mining. Since salt mining involves no chemical reactions and minimal processing requirements, it is assumed that negligible process emissions result from salt mining. Total suspended solids (TSS) are the only BPT limited water effluent from sodium chloride production (Reference I-2). No data are available for other water effluents. However, BPT limitations for sodium chloride production by solution mining stipulate that no process wastewater is returned to navigable waters. Any solution remaining after the recovery of salt brine can be returned to the body of water or salt deposit from which it originally came (Reference I-3). Salt deposits are relatively pure and require minimal beneficiation (Reference I-4). Any overburden that may be removed during rock salt mining can be returned to the mining site after the salt is recovered. Similarly, solution mining is a technology that does not generate significant amounts of solid wastes. It is thus assumed that salt mining produces negligible quantities of solid waste.

Table I-2 displays the energy requirements for the mining/extraction and purification of salt.

Sodium Hydroxide or 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.

There are three commercial processes for the electrolysis of sodium chloride: (1) the diaphragm cell process, (2) the mercury cathode cell process, and (3) the membrane cell process. Diaphragm cell electrolysis is used for 66.4 percent of production, mercury cathode cell electrolysis is used for 8.6 percent of production, and membrane cell electrolysis is used for 22.9 percent of production (Reference I-8). Membrane cell electrolysis is the most recent of these technologies and is gradually gaining commercial acceptance. Membrane cell electrolysis has relatively low energy requirements, but its high capital costs have hindered its growth (Reference I-8). Limited data are available for membrane cell electrolysis; this data module thus assigns 91.4 percent of chlorine and caustic soda production to diaphragm/membrane cell electrolysis and 8.6 percent of chlorine and caustic soda production to mercury cathode cell electrolysis (Reference I-3). The mercury cell technology is more likely to be used to produce high-purity caustic, than chlorine to be used in EDC; however, a small percentage (1.4 percent) of chlorine used in EDC does still come from mercury cells (Reference I-9).

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 with water 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 cell uses graphite anodes and mercury cathodes. Sodium reacts with the mercury cathode to produce an amalgam (an alloy of mercury and sodium) that is sent to another compartment of the cell and reacted with water to produce hydrogen and high purity sodium hydroxide. The chemistry that occurs at the mercury cathode includes the following reactions:

$NaCl + xHg \rightarrow 1/2\ Cl_2 + Na(Hg)x$ and
$Na(Hg)x + H_2O \rightarrow NaOH + 1/2H_2 + xHg$

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.

Table I-2

DATA FOR THE MINING OF SALT

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	15.1	kwh	155	33.3	kwh	0.36
Natural gas	397	cu ft	445	24.8	cu meters	1.04
Bit./Sbit. Coal	11.7	lb	131	11.7	kg	0.31
Distillate oil	1.21	gal	192	10.1	liter	0.45
Total Process			924			2.15
Transportation Energy						
Rail	1.25	ton-miles		4.02	tonne-km	
Diesel	0.0031	gal	0.49	0.026	liter	0.0011
Barge	1.25	ton-miles		4.02	tonne-km	
Diesel	0.0010	gal	0.16	0.0083	liter	3.7E-04
Residual oil	0.0033	gal	0.57	0.028	liter	0.0013
Pipeline-petroleum products	114	ton-miles		366.9	tonne-km	
Electricity	2.49	kwh	25.5	5.48	kwh	0.059
Total Transportation			26.7			0.062

References: I-5 through I-7

Source: Franklin Associates, A Division of ERG

Titanium anodes, coated with metal oxide finishes, are gaining commercial acceptance and are gradually replacing graphite anodes. The advantages of titanium anodes are (1) corrosion resistance and (2) the low activation energy for electrolysis at the anode surface (Reference I-10).

The reason coproduct credit was given is that 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 of 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 electrolysis of sodium chloride produces approximately 1.1 tons caustic soda per ton of chlorine. Caustic soda is usually handled and sold as a 50% solution in water.

The energy requirements and environmental emissions for the production of sodium hydroxide or chlorine are given in Tables I-3a and I-3b. Diaphragm and mercury cells are considered as the main source of chlorine/caustic in this analysis. Data was collected from one plant that used both the diaphragm and membrane technologies, and so their dataset represented both cells. According to a study performed by Chemical Market Associates, Inc. (CMAI), the approximate amount of chlorine from mercury cell technology going into U.S. EDC production is 1.4 percent. Two percent of the chlorine used by EDC plants is assumed to come from the mercury cell technology as shown in Table I-3a. For the overall chlorine/caustic industry, it is estimated that 85 percent of the cell technology is diaphragm and membrane, while 15 percent of the cell technology is mercury. The collected datasets were weighted using these fractions in Table I-3b.

As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies (Reference I-7). The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. While data was collected from a small sample of plants, the chlorine/caustic producer who provided data for this module verified that the characteristics of their plant are representative of the diaphragm/membrane cell technology for North American chlorine/caustic production. The average dataset was reviewed and accepted by the chlorine/caustic data provider.

One of the five company datasets was collected for this project and represents 2003 data, while the other four datasets comes from 1989-1992. The 2003 data were collected from direct measurements, calculated from equipment specifications, taken from purchasing/utility records, and engineering estimates. The collection methods for the older data are unknown.

Hydrochloric Acid Production

Although there are a number of processes used to produce hydrochloric acid, this analysis assumes that it is produced from the synthesis of the elements hydrogen and chloride ($H_2 + Cl_2 \rightarrow 2HCl$). Most hydrochloric acid used in the production of EDC comes from producing VCM. However, some EDC producers must supplement the amount of hydrochloric acid.

The dataset used in this analysis for hydrochloric acid comes from the ecoinvent Database. It is shown in Table I-4 as a cradle-to-gate process due to confidentiality issues concerning showing unit process data from the EcoInvent Database. The dataset itself is provided by Swiss Centre for LCI, EMPA from the 2007 Life Cycle Inventories of Chemicals. The dataset states that the data represents a cross-section of actual plants in Europe for the years 1997-2000.

Ethylene Dichloride (EDC) Production

Ethylene dichloride is produced from the reaction of ethylene and chlorine. Ethylene is chlorinated in the liquid phase at a temperature of 20° to 120° C and a pressure of 75 psi. A ferric chloride catalyst is used to drive the reaction. The crude product from the reactor is then purified by distillation to yield ethylene dichloride. Ethylene dichloride data was collected with VCM data and are included within the VCM dataset (Table I-5).

Vinyl Chloride Monomer (VCM) Production

Vinyl chloride monomer (VCM) is produced almost exclusively by thermal cleavage (dehydrochlorination) of ethylene dichloride. The ethylene dichloride is fed to the cracking unit to form VCM and HCl. The HCl from this process is fed back to the ethylene dichloride reaction. In the case of the collected EDC/VCM data, either the producer used all HCl produced or not enough HCl was produced, and supplemental HCl was purchased. Unreacted ethylene dichloride is separated from the VCM.

Data for the production of EDC/VCM were provided by three leading producers (3 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). The energy requirements and environmental emissions for the production of EDC/VCM are shown in Table I-5. Dichloroethane is produced as a coproduct during this process. A mass basis was used to partition the credit for this coproduct.

Table I-3a

DATA FOR THE PRODUCTION
OF SODIUM HYDROXIDE OR CHLORINE
(98.6% Diaphragm/Membrane and 1.4% Mercury Technologies)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Salt	892	lb		892	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	277	kwh	2,851	611	kwh	6.64
Electricity (cogeneration)	170	kwh	1,160	375	kwh	2.70
Natural gas	1,945	cu ft	2,178	121	cu meters	5.07
Bit./Sbit. Coal	25.6	lb	287	25.6	kg	0.67
Residual oil	0.060	gal	10.3	0.50	liter	0.024
Total Process			6,487			15.1
Transportation Energy						
Combination truck	24.6	ton-miles		79.2	tonne-km	
Diesel	0.26	gal	41.0	2.16	liter	0.10
Rail	66.5	ton-miles		214.0	tonne-km	
Diesel	0.16	gal	26.2	1.38	liter	0.061
Pipeline-petroleum products	2.60	ton-miles		8.37	tonne-km	
Electricity	0.057	kwh	0.58	0.12	kwh	0.0014
Total Transportation			67.8			0.16
Environmental Emissions						
Atmospheric Emissions						
Benzene	2.2E-05	lb		2.2E-05	kg	
Carbon Dioxide (fossil)	0.074	lb		0.074	kg	
Carbon Monoxide	1.4E-04	lb		1.4E-04	kg	
Carbon Tetrachloride	1.9E-04	lb		1.9E-04	kg	
Chlorine	0.0011	lb		0.0011	kg	
HFCs/HCFCs	1.8E-04	lb		1.8E-04	kg	
NM Hydrocarbons	2.7E-04	lb		2.7E-04	kg	
Hydrogen Chloride	3.2E-04	lb		3.2E-04	kg	
Lead	1.1E-08	lb		1.1E-08	kg	
Mercury	2.6E-05	lb		2.6E-05	kg	
Methane	1.1E-06	lb		1.1E-06	kg	
Nitrogen Oxides	0.0038	lb		0.0038	kg	
Other Organics	8.0E-06	lb		8.0E-06	kg	
Particulates	0.0028	lb		0.0028	kg	
PM2.5	1.2E-04	lb		1.2E-04	kg	
PM10	0.021	lb		0.021	kg	
Sulfur Oxides	5.5E-04	lb		5.5E-04	kg	
Solid Wastes						
Landfilled	0.63	lb		0.63	kg	
Burned	1.42	lb		1.42	kg	
Waterborne Wastes						
BOD	0.27	lb		0.27	kg	
Copper	1.2E-07	lb		1.2E-07	kg	
Dissolved Solids	44.3	lb		44.3	kg	
Lead	5.6E-07	lb		5.6E-07	kg	
Mercury	2.0E-07	lb		2.0E-07	kg	
Nickel	5.8E-07	lb		5.8E-07	kg	
Sulfides	7.3E-06	lb		7.3E-06	kg	
Suspended Solids	0.080	lb		0.080	kg	
Zinc	5.6E-07	lb		5.6E-07	kg	

Note: According to a study performed by Chemical Market Associates, Inc. (CMAI), the approximate amount of chlorine from mercury cell technology going into EDC production is 1.4 percent. This dataset assumes 98.6 percent of the chlorine used by EDC plants comes from the diaphragm/membrane technology.

References: I-6, I-11, I-12, and I-14

Source: Franklin Associates, A Division of ERG

Table I-3b

DATA FOR THE PRODUCTION
OF SODIUM HYDROXIDE OR CHLORINE
(91.4% Diaphragm/Membrane and 8.6% Mercury Technologies)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Salt	884	lb		884	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	306	kwh	3,149	675	kwh	7.33
Electricity (cogeneration)	157	kwh	1072	346	kwh	2.49
Natural gas	1,821	cu ft	2,040	114	cu meters	4.75
Bit./Sbit. Coal	25.0	lb	281	25.0	kg	0.65
Residual oil	0.15	gal	25.7	1.25	liter	0.060
Total Process			6,567			15.3
Transportation Energy						
Used in Rigid and Flexible Polyols						
Combination truck	67.4	ton-miles		216.9	tonne-km	
Diesel	0.71	gal	112.4	5.91	liter	0.26
Rail	20.6	ton-miles		66.3	tonne-km	
Diesel	0.05	gal	8.1	0.43	liter	0.019
Total Transportation			120			0.28
Used in MDI and TDI						
Pipeline-petroleum products	1.25	ton-miles		4.01	tonne-km	
Electricity	0.027	kwh	0.28	0.06	kwh	6.5E-04
Total Transportation			0.28			6.5E-04
Environmental Emissions						
Atmospheric Emissions						
Benzene	2.1E-05	lb		2.1E-05	kg	
Carbon Dioxide (fossil)	0.069	lb		6.9E-02	kg	
Carbon Monoxide	1.3E-04	lb		1.3E-04	kg	
Carbon Tetrachloride	1.8E-04	lb		0.000	kg	
Chlorine	0.0011	lb		0.0011	kg	
HFCs/HCFCs	1.7E-04	lb		1.7E-04	kg	
NM Hydrocarbons	2.5E-04	lb		2.5E-04	kg	
Hydrogen Chloride	3.0E-04	lb		3.0E-04	kg	
Lead	1.0E-08	lb		1.0E-08	kg	
Mercury	1.6E-04	lb		1.6E-04	kg	
Methane	9.9E-07	lb		9.9E-07	kg	
Nitrogen Oxides	0.0035	lb		0.0035	kg	
Other Organics	7.4E-06	lb		7.4E-06	kg	
Particulates	0.0027	lb		0.0027	kg	
PM2.5	1.1E-04	lb		1.1E-04	kg	
PM10	0.019	lb		0.019	kg	
Sulfur Oxides	5.1E-04	lb		5.1E-04	kg	
Solid Wastes						
Landfilled	1.20	lb		1.20	kg	
Burned	1.32	lb		1.32	kg	
Waterborne Wastes						
BOD	0.25	lb		0.25	kg	
Copper	1.1E-07	lb		1.1E-07	kg	
Dissolved Solids	41.0	lb		41.0	kg	
Lead	5.2E-07	lb		5.2E-07	kg	
Mercury	5.1E-07	lb		5.1E-07	kg	
Nickel	5.4E-07	lb		5.4E-07	kg	
Sulfides	4.5E-05	lb		4.5E-05	kg	
Suspended Solids	0.074	lb		0.074	kg	
Zinc	5.2E-07	lb		5.2E-07	kg	

References: I-6, I-11, I-12, and I-14

Source: Franklin Associates, A Division of ERG

Table I-4

DATA FOR THE PRODUCTION OF HYDROCHLORIC ACID
(Cradle-to-Gate)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	433	kwh	4455	954	kwh	10.37
Electricity (cogeneration)	166	kwh	1131	365	kwh	2.63
Natural gas	2,638	cu ft	2,955	165	cu meters	6.88
Coal	35.1	lb	395	395	kg	1
Distillate oil	1.05	gal	167	8.78	liter	0
Residual oil	0.059	gal	10	0.49	liter	0
Total Process			9,113			21.22
Transportation Energy						
Combination truck	24.0	ton-miles		13.5	tonne-km	
Diesel	0.25	gal	40.0	2.10	liter	0.09
Rail	65.9	ton-miles		37.2	tonne-km	
Diesel	0.16	gal	26.0	1.36	liter	0.06
Barge	1.09	ton-miles		0.61	tonne-km	
Diesel	8.7E-04	gal	0.14	0.0073	liter	0.00
Residual oil	0.0029	gal	0.50	0.024	liter	0.00
Pipeline-petroleum products	104	ton-miles		58.5	tonne-km	
Electricity	2.26	kwh	23.2	4.98	kwh	0.05
Total Transportation			89.7			0.21
Environmental Emissions (Process)						
Atmospheric Emissions						
Benzene	2.1E-05	lb		2.1E-05	kg	
Carbon Dioxide (Fossil)	0.072	lb		0.072	kg	
Carbon Monoxide	1.4E-04	lb		1.4E-04	kg	
Carbon Tetrachloride	1.9E-04	lb		1.9E-04	kg	
Chlorine	1.90	lb		1.90	kg	
HCFC-123	8.8E-05	lb		8.8E-05	kg	
HFC-134a	8.8E-05	lb		8.8E-05	kg	
Hydrogen Chloride	3.1E-04	lb		3.1E-04	kg	
Lead	1.1E-08	lb		1.1E-08	kg	
Mercury	2.5E-05	lb		2.5E-05	kg	
Methane	1.1E-06	lb		1.1E-06	kg	
Nitrogen Oxides	0.0037	lb		0.0037	kg	
Non Methane Hydrocarbons	2.6E-04	lb		2.6E-04	kg	
Odorous Sulfur	0.32	lb		0.32	kg	
Other Organics	7.8E-06	lb		7.8E-06	kg	
Particulates (PM10)	0.020	lb		0.020	kg	
Particulates (PM2.5)	1.2E-04	lb		1.2E-04	kg	
Particulates (unknown)	0.0027	lb		0.0027	kg	
Propylene Oxide	0.0011	lb		0.0011	kg	
Sulfur Oxides	5.3E-04	lb		5.3E-04	kg	
Solid Wastes						
Landfilled	0.61	lb		0.61	kg	
Burned	1.38	lb		1.38	kg	
Waterborne Wastes						
BOD	0.26	lb		0.26	kg	
Copper	1.2E-07	lb		1.2E-07	kg	
Dissolved Solids	43.2	lb		43.2	kg	
Lead	5.5E-07	lb		5.5E-07	kg	
Mercury	2.0E-07	lb		2.0E-07	kg	
Nickel	5.7E-07	lb		5.7E-07	kg	
Sulfides	7.1E-06	lb		7.1E-06	kg	
Suspended Solids	0.078	lb		0.078	kg	
Zinc	5.5E-07	lb		5.5E-07	kg	

Reference: I-16

Source: Franklin Associates, A Division of ERG

Table I-5

DATA FOR THE PRODUCTION OF ETHYLENE DICHLORIDE (EDC)/VINYL CHLORIDE MONOMER (VCM)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Ethylene	453	lb			453	kg	
Chlorine	535	lb			535	kg	
Oxygen	144	lb			144	kg	
Hydrochloric acid	85.4	lb			85.4	kg	
Water Consumption	104	gal			868	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	68.6	kwh		706	151	kwh	1.64
Electricity (cogeneration)	94.9	kwh		648	209	kwh	1.51
Natural gas	2,006	cu ft		2,247	125	cu meters	5.23
Total Process				3,600			8.38
Transportation Energy							
Rail	87.2	ton-miles			280.4	tonne-km	
Diesel	0.22	gal		34.3	1.80	liter	0.080
Pipeline-petroleum products	1.20	ton-miles			3.86	tonne-km	
Electricity	0.026	kwh		0.27	0.058	kwh	6.2E-04
Total Transportation				34.6			0.080
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.011	lb			0.011	kg	
Carbon Dioxide	37.3	lb			37.3	kg	
Chlorine	0.0010	lb	(1)		0.0010	kg	
Hydrochloric Acid	0.0026	lb			0.0026	kg	
Nitrogen Oxides	0.032	lb			0.032	kg	
Other Organics	0.0069	lb	(2)		0.0069	kg	
Particulates (unknown)	0.010	lb	(1)		0.010	kg	
PM2.5	0.0010	lb	(1)		0.0010	kg	
PM10	0.0010	lb	(1)		0.0010	kg	
Solid Wastes							
Landfilled	0.36	lb			0.36	kg	
Burned	3.32	lb			3.32	kg	
Waste-to-Energy	21.7	lb			21.7	kg	
Waterborne Wastes							
Chlorides	1.0E-05	lb	(1)		1.0E-05	kg	
Copper	1.0E-07	lb	(1)		1.0E-07	kg	
Vinyl Chloride	0.0010	lb	(3)		0.0010	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(2) This category contains small amounts of EDC and VCM as well as other hydrocarbons which were not separated out by the data providers. These amounts may be overcounting the VCM emissions as the Vinyl Institute provided atmospheric VCM emissions for the production of EDC/VCM/PVC as shown in Table I-5.

(3) This vinyl chloride emission was provided by the Vinyl Institute, based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average.

References: I-6, I-14, and I-15.

Source: Franklin Associates, A Division of ERG

As of 2003 there were 8 VCM producers and 12 VCM plants in the U.S. (Reference I-13). While data was collected from a small sample of plants, the EDC/VCM producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American EDC/VCM production. The average dataset was reviewed and accepted by all EDC/VCM data providers.

To assess the quality of the data collected for EDC/VCM, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for EDC/VCM include direct measurements, information provided by purchasing and utility records, calculated from equipment specifications, and engineering estimates. All data submitted for EDC/VCM ranges from 2003-2004 and represents U.S. production.

PVC Resin Production

PVC resin is produced by suspension, emulsion, mass, or solution polymerization of VCM. The data presented in this appendix represents suspension polymerization.

In the suspension process, VCM and initiators are mixed with water and kept in the form of aqueous droplets by agitation and suspension stabilizers. The polymerization generally is carried out in a nitrogen atmosphere in large agitated reactors. The reaction time is typically about 12 hours, and conversion of VCM approaches 90 percent. After polymerization, the unreacted monomer is removed and recycled. The polymer is blended with additives and modifiers and centrifuged to remove water. The resin is then dried and packaged for shipment.

Table I-6 presents the data for the production of PVC resin by suspension polymerization. Data for the production of PVC were provided by three leading producers (3 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for the scrap.

As of 2003 there were 12 PVC producers and 25 PVC plants in the U.S. (Reference I-7). While data was collected from a small sample of plants, the PVC producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American PVC suspension technology production. The average dataset was reviewed and accepted by all PVC data providers.

To assess the quality of the data collected for PVC, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for PVC include direct measurements, information provided by purchasing and utility records, calculated from equipment specifications, and engineering estimates. All data submitted for PVC ranges from 2003-2004 and represents U.S. production.

Table I-6

DATA FOR THE PRODUCTION OF POLYVINYL CHLORIDE (PVC) RESIN

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Vinyl Chloride Monomer	1,001	lb			1,001	kg	
Water Consumption	121	gal			1,010	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	74.4	kwh		766	164	kwh	1.78
Electricity (cogeneration)	41.3	kwh		282	91.1	kwh	0.66
Natural gas	925	cu ft		1,036	57.7	cu meters	2.41
Total Process				2,084			4.85
Environmental Emissions							
Atmospheric Emissions							
Chlorine	0.010	lb	(1)		0.010	kg	
HFCs/HCFCs	0.0010	lb	(1)		0.0010	kg	
Hydrochloric Acid	1.0E-04	lb	(1)		1.0E-04	kg	
Other Organics	0.039	lb			0.039	kg	
Particulates (unknown)	0.087	lb			0.087	kg	
Vinyl Chloride	0.039	lb	(2)		0.039	kg	
Dioxins	1.6E-08	lb	(3)		1.6E-08	kg	
Solid Wastes							
Landfilled	1.09	lb			1.09	kg	
Burned	5.2E-04	lb			5.2E-04	kg	
Waterborne Wastes							
Ammonia	0.0010	lb	(1)		0.0010	kg	
BOD	0.012	lb			0.012	kg	
Chromium (unknown)	1.0E-04	lb	(1)		1.0E-04	kg	
COD	0.068	lb			0.068	kg	
Cyanide	1.0E-06	lb	(1)		1.0E-06	kg	
Nitrates	0.010	lb	(1)		0.010	kg	
Oil	0.0010	lb	(1)		0.0010	kg	
Phenol	9.9E-05	lb			9.9E-05	kg	
Suspended solids	0.16	lb			0.16	kg	
Zinc	1.0E-04	lb	(1)		1.0E-04	kg	
Dioxins	5.8.E-08	lb	(3)		5.8E-08	kg	

Note: No additives or plasticizers were included in this data.

(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(2) This vinyl chloride emission was provided by the Vinyl Institute, based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. This amount includes both the EDC/VCM plant as well as the PVC plant. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average.

(3) This emission was provided by the Vinyl Institute based on 2003 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. The values are based on TM 17 congeners. If these amounts were converted to toxic equivalents, the TEQ would be 200 to 300 times lower.

References: I-15

Source: Franklin Associates, A Division of ERG

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APPENDIX J

ACRYLONITRILE-BUTADIENE-STYRENE (ABS)

INTRODUCTION

This appendix discusses the manufacture of acrylonitrile-butadiene-styrene (ABS) resin. ABS is used to manufacture boats, mobile homes, luggage, and pipelines. Approximately 1.37 billion pounds of ABS were produced in the U.S., Mexico, and Canada in 2004 (Reference J-1). The material flow for ABS resin is shown in Figure J-1. The total unit process energy and emissions data (cradle-to-ABS) for ABS are displayed in Table J-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Ammonia Production
- Acrylonitrile Production
- ABS Resin

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B. Mixed xylenes production is discussed in Appendix F. Pygas production, benzene production, and ethylbenzene/styrene production are discussed in Appendix G. Butadiene production and polybutadiene production are discussed in Appendix H.

Ammonia Production

Ammonia is produced primarily by steam reforming natural gas. Natural gas is fed with steam into a tubular furnace where the reaction over a nickel reforming catalyst produces hydrogen and carbon oxides. The primary reformer products are then mixed with preheated air and reacted in a secondary reformer to produce the nitrogen needed in ammonia synthesis. The gas is then cooled to a lower temperature and subjected to the water shift reaction in which carbon monoxide and steam are reacted to form carbon dioxide and hydrogen. The carbon dioxide is removed from the shifted gas in an absorbent solution. Hydrogen and nitrogen are reacted in a synthesis converter to form ammonia (Reference J-2).

Table J-2 presents the energy and emissions data for the production of ammonia. The energy data for ammonia was calculated from secondary sources (Reference J-2) and from stoichiometry. The transportation data was estimated from the ammonia and acrylonitrile chemical profiles (Reference J-3) and from the acrylonitrile data provider. The atmospheric emissions and solid wastes are estimates, while the waterborne emissions are from a 1970's source (Reference J-4), although these emissions were reviewed and revised in 1994.

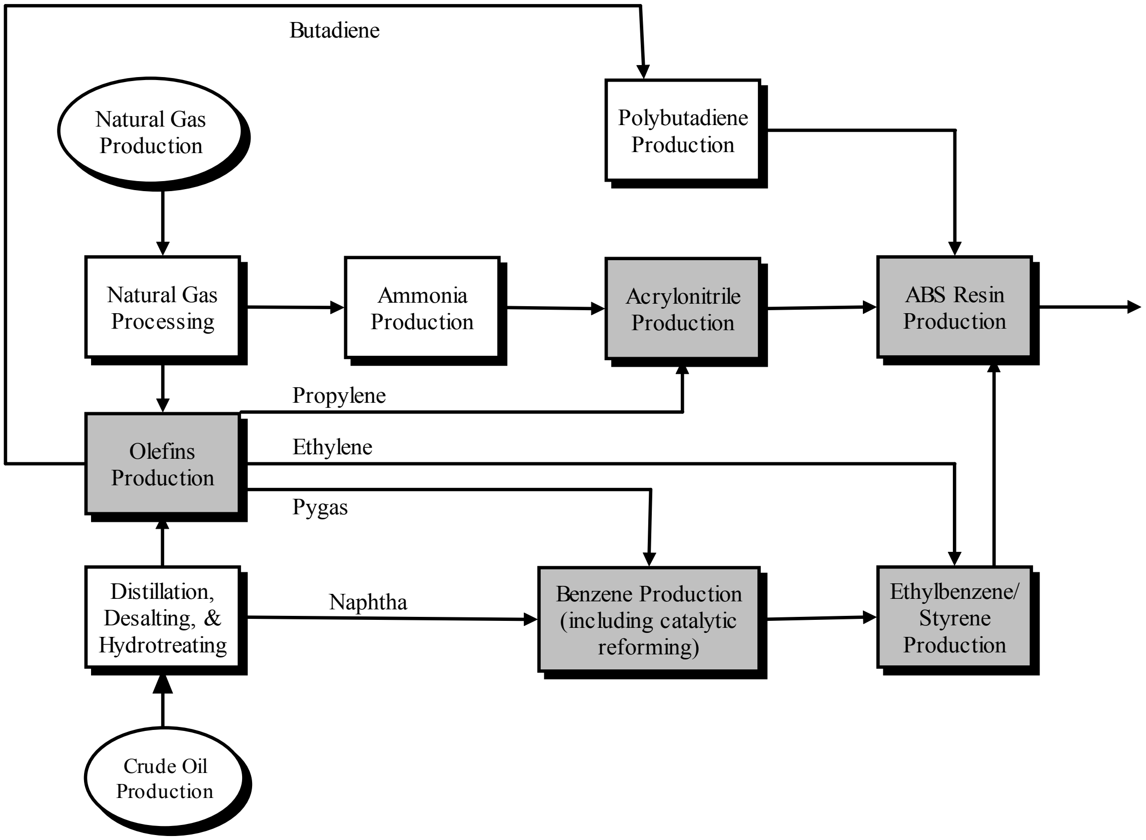

Figure J-1. Flow diagram for the production of acrylonitrile-butadiene-styrene (ABS) resin. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Acrylonitrile Production

Acrylonitrile production in the U.S. and most of the world is based on the Sohio process. Propylene, air, and ammonia are catalytically converted to acrylonitrile using a fluidized bed reactor. Operating temperatures are 400° to 500° Celsius and gauge pressures are 30 to 300 kPa. The reaction is exothermic with recovered heat being used to generate steam for use in the process. The chemical equation for the process is:

$$2CH_2{=}CH\text{-}CH_3 + 2NH_3 + 3O_2 \rightarrow 2CH_2{=}CH\text{-}CN + 6H_2O$$

Major by-products are hydrogen cyanide and acetonitrile, which are normally incinerated because supply often exceeds demand. Unused ammonia can be recovered as ammonium sulfate and then disposed of, but it is commonly vented to the atmosphere (Reference J-2).

Table J-1

DATA FOR THE PRODUCTION OF ACRYLONITRILE-BUTADIENE-STYRENE (ABS) RESIN
(Cradle-to-Resin)
(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	611	lb		611	kg	
Natural Gas	541	lb		541	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			12,575			29.3
Petroleum			11,937			27.8
Total Resource			24,512			57.1
Process Energy						
Electricity (grid)	505	kwh	5,371	1,113	kwh	12.5
Electricity (cogeneration)	37.1	kwh	- (2)	81.8	kwh	-
Natural gas	9,037	cu ft	10,121	564	cu meters	23.6
LPG	0.090	gal	9.75	0.75	liter	0.023
Bit./Sbit. Coal	68.4	lb	768	68.4	kg	1.79
Distillate oil	0.41	gal	65.2	3.43	liter	0.15
Residual oil	4.31	gal	740	36.0	liter	1.72
Gasoline	0.11	gal	16.3	0.95	liter	0.038
Diesel	0.0030	gal	0.48	0.025	liter	0.0011
Internal Offgas use (1)						
From Oil	53.2	lb	1,483	53.2	kg	3.45
From Natural Gas	100	lb	2,841	100	kg	6.61
Recovered Energy	207	thousand Btu	207	482	MJ	0.48
Total Process			21,208			49.4
Transportation Energy						
Combination truck	57.9	ton-miles		32.6	tonne-km	
Diesel	0.61	gal	96.5	5.07	liter	0.22
Rail	127	ton-miles		71.4	tonne-km	
Diesel	0.31	gal	49.9	2.62	liter	0.12
Barge	414	ton-miles		233	tonne-km	
Diesel	0.33	gal	52.6	2.76	liter	0.12
Residual oil	1.10	gal	189	9.18	liter	0.44
Ocean freighter	1,138	ton-miles		642	tonne-km	
Diesel	0.22	gal	34.3	1.80	liter	0.080
Residual	1.95	gal	334	16.2	liter	0.78
Pipeline-natural gas	313	ton-miles		176	tonne-km	
Natural gas	216	cu ft	242	13.5	cu meter	0.56
Pipeline-petroleum products	223	ton-miles		126	tonne-km	
Electricity	4.85	kwh	49.7	10.7	kwh	0.12
Total Transportation			1,048			2.44

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table J-1

DATA FOR THE PRODUCTION
OF ACRYLONITRILE-BUTADIENE-STYRENE (ABS) RESIN
(Cradle-to-Resin)
(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.027	lb	0.027	kg
Ammonia	0.11	lb	0.11	kg
Benzene	0.060	lb	0.060	kg
Carbon Dioxide (fossil)	260	lb	260	kg
Carbon Monoxide	9.18	lb	9.18	kg
Carbon Tetrachloride	7.7E-09	lb	7.7E-09	kg
Chlorine	1.1E-04	lb	1.1E-04	kg
Ethylbenzene	0.0075	lb	0.0075	kg
HCFC-22	1.0E-04	lb	1.0E-04	kg
Hydrocarbons (NM)	3.46	lb	3.46	kg
Hydrogen	0.0029	lb	0.0029	kg
Hydrogen Chloride	5.9E-07	lb	5.9E-07	kg
Hydrogen Cyanide	0.010	lb	0.010	kg
Methane	11.2	lb	11.2	kg
Nitrogen Oxides	0.90	lb	0.90	kg
Other Organics	0.14	lb	0.14	kg
Particulates (unknown)	0.31	lb	0.31	kg
PM2.5	0.0053	lb	0.0053	kg
PM10	0.074	lb	0.074	kg
Sulfur Oxides	17.0	lb	17.0	kg
Toluene	0.094	lb	0.094	kg
Trichloroethane	6.2E-08	lb	6.2E-08	kg
VOC	0.50	lb	0.50	kg
Xylene	0.054	lb	0.054	kg
Solid Wastes				
Landfilled	52.1	lb	52.1	kg
Burned	7.29	lb	7.29	kg
Waste-to-Energy	0.81	lb	0.81	kg
Waterborne Wastes				
1-Methylfluorene	5.8E-07	lb	5.8E-07	kg
2,4-Dimethylphenol	1.4E-04	lb	1.4E-04	kg
2-Hexanone	3.4E-05	lb	3.4E-05	kg
2-Methylnapthalene	8.1E-05	lb	8.1E-05	kg
4-Methyl-2-Pentanone	2.2E-05	lb	2.2E-05	kg
Acetone	5.1E-05	lb	5.1E-05	kg
Alkylated benzenes	1.4E-04	lb	1.4E-04	kg
Alkylated fluorenes	8.3E-06	lb	8.3E-06	kg
Alkylated naphthalenes	2.4E-06	lb	2.4E-06	kg
Alkylated phenanthrenes	9.8E-07	lb	9.8E-07	kg
Alkalinity	0.41	lb	0.41	kg
Aluminum	0.26	lb	0.26	kg
Ammonia	0.19	lb	0.19	kg
Antimony	1.6E-04	lb	1.6E-04	kg
Arsenic	0.0013	lb	0.0013	kg
Barium	3.69	lb	3.69	kg
Benzene	0.0086	lb	0.0086	kg
Benzoic acid	0.0052	lb	0.0052	kg
Beryllium	6.4E-05	lb	6.4E-05	kg
BOD	1.24	lb	1.24	kg
Boron	0.016	lb	0.016	kg
Bromide	1.10	lb	1.10	kg
Cadmium	1.9E-04	lb	1.9E-04	kg
Calcium	16.5	lb	16.5	kg
Chlorides	185	lb	185	kg
Chromium (unspecified)	0.0074	lb	0.0074	kg
Chromium (hexavalent)	2.4E-05	lb	2.4E-05	kg
Cobalt	1.1E-04	lb	1.1E-04	kg
COD	5.25	lb	5.25	kg
Copper	0.0011	lb	0.0011	kg
Cyanide	3.7E-07	lb	3.7E-07	kg

Table J-1

DATA FOR THE PRODUCTION OF ACRYLONITRILE-BUTADIENE-STYRENE (ABS) RESIN

(Cradle-to-Resin)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Dibenzofuran	9.8E-07	lb	9.8E-07	kg
Dibenzothiophene	7.9E-07	lb	7.9E-07	kg
Dissolved Solids	230	lb	230	kg
Ethylbenzene	0.0012	lb	0.0012	kg
Fluorine	4.3E-06	lb	4.3E-06	kg
Hardness	50.8	lb	50.8	kg
Hexanoic acid	0.0011	lb	0.0011	kg
Iron	0.58	lb	0.58	kg
Lead	0.0023	lb	0.0023	kg
Lead 210	5.3E-13	lb	5.3E-13	kg
Lithium	2.97	lb	2.97	kg
Magnesium	3.23	lb	3.23	kg
Manganese	0.0052	lb	0.0052	kg
Mercury	2.9E-06	lb	2.9E-06	kg
Metal Ion (unspecified)	1.0E-04	lb	1.0E-04	kg
Methylchloride	2.1E-07	lb	2.1E-07	kg
Methyl Ethyl Ketone	4.1E-07	lb	4.1E-07	kg
Molybdenum	1.2E-04	lb	1.2E-04	kg
m-Xylene	1.6E-04	lb	1.6E-04	kg
Naphthalene	9.3E-05	lb	9.3E-05	kg
n-Decane	1.5E-04	lb	1.5E-04	kg
n-Docosane	5.5E-06	lb	5.5E-06	kg
n-Dodecane	2.8E-04	lb	2.8E-04	kg
n-Eicosane	7.8E-05	lb	7.8E-05	kg
n-Hexacosane	3.4E-06	lb	3.4E-06	kg
n-Hexadecane	3.1E-04	lb	3.1E-04	kg
Nickel	0.0011	lb	0.0011	kg
Nitrates as NO3	0.010	lb	0.010	kg
n-Octadecane	7.7E-05	lb	7.7E-05	kg
n-Tetradecane	1.2E-04	lb	1.2E-04	kg
o + p-Xylene	1.1E-04	lb	1.1E-04	kg
o-Cresol	1.5E-04	lb	1.5E-04	kg
Oil and grease	0.23	lb	0.23	kg
Other Organics	1.0E-04	lb	1.0E-04	kg
p-Cresol	1.6E-04	lb	1.6E-04	kg
p-Cymene	5.1E-07	lb	5.1E-07	kg
Pentamethylbenzene	3.8E-07	lb	3.8E-07	kg
Phenanthrene	1.0E-06	lb	1.0E-06	kg
Phenol	0.0032	lb	0.0032	kg
Phosphates	0.010	lb	0.010	kg
Radium 226	1.9E-10	lb	1.9E-10	kg
Radium 228	9.5E-13	lb	9.5E-13	kg
Selenium	3.2E-05	lb	3.2E-05	kg
Silver	0.011	lb	0.011	kg
Sodium	52.3	lb	52.3	kg
Strontium	0.28	lb	0.28	kg
Styrene	6.7E-04	lb	6.7E-04	kg
Sulfates	0.38	lb	0.38	kg
Sulfides	6.5E-04	lb	6.5E-04	kg
Sulfur	0.014	lb	0.014	kg
Surfactants	0.0047	lb	0.0047	kg
Suspended Solids	9.45	lb	9.45	kg
Thallium	3.5E-05	lb	3.5E-05	kg
Tin	8.4E-04	lb	8.4E-04	kg
Titanium	0.0025	lb	0.0025	kg
TOC	7.4E-04	lb	7.4E-04	kg
Toluene	0.0082	lb	0.0082	kg
Total biphenyls	9.3E-06	lb	9.3E-06	kg
Total dibenzothiophenes	2.9E-08	lb	2.9E-08	kg
Vanadium	1.4E-04	lb	1.4E-04	kg
Xylene (unspecified)	0.0041	lb	0.0041	kg
Yttrium	3.5E-05	lb	3.5E-05	kg
Zinc	0.0064	lb	0.0064	kg

References: Tables B-2 through B-6, E-2, G-2, G-3, G-4, H-2, H-3, J-2, and J-3.

Source: Franklin Associates, A Division of ERG models

Table J-2

DATA FOR THE PRODUCTION OF AMMONIA

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Processed Natural Gas	267	lb		267	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	63.5	kwh	653	140	kwh	1.52
Natural gas	2,239	cu ft	2,508	140	cu meters	5.84
Total Process			3,161			7.36
Transportation Energy						
Rail	125	ton-miles		402.3	tonne-km	
Diesel	0.31	gal	49.2	2.59	liter	0.11
Pipeline-petroleum products	1.25	ton-miles		4.02	tonne-km	
Electricity	0.027	kwh	0.28	0.060	kwh	0.0006
Total Transportation			49.5			0.12
Environmental Emissions						
Atmospheric Emissions						
Ammonia	1.00	lb		1.00	kg	
Other Organics	1.00	lb		1.00	kg	
Fossil Carbon Dioxide	97.0	lb		97.0	kg	
Solid Wastes						
Landfilled	0.20	lb		0.20	kg	
Waterborne Wastes						
Ammonia	0.060	lb		0.060	kg	
BOD	0.050	lb		0.050	kg	
COD	0.23	lb		0.23	kg	
Oil	0.050	lb		0.050	kg	
Suspended solids	0.050	lb		0.050	kg	

References: J-2 through J-5

Source: Franklin Associates, A Division of ERG

The energy and emissions data for acrylonitrile production is from a confidential source and is not shown to protect its confidentiality (Reference J-6). The company provided ranges for the material inputs and coproducts. The median of these ranges was used in the acrylonitrile dataset. Hydrogen cyanide and acetonitrile are produced as coproducts during this process. A mass basis was used to partition the credit for these coproducts. Waterborne emissions from the confidential dataset collected for acrylonitrile are sent to deepwell disposal, which is not included in this analysis, as it is not released to a water source.

ABS Production

The two standard technologies for ABS production in North America are suspension or mass polymerization. Both of these technologies are represented within the ABS production dataset.

ABS is produced by grafting styrene and acrylonitrile onto a polybutadiene matrix. The three basic steps in the suspension process are: prepolymerization, polymerization, and product separation. The processing steps for mass polymerization are: prepolymerization, polymerization, devolatilization, and extrusion. Mass polymerization generates a minimum of wastewater and eliminates the need for dewatering and drying. In both the suspension and mass processes the polybutadiene must be soluble in styrene. Polybutadiene resin may be added as a dry resin rather than a latex.

Table J-3 presents the data for the production of ABS resin. Data for the production of ABS were provided by three leading producers (5 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). Scrap and heat are produced as coproducts during this process. A mass basis was used to partition the credit for scrap, while the energy amount for the heat is reported separately as recovered energy.

As of 2003 there were 4 ABS producers and 7 ABS plants in the U.S. (Reference J-7). The ABS data collected represents a majority of the total North American ABS production amount. The ABS producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American ABS production. The average dataset was reviewed and accepted by all ABS data providers.

To assess the quality of the data collected for ABS, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for ABS include direct measurements and information provided by purchasing and utility records. All data submitted for ABS ranges from 2003-2004 and represents U.S. and Mexican production.

Table J-3

DATA FOR THE PRODUCTION OF ACRYLONITRILE-BUTADIENE-STYRENE (ABS)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Acrylonitrile	220	lb			220	kg	
Styrene	672	lb			672	kg	
Polybutadiene	144	lb			144	kg	
Water Consumption	314	gal			2,620	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	296	kwh		3,046	653	kwh	7.09
Electricity (cogeneration)	18.7	kwh		128	41.2	kwh	0.30
Natural gas	751	cu ft		841	46.9	cu meters	1.96
Bit./Sbit. Coal	68.4	lb		768	68.4	kg	1.79
Residual oil	0.045	gal		7.72	0.38	liter	0.018
Recovered Energy	204	thousand Btu		204	1,699	GJ	0.47
Total Process				4,587			10.7
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.010	lb	(1)		0.010	kg	
NM Hydrocarbons	0.12	lb			0.12	kg	
Nitrogen Oxides	0.010	lb	(1)		0.010	kg	
HFCs/HCFCs	1.0E-04	lb	(1)		1.0E-04	kg	
Other Organics	0.036	lb			0.036	kg	
Particulates	0.11	lb			0.11	kg	
Solid Wastes							
Landfilled	13.7	lb			13.7	kg	
Burned	2.29	lb			2.29	kg	
Waste-to-Energy	0.80	lb			0.80	kg	
Waterborne Wastes							
Ammonia	0.10	lb	(1)		0.10	kg	
BOD	0.010	lb	(1)		0.010	kg	
COD	2.91	lb			2.91	kg	
Dissolved solids	1.00	lb	(1)		1.00	kg	
Metal Ion	1.0E-04	lb	(1)		1.0E-04	kg	
Nitrates	0.010	lb	(1)		0.010	kg	
Oil	0.10	lb	(1)		0.10	kg	
Other Organics	1.0E-04	lb	(1)		1.0E-04	kg	
Phosphates	0.010	lb	(1)		0.010	kg	
Suspended solids	0.98	lb			0.98	kg	
Zinc	1.0E-04	lb	(1)		1.0E-04	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

Reference: J-8

Source: Franklin Associates, A Division of ERG

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J-8. Information and data collected from APC member and non-member companies producing ABS resin. 2003-2004.

APPENDIX K

POLYETHER POLYOL FOR RIGID FOAM POLYURETHANE

INTRODUCTION

This appendix discusses the manufacture of the polyether polyol used for rigid foam polyurethanes. Examples of uses of rigid foam polyurethanes are insulation, packaging, and aviation. Over 200 million pounds of polyether polyols for use in rigid foam polyurethanes were produced in the U.S. and Canada in 2002 (Reference K-1). The material flow for this polyether polyol is shown in Figure K-1. The total unit process energy and emissions data (cradle-to-polyol) for this polyether polyol are displayed in Table K-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Limestone Mining
- Sugar Beet Cultivation and Harvesting
- Sucrose Production
- Propylene Oxide Production
- Polyether Polyol for Rigid Foam Polyurethane

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, and natural gas processing are discussed in Appendix B. Propylene production is discussed in Appendix E. Acetic acid production and oxygen production are discussed in Appendix F. Salt mining and sodium hydroxide/chlorine production are discussed in Appendix I.

Limestone Mining

Limestone is composed mainly of calcium carbonate in the form of the mineral calcite. It is quarried primarily from open pits. The most economical method of recovering the limestone is through blasting, followed by mechanical crushing and screening.

Particulate emissions arise from limestone crushing and screening operations (Reference K-3). Based on the type of technologies employed for limestone mining and processing, it is assumed that the release of other air emissions or water effluents is negligible (Reference K-4 and K-5).

Any overburden or tailings produced from limestone mining and processing are assumed to be returned to the mine site (References K-4 and K-5) and are not reported as solid waste.

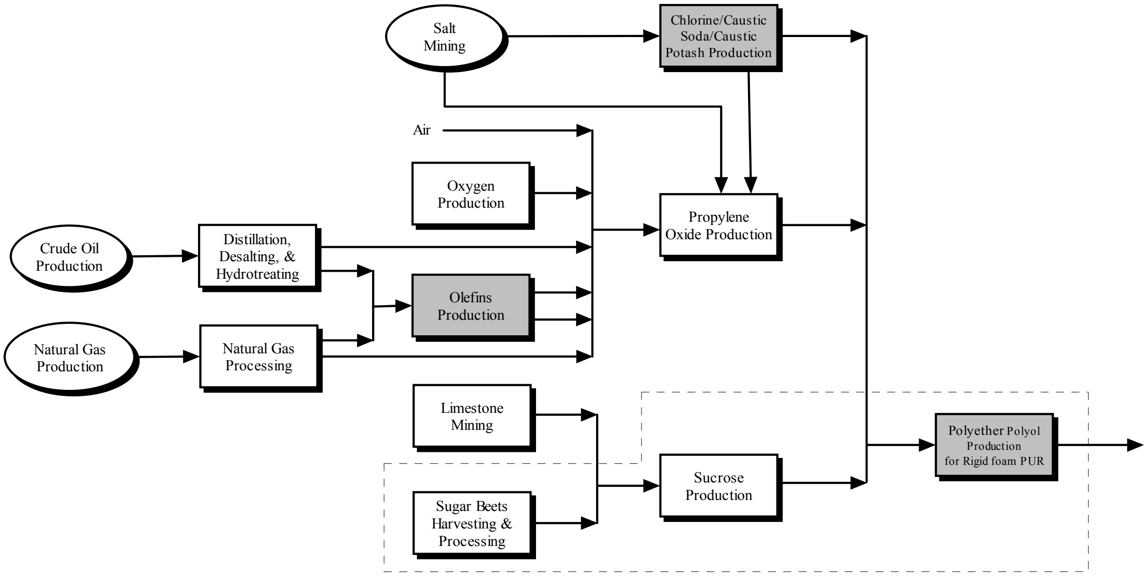

Figure K-1. Flow diagram for the manufacture of polyether polyol for rigid foam polyurethane. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted lines are included in an aggregated dataset. Polyol types vary greatly by use. Additives are not included in this analysis of polyether polyols.

The energy requirements and environmental emissions for the mining and processing of limestone are shown in Table K-2.

Sugar Beet Cultivation and Harvesting

The sugar beet is a rotational crop, which requires nearly 4 times the land area of the equivalent cane crop (Reference K-6). Sugar beets are planted in the early spring. Agricultural practices include the application of fertilizer and pre-emergence herbicide at the time of planting. During the growing season, post-emergence herbicide is frequently applied as weeds can easily take away the water and nutrients from the soil. The root of the sugar beet plant is harvested in the fall, after a growing period of 120 to 200 days depending on the climate. The farmers defoliate the beets, then harvest them. Dirt is removed by shaking the beets using rollers on the way to the harvesting bin. The sugar beets are transported to a processing plant to where sucrose is produced.

The energy and emissions data for sugar beet cultivation and harvesting are from secondary sources. This dataset has been included with the polyether polyol average dataset (Table K-4) to conceal the confidential data of the limited number of provider companies.

Table K-1

DATA FOR THE PRODUCTION OF POLYETHER POLYOL FOR RIGID FOAM POLYURETHANES

(Cradle-to-Polyol)

(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	217	lb		217	kg	
Natural Gas	388	lb		388	kg	
Salt	1,573	lb		1,573	kg	
Sugar Beets	1,000	lb		1,000	kg	
Limestone	72.5	lb		72.5	kg	
Oxygen	74.9	lb		74.9	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			9,034			21.0
Petroleum			4,237			9.86
Total Resource			13,271			30.9
Process Energy						
Electricity (grid)	556	kwh	5,917	1,226	kwh	13.8
Electricity (cogeneration)	215	kwh	- (2)	474	kwh	-
Natural gas	8,270	cu ft	9,262	516	cu meters	21.6
LPG	0.035	gal	3.76	0.29	liter	0.0088
Bit./Sbit. Coal	96.5	lb	1,084	96.5	kg	2.52
Distillate oil	2.02	gal	321	16.8	liter	0.75
Residual oil	13.0	gal	2,237	109	liter	5.21
Gasoline	3.10	gal	441	25.9	liter	1.03
Diesel	1.82	gal	289	15.2	liter	0.67
Internal Offgas use (1)						
From Oil	38.9	lb	1,107	38.9	kg	2.58
From Natural Gas	69.2	lb	1,968	69.2	kg	4.58
Recovered Energy	1.35	thousand Btu	1.35	3.14	MJ	0.0031
Total Process			22,629			52.7
Transportation Energy						
Combination truck	102	ton-miles		57.8	tonne-km	
Diesel	1.08	gal	171	8.97	liter	0.40
Rail	64.6	ton-miles		36.4	tonne-km	
Diesel	0.16	gal	25.4	1.34	liter	0.059
Barge	21.3	ton-miles		12.0	tonne-km	
Diesel	0.017	gal	2.71	0.14	liter	0.0063
Residual oil	0.057	gal	9.74	0.47	liter	0.023
Ocean freighter	378	ton-miles		213	tonne-km	
Diesel	0.072	gal	11.4	0.60	liter	0.027
Residual	0.65	gal	111	5.40	liter	0.26
Pipeline-natural gas	224	ton-miles		126	tonne-km	
Natural gas	154	cu ft	173	9.62	cu meter	0.40
Pipeline-petroleum products	288	ton-miles		162	tonne-km	
Electricity	6.28	kwh	64.3	13.8	kwh	0.15
Total Transportation			568			1.32

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table K-1

DATA FOR THE PRODUCTION
OF POLYETHER POLYOL FOR RIGID FOAM POLYURETHANES
(Cradle-to-Polyol)
(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Acid (unknown)	0.033	lb	0.033	kg
Aldehydes	0.010	lb	0.010	kg
Ammonia	0.042	lb	0.042	kg
Benzene	0.043	lb	0.043	kg
Carbon Dioxide (fossil)	63.2	lb	63.2	kg
Carbon Monoxide	3.44	lb	3.44	kg
Carbon Tetrachloride	1.6E-04	lb	1.6E-04	kg
Chlorine	0.0022	lb	0.0022	kg
Ethylbenzene	0.73	lb	0.73	kg
HCFC-22	5.9E-07	lb	5.9E-07	kg
HCFC-123	7.3E-05	lb	7.3E-05	kg
HFC-134a	7.3E-05	lb	7.3E-05	kg
Hydrocarbons (NM)	5.00	lb	5.00	kg
Hydrogen	0.0030	lb	0.0030	kg
Hydrogen Chloride	2.7E-04	lb	2.7E-04	kg
Lead	9.3E-09	lb	9.3E-09	kg
Mercury	2.7E-04	lb	2.7E-04	kg
Methane	8.06	lb	8.06	kg
Nitrogen Oxides	0.51	lb	0.51	kg
Other Organics	0.11	lb	0.11	kg
Particulates (unknown)	0.32	lb	0.32	kg
PM2.5	0.010	lb	0.010	kg
PM10	0.11	lb	0.11	kg
Propylene Oxide	0.36	lb	0.36	kg
Sulfur Oxides	11.4	lb	11.4	kg
Toluene	0.067	lb	0.067	kg
Trichloroethane	2.4E-08	lb	2.4E-08	kg
VOC	0.35	lb	0.35	kg
Xylene	0.039	lb	0.039	kg
Solid Wastes				
Landfilled	21.5	lb	21.5	kg
Burned	4.48	lb	4.48	kg
Waste-to-Energy	0.0026	lb	0.0026	kg
Waterborne Wastes				
1-Methylfluorene	3.3E-07	lb	3.3E-07	kg
2,4-Dimethylphenol	8.1E-05	lb	8.1E-05	kg
2-Hexanone	1.9E-05	lb	1.9E-05	kg
2-Methylnapthalene	4.6E-05	lb	4.6E-05	kg
4-Methyl-2-Pentanone	1.2E-05	lb	1.2E-05	kg
Acetone	2.9E-05	lb	2.9E-05	kg
Acid (unspecified)	7.56	lb	7.56	kg
Alkylated benzenes	6.4E-05	lb	6.4E-05	kg
Alkylated fluorenes	3.7E-06	lb	3.7E-06	kg
Alkylated naphthalenes	1.1E-06	lb	1.1E-06	kg
Alkylated phenanthrenes	4.4E-07	lb	4.4E-07	kg
Alkalinity	0.23	lb	0.23	kg
Aluminum	0.12	lb	0.12	kg
Ammonia	0.042	lb	0.042	kg
Antimony	7.3E-05	lb	7.3E-05	kg
Arsenic	6.9E-04	lb	6.9E-04	kg
Barium	1.68	lb	1.68	kg
Benzene	0.0049	lb	0.0049	kg
Benzoic acid	0.0029	lb	0.0029	kg
Beryllium	3.4E-05	lb	3.4E-05	kg
BOD	1.63	lb	1.63	kg
Boron	0.0091	lb	0.0091	kg
Bromide	0.62	lb	0.62	kg
Cadmium	1.0E-04	lb	1.0E-04	kg
Calcium	9.29	lb	9.29	kg
Chlorides	104	lb	104	kg
Chromium (unspecified)	0.0033	lb	0.0033	kg
Chromium (hexavalent)	9.2E-06	lb	9.2E-06	kg
Cobalt	6.4E-05	lb	6.4E-05	kg

Table K-1

DATA FOR THE PRODUCTION
OF POLYETHER POLYOL FOR RIGID FOAM POLYURETHANES
(Cradle-to-Polyol)
(page 3 of 3)

	English units (Basis: 1,000 lb)	SI units (Basis: 1,000 kg)
COD	1.89 lb	1.89 kg
Copper	5.4E-04 lb	5.4E-04 kg
Cyanide	2.1E-07 lb	2.1E-07 kg
Dibenzofuran	5.5E-07 lb	5.5E-07 kg
Dibenzothiophene	4.5E-07 lb	4.5E-07 kg
Dissolved Solids	166 lb	166 kg
Ethylbenzene	2.8E-04 lb	2.8E-04 kg
Fluorine	2.0E-06 lb	2.0E-06 kg
Hardness	28.6 lb	28.6 kg
Hexanoic acid	6.1E-04 lb	6.1E-04 kg
Hydrocarbon	0.70 lb	0.70 kg
Iron	0.28 lb	0.28 kg
Lead	0.0012 lb	0.0012 kg
Lead 210	3.0E-13 lb	3.0E-13 kg
Lithium	2.12 lb	2.12 kg
Magnesium	1.82 lb	1.82 kg
Manganese	0.0029 lb	0.0029 kg
Mercury	2.0E-06 lb	2.0E-06 kg
Methylchloride	1.2E-07 lb	1.2E-07 kg
Methyl Ethyl Ketone	2.3E-07 lb	2.3E-07 kg
Molybdenum	6.6E-05 lb	6.6E-05 kg
m-Xylene	8.8E-05 lb	8.8E-05 kg
Naphthalene	5.3E-05 lb	5.3E-05 kg
n-Decane	8.4E-05 lb	8.4E-05 kg
n-Docosane	3.1E-06 lb	3.1E-06 kg
n-Dodecane	1.6E-04 lb	1.6E-04 kg
n-Eicosane	4.4E-05 lb	4.4E-05 kg
n-Hexacosane	1.9E-06 lb	1.9E-06 kg
n-Hexadecane	1.7E-04 lb	1.7E-04 kg
Nickel	6.0E-04 lb	6.0E-04 kg
Nitrogen	0.91 lb	0.91 kg
n-Octadecane	4.3E-05 lb	4.3E-05 kg
n-Tetradecane	7.0E-05 lb	7.0E-05 kg
o + p-Xylene	6.4E-05 lb	6.4E-05 kg
o-Cresol	8.3E-05 lb	8.3E-05 kg
Oil	0.059 lb	0.059 kg
p-Cresol	9.0E-05 lb	9.0E-05 kg
p-Cymene	2.9E-07 lb	2.9E-07 kg
Pentamethylbenzene	2.2E-07 lb	2.2E-07 kg
Phenanthrene	5.1E-07 lb	5.1E-07 kg
Phenol	1.01 lb	1.01 kg
Radium 226	1.0E-10 lb	1.0E-10 kg
Radium 228	5.3E-13 lb	5.3E-13 kg
Selenium	1.4E-05 lb	1.4E-05 kg
Silver	0.0061 lb	0.0061 kg
Sodium	29.4 lb	29.4 kg
Sodium Hydroxide	1.08 lb	1.08 kg
Strontium	0.16 lb	0.16 kg
Styrene	5.9E-07 lb	5.9E-07 kg
Sulfates	0.21 lb	0.21 kg
Sulfides	1.2E-04 lb	1.2E-04 kg
Sulfur	0.0077 lb	0.0077 kg
Surfactants	0.0027 lb	0.0027 kg
Suspended Solids	3.84 lb	3.84 kg
Thallium	1.5E-05 lb	1.5E-05 kg
Tin	4.2E-04 lb	4.2E-04 kg
Titanium	0.0011 lb	0.0011 kg
TOC	5.9E-04 lb	5.9E-04 kg
Toluene	0.0046 lb	0.0046 kg
Total biphenyls	4.2E-06 lb	4.2E-06 kg
Total dibenzothiophenes	1.3E-08 lb	1.3E-08 kg
Vanadium	7.8E-05 lb	7.8E-05 kg
Xylene (unspecified)	0.0023 lb	0.0023 kg
Yttrium	1.9E-05 lb	1.9E-05 kg
Zinc	0.0029 lb	0.0029 kg

References: Tables B-2 through B-6, E-2, F-4, I-2, I-3b, K-2, K-3, and K-4.

Source: Franklin Associates, A Division of ERG models

Table K-2

DATA FOR THE MINING AND PROCESSING OF LIMESTONE

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	1.92	kwh	19.8	4.23	kwh	0.046
Natural gas	2.25	cu ft	2.52	0.14	cu meters	0.0059
Bit./Sbit. Coal	0.036	lb	0.40	0.036	kg	9.4E-04
Distillate oil	0.070	gal	11.1	0.58	liter	0.026
Gasoline	0.0061	gal	0.87	0.051	liter	0.0020
Total Process			34.7			0.081
Transportation Energy						
Combination truck	21.0	ton-miles		67.6	tonne-km	
Diesel	0.22	gal	35.0	1.84	liter	0.081
Rail	5.00	ton-miles		16.09	tonne-km	
Diesel	0.012	gal	1.97	0.10	liter	0.0046
Barge	13.0	ton-miles		41.83	tonne-km	
Diesel	0.010	gal	1.65	0.087	liter	0.0038
Residual oil	0.035	gal	5.93	0.29	liter	0.014
Total Transportation			44.6			0.10
Environmental Emissions						
Atmospheric Emissions						
Particulates (unknown)	0.051	lb		0.051	kg	

References: K-2 through K-5

Source: Franklin Associates, A Division of ERG

Sucrose Production

Sucrose is commonly produced from sugar cane and sugar beets. For this project, sucrose production is based on production from sugar beets. Both cane and beet sucrose are produced in North America and could be used for this purpose. Other principal products of sugar beet processing are molasses and beet pulp. These have been given coproduct credit on a mass basis.

When the beets arrive to be processed into granulated sugar, they are washed, sliced, and weighed. Significant amounts of soil associated with the incoming beets are removed here, as well as beet tops and other organic matter; these are commonly land applied. The sliced beets are fed to a counter-current diffuser where sugar and other soluble materials are dissolved from the beets. From the diffuser, the beet slices are pressed in screw presses to squeeze as much juice as possible from them. The "raw juice" is carbonated and clarified by adding milk of lime (CaOH) and carbon dioxide. The juice is then thickened in multiple effect evaporators and crystallized in vacuum pans to obtain sugar. The sugar is centrifuged to separate it from adhering syrup, and then dried. In many beet processing plants, a Steffan process has been added to further extract sugar from molasses. This process increases the sugar yield while reducing the molasses output, but also increases the limestone requirements (Reference K-6).

Energy requirements and environmental emissions for sucrose production are from a 1991 European confidential source, which was reviewed and updated in 2005 by an expert in the U.S. sucrose industry. The energy requirements, solid waste, and atmospheric emissions were edited to represent the current U.S. sucrose industry.

The sucrose dataset has been included with the polyether polyol average dataset (Table K-4) to conceal the confidential data of all provider companies.

Propylene Oxide Production

Two different processes for the production of propylene oxide are currently in use. These are the chlorohydrin process and hydroperoxidation processes, using either ethylbenzene, isobutene, or MTBE. The MTBE hydroperoxidation process is approximately the same as the isobutene hydroperoxidation process. The chlorohydrin process is the oldest and is less flexible because it produces only propylene oxide. The hydroperoxide reactions, however, produce marketable co-products in addition to propylene oxide.

The data in Table K-3 represent the energy requirements and environmental emissions for the production of propylene oxide. The energy requirements are based on data in a Department of Energy report from 2000 (Reference K-7). No information was given in the DoE report about the technology or mix of technologies represented by the energy data. The environmental emissions and raw materials are based on three datasets from a confidential secondary source. These amounts are a weighted average of the three technologies based on 2001 capacity. The chlorohydrin process generates 42.1 percent of the propylene oxide, the isobutene hydroperoxidation (including MTBE hydroperoxidation) 34.6 percent, and the ethylbenzene hydroperoxidation 23.3 percent (Reference K-8). In the two hydroperoxidation datasets, coproduct credit was given on a mass basis.

The chlorohydrin process begins with a equal molar mixture of propylene and chlorine in water, which forms the solution propylene chlorohydrin. The chlorohydrin solution is treated with a base, usually cell liquor from a chlorine plant, to form the oxide. Propylene oxide is then stripped from the alkaline solution and purified by distilling the light ends, then the oxide.

In the isobutene hydroperoxide process, propylene oxide and tert-butyl alcohol are formed from isobutene, oxygen, and propylene. Isobutane is first oxidized to the intermediate, tert-butyl hydroperoxide. This intermediate and an alcohol mixture coproduct is combined with propylene. This is reacted to nearly 100 percent conversion of the hydroperoxide over a catalyst. The products stream contains propylene oxide and tert-butyl alcohol. The products are separated in distillation columns.

Table K-3

DATA FOR THE PRODUCTION OF PROPYLENE OXIDE

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Propylene	773	lb		773	kg	
Chlorine	573	lb		573	kg	
Sodium Hydroxide	689	lb		689	kg	
Sodium Chloride	928	lb		928	kg	
Oxygen	98.6	lb		98.6	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	128	kwh	1,322	283	kwh	3.08
Natural gas	2,328	cu ft	2,607	145	cu meters	6.07
Residual oil	15.7	gal	2,692	131	liter	6.27
Total Process			6,621			15.41
Transportation Energy						
Used in polyether polyols for rigid foam PUR						
Combination truck	50.0	ton-miles		160.9	tonne-km	
Diesel	0.53	gal	83.4	4.38	liter	0.19
Pipeline-petroleum products	0.50	ton-miles		1.61	tonne-km	
Electricity	0.011	kwh	0.11	0.024	kwh	2.6E-04
Total Transportation			83.5			0.19
Used in polyether polyols for flexible foam PUR						
Combination truck	4.57	ton-miles		14.71	tonne-km	
Diesel	0.048	gal	7.62	0.40	liter	0.018
Rail	9.39	ton-miles		30.22	tonne-km	
Diesel	0.023	gal	3.70	0.19	liter	0.009
Pipeline-petroleum products	0.40	ton-miles		1.29	tonne-km	
Electricity	0.0087	kwh	0.089	0.019	kwh	2.1E-04
Total Transportation			11.4			0.027
Environmental Emissions						
Atmospheric Emissions						
Acid (unknown)	0.044	lb		0.044	kg	
Ammoina	0.049	lb		0.049	kg	
Carbon Dioxide	12.8	lb		12.8	kg	
Chlorine	0.0013	lb		0.0013	kg	
Ethylbenzene	0.96	lb		0.96	kg	
Hydrocarbons	5.83	lb		5.83	kg	
Propylene Oxide	0.47	lb		0.47	kg	
Solid Wastes						
Landfilled	0.20	lb		0.20	kg	
Waterborne Wastes						
Acid (unknown)	9.95	lb		9.95	kg	
Hydrocarbons	0.92	lb		0.92	kg	
Phenol	1.33	lb		1.33	kg	
Sodium Hydroxide	1.42	lb		1.42	kg	

References: K-7 through K-9.

Source: Franklin Associates, A Division of ERG

In the ethylbenzene hydroperoxide reaction, propylene oxide and styrene are produced. Ethylbenzene and oxygen are reacted to form ethylbenzene hydroperoxide and small amounts of methylbenzyl alcohol and acetophenone. This solution and propylene are fed to the epoxidation reactor. The products stream contains propylene oxide, propylene, methylbenzyl alcohol, and small amounts of several other hydrocarbons. Propylene oxide is purified by a multi-tower distillation scheme.

Polyether Polyol Production for Rigid Foam Polyurethane

The manufacturing of the polyether polyol used in rigid foam polyurethane production begins with the introduction of a potassium hydroxide catalyst to an initiator. In this analysis, sucrose was chosen as the initiator; however, glycerine and sorbitol are also common initiators used to produce polyether polyols for rigid foam polyurethane. This solution is then reacted with propylene oxide to form an intermediate. The catalyst is removed using an acid, which produces a salt that must be filtered. This acid amount is small and considered negligible in this analysis. Finally, the polyol is purified of side products and water through distillation. Sodium hydroxide data is used in place of potassium hydroxide data which were not available. The manufacture of sodium hydroxide utilizes a process similar to the manufacture of potassium hydroxide.

Table K-4 presents the data for the production of polyether polyol for use in rigid foam polyurethane. Data for the production of polyether polyol were provided by two leading producers (2 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). Heat was a coproduct for one producer. The energy for exported heat was reported separately as recovered energy.

As of 2002, it is estimated that for all polyurethane applications, there were 7 polyether polyol producers and 9 polyether polyol plants in the U.S. (Reference K-1 and K-18). The polyether polyol data collected represents a majority of the total North American production of polyether polyol for rigid foam polyurethane. The polyether polyol producers who provided data for this module verified that the characteristics of their plants are representative of a majority of the North American production. The average dataset was reviewed and accepted by both polyether polyol data providers.

To assess the quality of the data collected for polyether polyols in rigid foam polyurethane, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for these polyether polyols include direct measurements, information provided by purchasing and utility records, and engineering estimates. All data submitted for polyether polyols represents the year 2003 and represents U.S. production.

Table K-4

DATA FOR THE PRODUCTION OF POLYETHER POLYOLS FOR RIGID FOAM POLYURETHANES

(includes sugar beet harvesting/processing and sucrose production)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Propylene oxide	760	lb			760	kg	
Potassium hydroxide	13.0	lb			13.0	kg	
Limestone	72.5	lb			72.5	kg	
Sugar beets	1,215	lb			1,215	kg	
Water Consumption	0.5	gal			4.17	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	48.3	kwh		497	106	kwh	1.16
Electricity (cogeneration)	60.6	kwh		414	134	kwh	0.96
Natural gas	1,087	cu ft		1,217	67.9	cu meters	2.83
Bit./Sbit. Coal	54.4	lb		611	54.4	kg	1.42
Gasoline	3.04	gal		432	25.4	liter	1.01
Diesel	1.82	gal		289	15.2	liter	0.67
Recovered Energy	98.1	thousand Btu		98.1	228	MJ	0.23
Total Process				3,362			7.83
Transportation Energy (1)							
Combination truck	39.5	ton-miles			127.1	tonne-km	
Diesel	0.41	gal		65.9	3.46	liter	0.15
Rail	9.72	ton-miles			31.28	tonne-km	
Diesel	0.024	gal		3.83	0.20	liter	0.0089
Total Transportation				69.7			0.16
Environmental Emissions							
Atmospheric Emissions							
Carbon Dioxide	16.8	lb			16.8	kg	
Carbon Monoxide	0.13	lb			0.13	kg	
Chlorine	1.0E-04	lb	(2)		1.0E-04	kg	
Nitrogen Oxides	0.42	lb			0.42	kg	
Other Organics	0.11	lb			0.11	kg	
Particulates (unknown)	0.25	lb			0.25	kg	
PM2.5	0.010	lb	(2)		0.010	kg	
PM10	0.033	lb			0.033	kg	
Sulfur Oxides	0.0010	lb			0.0010	kg	
Solid Wastes							
Landfilled	0.064	lb			0.064	kg	
Waterborne Wastes (3)							
BOD	0.89	lb			0.89	kg	
COD	1.00	lb	(2)		1.00	kg	
Nitrogen	0.91	lb			0.91	kg	
Suspended solids	1.0.E-04	lb	(2)		1.0E-04	kg	

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(1) Transportation energy represents transporting the sugar beets to the sucrose plant and the sucrose to the polyols plant.

(2) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(3) These waterborne emissions may be overstated as 1 or more of the plants providing data were only able to supply waterborne emissions before the effluent was sent to a water treatment plant.

References: K-11 through K-17.

Source: Franklin Associates, A Division of ERG

REFERENCES

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K-2. **Energy and Environmental Profile of the U.S. Mining Industry.** U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. December 2002.

K-3. **AP-42 Emission Factors. Chapter 11.19.2.** Crushed Stone Processing and Pulverized Mineral Processing. US EPA. August 2004.

K-4. Based on discussions between Franklin Associates and confidential industry sources, January 1998.

K-5. Based on assumptions by Franklin Associates.

K-6. Information compiled from the website: http://www.sucrose.com/lbeet.html

K-7. **Energy and Environmental Profile of the U.S. Chemical Industry.** Prepared by Energetics Inc. for the U.S. Department of Energy. May, 2000.

K-8. Chemical profiles information taken from the website: http://www.the-innovation-group.com/welcome.htm.

K-9. Data compiled by Franklin Associates, based on a confidential secondary source. 1993.

K-10. Polyurethane 102, Polyurethane Chemistry and Raw Materials. Slides and notes from the Polyurethane Professional Development Program produced by the Alliance for the Polyurethanes Industry. 2003 edition.

K-11. Franklin Associates estimate.

K-12. Data taken from the report **Resource and Environmental Profile Analysis of Three Methods of Manufacturing Liquid Sweeteners** performed by Midwest Research Institute. 1974.

K-13. Personal communication between Franklin Associates and Paul Fry of Fry Engineering, consultant to the sucrose industry. 2005.

K-14. Calculations based on estimates given by Paul Fry of Fry Engineering, consultant to the sucrose industry. 2005.

K-15. Calculations performed by Paul Fry of Fry Engineering, consultant to the sucrose industry. 2005.

K-16. Data compiled by Franklin Associates, Ltd., based on contact with a confidential European source. 1991.

K-17. Information and data collected from APC member and non-member companies producing polyether polyol for rigid foam polyurethane. 2003.

K-18. Research by Franklin Associates on each polyol producing companies' website.

APPENDIX L

POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANE

INTRODUCTION

This appendix discusses the manufacture of the polyether polyol used for flexible foam polyurethanes. Examples of uses of flexible foam polyurethanes are furniture, carpet underlay, and automotive seats. Over 1.2 billion pounds of polyether polyols used in flexible foam polyurethanes were produced in the U.S. and Canada in 2002 (Reference L-1). The material flow for this polyether polyol is shown in Figure L-1. The total unit process energy and emissions data (cradle-to-polyol) for this polyether polyol are displayed in Table L-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in a previous appendix have been omitted from this appendix. The following processes are included in this appendix:

- Fresh fruit bunch harvesting
- Palm kernels production
- Palm kernel oil processing
- Palm kernel oil refining, bleaching and deodorizing
- Glycerine production
- Polyether polyol for flexible foam polyurethane

Crude oil production, distillation, desalting, and hydrotreating, natural gas production, natural gas processing, and ethylene production are discussed in Appendix B. Propylene production is discussed in Appendix E. Ethylene oxide production, methanol production, and oxygen production are discussed in Appendix F. Salt mining and sodium hydroxide/chlorine production are discussed in Appendix I. Propylene oxide production is discussed in Appendix K.

Fresh Fruit Bunch Harvesting

With an average rainfall of 210 centimeters per year, an average temperature of 85° to 90° Fahrenheit, and the generally flat geographic terrain, Malaysia is ideal for growing palm trees for palm oil production. A palm tree produces its first harvest between the ages of 30 and 36 months. Once the tree begins producing fruit it may be harvested every 10 to 21 days for the remainder of its life (approximately 25 years) (Reference L-2).

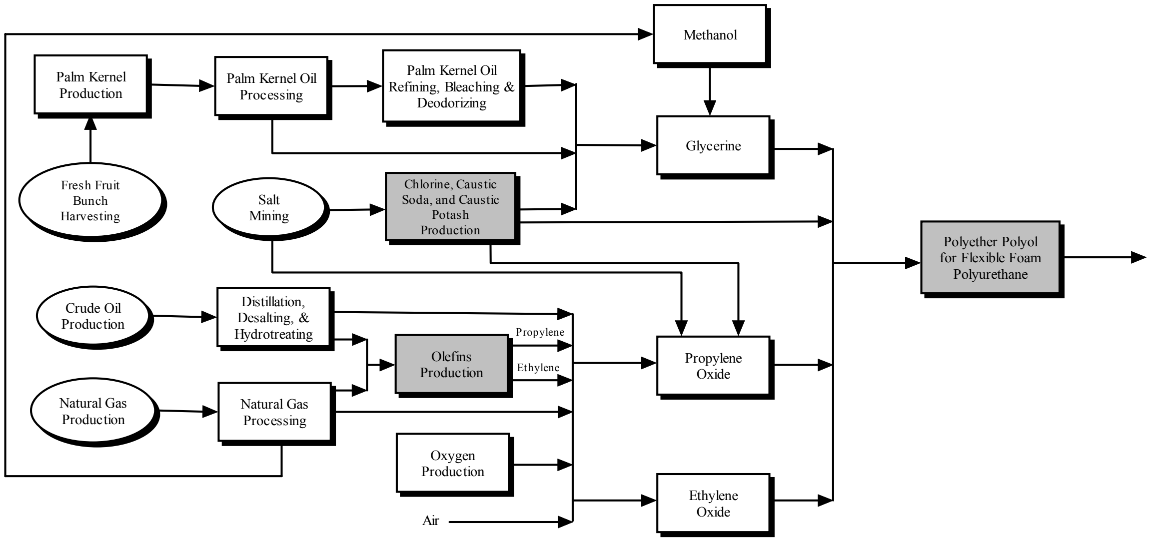

Figure L-1. Flow diagram for the manufacture of polyether polyol for flexible foam polyurethane. Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

There are approximately 54 palm trees per acre, or 130 palm trees per hectare (Reference L-3). An individual palm fruit is four centimeters long and grows in a cluster or bunch on the inner base of the palm frond. Therefore, in order to harvest a fresh fruit bunch (FFB), a palm frond must be manually cut from the tree. Once the frond has been removed, the stalk of the FFB falls to the ground. To prevent bruising of FFBs, harvesting crews typically catch the FFB before it hits the ground.

The FFB are then taken to one of the plantation's access roads where they are loaded into trucks or trailers and shipped to the palm oil mill for processing (Reference L-4). Less than 5 percent of the harvested FFB are transported to the mill by rail.

The energy required for harvesting comes from transporting FFB from the fields to the palm oil mill. Environmental emissions result primarily from burning of older trees on the plantation. Older trees are taken out of production in part because their height makes harvesting very difficult. At any given time, 10 percent of a plantation will be in the stages of replanting (Reference L-3).

The pruned palm fronds, as well as the fallen and burned tree, are utilized as soil conditioners or additives (Reference L-2). The pruned palm fronds are left on the ground under the palm tree as a mulch material and allowed to naturally degrade. It is not uncommon for palm oil mill effluent (POME), which is relatively high in potassium, phosphorus, and nitrogen, to be applied to the soil or fronds to aid in their degradation and act as a fertilizer. With the palm fronds and the resultant ash from burning the tree being utilized, the only emissions to report are the atmospheric emissions from burning the older palm trees.

Table L-1

DATA FOR THE PRODUCTION OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES

(Cradle-to-Polyol)

(page 1 of 4)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	261	lb		261	kg	
Natural Gas	515	lb		515	kg	
Salt	1,753	lb		1,753	kg	
Fresh Fruit Bunches	76.5	lb		76.5	kg	
Oxygen	176	lb		176	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			11,993			27.9
Petroleum			5,107			11.9
Total Resource			17,100			39.8
Process Energy						
Electricity (grid)	580	kwh	6,167	1,278	kwh	14.4
Electricity (cogeneration)	236	kwh	- (2)	520	kwh	-
Natural gas	8,599	cu ft	9,631	537	cu meters	22.4
LPG	0.042	gal	4.52	0.35	liter	0.011
Bit./Sbit. Coal	48.9	lb	549	48.9	kg	1.28
Distillate oil	2.41	gal	383	20.1	liter	0.89
Residual oil	14.7	gal	2,517	122	liter	5.86
Gasoline	0.081	gal	11.5	0.67	liter	0.027
Diesel	0.15	gal	24.1	1.27	liter	0.056
Biomass		thousand Btu	0	0	MJ	0
Internal Offgas use (1)						
From Oil	46.2	lb	1,318	46.2	kg	3.07
From Natural Gas	88.5	lb	2,541	88.5	kg	5.92
Recovered Energy	81.6	thousand Btu	81.6	190	MJ	0.19
Total Process			23,065			53.7
Transportation Energy						
Combination truck	85.0	ton-miles		273.7	tonne-km	
Diesel	0.89	gal	142	7.45	liter	0.33
Single unit truck	0.79	ton-miles		2.55	tonne-km	
Diesel	0.018	gal	2.83	0.15	liter	0.0066
Rail	40.8	ton-miles		131.4	tonne-km	
Diesel	0.10	gal	16.1	0.84	liter	0.037
Barge	24.4	ton-miles		78.6	tonne-km	
Diesel	0.020	gal	3.10	0.16	liter	0.0072
Residual oil	0.065	gal	11.1	0.54	liter	0.026
Ocean freighter	557	ton-miles		1792	tonne-km	
Diesel	0.11	gal	16.8	0.88	liter	0.039
Residual	0.95	gal	163	7.95	liter	0.38
Pipeline-natural gas	295	ton-miles		950	tonne-km	
Natural gas	204	cu ft	228	12.7	cu meter	0.53
Pipeline-petroleum products	311	ton-miles		1001	tonne-km	
Electricity	6.78	kwh	69.4	14.9	kwh	0.16
Total Transportation			653			1.52

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table L-1

DATA FOR THE PRODUCTION
OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES
(Cradle-to-Polyol)
(page 2 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Acid (unknown)	0.038	lb	0.038	kg
Aldehydes	0.044	lb	0.044	kg
Ammonia	0.048	lb	0.048	kg
Benzene	0.057	lb	0.057	kg
Carbon Dioxide (fossil)	154	lb	154	kg
Carbon Dioxide (nonfossil)	16.9	lb	16.9	kg
Carbon Monoxide	4.01	lb	4.01	kg
Carbon Tetrachloride	2.0E-04	lb	2.0E-04	kg
Chlorine	0.0024	lb	0.0024	kg
Ethylbenzene	0.83	lb	0.83	kg
Ethylene Oxide	0.011	lb	0.011	kg
HCFC-22	7.5E-07	lb	7.5E-07	kg
HCFC-123	9.2E-05	lb	9.2E-05	kg
HFC-134a	9.2E-05	lb	9.2E-05	kg
Hydrocarbons (NM)	7.93	lb	7.93	kg
Hydrogen	0.0038	lb	0.0038	kg
Hydrogen Chloride	3.3E-04	lb	3.3E-04	kg
Lead	1.1E-07	lb	1.1E-07	kg
Mercury	1.7E-04	lb	1.7E-04	kg
Methane	11.5	lb	11.5	kg
Nitrogen Oxides	0.17	lb	0.17	kg
Nitrous Oxide	1.0E-04	lb	1.0E-04	kg
Odorous Sulfur	3.9E-03	lb	3.9E-03	kg
Other Organics	0.10	lb	0.10	kg
Particulates (unknown)	0.16	lb	0.16	kg
PM2.5	0.010	lb	0.010	kg
PM10	0.15	lb	0.15	kg
Propylene Oxide	0.40	lb	0.40	kg
Sulfur, Odorous	0.0039	lb	0.0039	kg
Sulfur Oxides	15.1	lb	15.1	kg
Toluene	0.088	lb	0.088	kg
Trichloroethane	2.9E-08	lb	2.9E-08	kg
VOC	0.46	lb	0.46	kg
Xylene	0.051	lb	0.051	kg
Solid Wastes				
Landfilled	30.5	lb	30.5	kg
Burned	5.46	lb	5.46	kg
Waste-to-Energy	0.0050	lb	0.0050	kg
Waterborne Wastes				
1-Methylfluorene	4.2E-07	lb	4.2E-07	kg
2,4-Dimethylphenol	1.0E-04	lb	1.0E-04	kg
2-Hexanone	2.4E-05	lb	2.4E-05	kg
2-Methylnapthalene	5.9E-05	lb	5.9E-05	kg
4-Methyl-2-Pentanone	1.6E-05	lb	1.6E-05	kg
Acetone	3.7E-05	lb	3.7E-05	kg
Acetaldehyde	0.011	lb	0.011	kg
Acid (unspecified)	8.52	lb	8.52	kg
Alkylated benzenes	8.0E-05	lb	8.0E-05	kg
Alkylated fluorenes	4.6E-06	lb	4.6E-06	kg
Alkylated naphthalenes	1.3E-06	lb	1.3E-06	kg
Alkylated phenanthrenes	5.4E-07	lb	5.4E-07	kg
Alkalinity	0.30	lb	0.30	kg
Aluminum	0.15	lb	0.15	kg
Ammonia	0.063	lb	0.063	kg
Antimony	9.1E-05	lb	9.1E-05	kg
Arsenic	8.8E-04	lb	8.8E-04	kg

Table L-1

DATA FOR THE PRODUCTION
OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES
(Cradle-to-Polyol)
(page 3 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Barium	2.09	lb	2.09	kg
Benzene	0.0062	lb	0.0062	kg
Benzoic acid	0.0038	lb	0.0038	kg
Beryllium	4.3E-05	lb	4.3E-05	kg
BOD	1.47	lb	1.47	kg
Boron	0.012	lb	0.012	kg
Bromide	0.79	lb	0.79	kg
Cadmium	1.3E-04	lb	1.3E-04	kg
Calcium	11.9	lb	11.9	kg
Chlorides	134	lb	134	kg
Chromium (unspecified)	0.0070	lb	0.0070	kg
Chromium (hexavalent)	1.1E-05	lb	1.1E-05	kg
Cobalt	8.2E-05	lb	8.2E-05	kg
COD	4.48	lb	4.48	kg
Copper	6.8E-04	lb	6.8E-04	kg
Cyanide	2.7E-07	lb	2.7E-07	kg
Dibenzofuran	7.0E-07	lb	7.0E-07	kg
Dibenzothiophene	5.7E-07	lb	5.7E-07	kg
Dissolved Solids	211	lb	211	kg
Ethylbenzene	3.6E-04	lb	3.6E-04	kg
Fluorides	2.3E-05	lb	2.3E-05	kg
Fluorine	2.5E-06	lb	2.5E-06	kg
Hardness	36.7	lb	36.7	kg
Hexanoic acid	7.8E-04	lb	7.8E-04	kg
Hydrocarbon	0.89	lb	0.89	kg
Iron	0.35	lb	0.35	kg
Lead	0.0015	lb	0.0015	kg
Lead 210	3.9E-13	lb	3.9E-13	kg
Lithium	2.80	lb	2.80	kg
Magnesium	2.33	lb	2.33	kg
Manganese	0.0037	lb	0.0037	kg
Mercury	2.1E-06	lb	2.1E-06	kg
Metal Ion (unspecified)	1.00	lb	1.00	kg
Methylchloride	1.5E-07	lb	1.5E-07	kg
Methyl Ethyl Ketone	3.0E-07	lb	3.0E-07	kg
Molybdenum	8.5E-05	lb	8.5E-05	kg
m-Xylene	1.1E-04	lb	1.1E-04	kg
Naphthalene	6.7E-05	lb	6.7E-05	kg
n-Decane	1.1E-04	lb	1.1E-04	kg
n-Docosane	4.0E-06	lb	4.0E-06	kg
n-Dodecane	2.0E-04	lb	2.0E-04	kg
n-Eicosane	5.6E-05	lb	5.6E-05	kg
n-Hexacosane	2.5E-06	lb	2.5E-06	kg
n-Hexadecane	2.2E-04	lb	2.2E-04	kg
Nickel	7.6E-04	lb	7.6E-04	kg
Nitrates	1.00	lb	1.00	kg
Nitrogen	0.0025	lb	0.0025	kg
n-Octadecane	5.5E-05	lb	5.5E-05	kg
n-Tetradecane	9.0E-05	lb	9.0E-05	kg
o + p-Xylene	8.2E-05	lb	8.2E-05	kg
o-Cresol	1.1E-04	lb	1.1E-04	kg
Oil	0.078	lb	0.078	kg
p-Cresol	1.2E-04	lb	1.2E-04	kg
p-Cymene	3.7E-07	lb	3.7E-07	kg
Pentamethylbenzene	2.8E-07	lb	2.8E-07	kg
Phenanthrene	6.5E-07	lb	6.5E-07	kg
Phenol	1.14	lb	1.14	kg
Radium 226	1.3E-10	lb	1.3E-10	kg
Radium 228	6.9E-13	lb	6.9E-13	kg
Selenium	1.8E-05	lb	1.8E-05	kg
Silver	0.0078	lb	0.0078	kg
Sodium	37.8	lb	37.8	kg
Sodium Hydroxide	1.22	lb	1.22	kg
Strontium	0.20	lb	0.20	kg
Styrene	7.5E-07	lb	7.5E-07	kg

Table L-1

DATA FOR THE PRODUCTION
OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES
(Cradle-to-Polyol)
(page 4 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Sulfates	0.27	lb	0.27	kg
Sulfides	1.1E-04	lb	1.1E-04	kg
Sulfur	0.0098	lb	0.0098	kg
Surfactants	0.0035	lb	0.0035	kg
Suspended Solids	4.83	lb	4.83	kg
Thallium	1.9E-05	lb	1.9E-05	kg
Tin	5.3E-04	lb	5.3E-04	kg
Titanium	0.0014	lb	0.0014	kg
TOC	0.011	lb	0.011	kg
Toluene	0.0059	lb	0.0059	kg
Total biphenyls	5.2E-06	lb	5.2E-06	kg
Total dibenzothiophenes	1.6E-08	lb	1.6E-08	kg
Vanadium	1.0E-04	lb	1.0E-04	kg
Xylene (unspecified)	0.0030	lb	0.0030	kg
Yttrium	2.5E-05	lb	2.5E-05	kg
Zinc	0.0047	lb	0.0047	kg

References: Tables B-2 through B-6, E-2, F-2, F-4, F-5, I-2, I-3b, K-3, and L-2 through L-7.

Source: Franklin Associates, A Division of ERG models

Table L-2 displays the energy and emissions for harvesting fresh fruit bunches in Malaysia.

Palm Kernels Production

The FFB are delivered to palm oil mills in lorries or trailers. A small portion of the FFB are shipped in sterilizer cages; the majority are placed in sterilizer cages at the mill, where they are then passed through steam. This sterilization deactivates or kills the enzymes, which cause the breakdown of oil into free fatty acids (FFA), which are undesirable in the palm oil. The industry tries to keep the entering FFA to less than 5 percent (Reference L-2). The sterilization process also helps loosen the individual fruit from the bundles.

From the sterilizer, the fruit bunches are sent to a stripper where the fruitlets are separated from then stalk/stem. The empty bunches, approximately 70 percent moisture, are sent to an incinerator (no energy recovery). The resulting incinerator ash, 0.5 percent of the weight of the FFB, is then landspread on the plantation.

The fruitlets from the stripper are sent to a digester where the fruitlets are converted by a mechanical stirring process into homogeneous oily mash. A screw press is used to remove the majority of crude palm oil from the digested mash.

Table L-2

DATA FOR THE GROWING AND HARVESTING OF FRESH FRUIT BUNCHES

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Diesel	1.96	gal	311	16.4	liter	0.72
Total Process			311			0.72
Transportation Energy						
Single unit truck	6.30	ton-miles		20.27	tonne-km	
Diesel	0.14	gal	22.5	1.18	liter	0.052
Total Transportation			22.5			0.052
Environmental Emissions						
Atmospheric Emissions						
Carbon Dioxide (fossil)	8.56	lb		8.5600	kg	
Carbon Monoxide	0.0023	lb		0.0023	kg	
Hydrocarbons	0.0010	lb		0.0010	kg	
Nitrogen Oxides	0.0055	lb		0.0055	kg	
Particulates (unknown)	0.066	lb		0.066	kg	
Sulfur Oxides	0.0023	lb		0.0023	kg	
Solid Wastes						
Landfilled	0.012	lb		0.012	kg	

References: L-3 and L-5 through L-9.

Source: Franklin Associates, A Division of ERG

At this point the crude palm oil contains oil, water, and fruit solids. Therefore, the liquid is clarified in a continuous settling tank operation. The decanted palm oil passes through a centrifugal purifier from which the oil layer is vacuum dried to remove any remaining solids and moisture. The oil is then pumped to storage tanks before it is sent on for refining. Crude palm oil yields are approximately 21 percent, by weight, of the FFB.

The deoiled fiber/nut press cake passes to an air separation system, which separates the fiber from the nut. After separation the fiber (30 percent moisture) is used as a fuel for the mill (Reference L-3). The nuts are dried in silo driers and then cracked using centrifugal crackers. The kernel or the nut meat is removed from the shell using air and water separation systems. Kernels are further dried in silo driers and stored awaiting shipment to a processor. Dried kernels account for 6 percent of the FFB weight and contain between 40 and 50 percent oil.

The shells, 15 percent moisture (Reference L-3), are mixed with the fiber and used as boiler fuel. Most boiler designs limit the ratio of fiber/shell feed. For this reason excess shell material typically requires alternative handling. The most common practiced is to use the shell material as a base or surface material on the numerous roads of the plantation (Reference L-3).

Bunch ash, crude palm oil, and shells used in road construction have been treated as coproducts, for which credit has been given on a mass basis. The energy recovered from fiber and shells used as a fuel in this process, as well as any biogas utilization, is greater than the process energy demands. Therefore, only transportation energy is reported for palm oil production. Because the amount of palm kernels produced is relatively small, separate processing plants have been established for extracting palm kernel oil.

The major environmental discharges from a palm oil mill are atmospheric emissions from the incinerator and boiler operations, solid waste in the form of the boiler ash and wastewater treatment sludges, and waterborne wastes in the form of treated palm oil mill effluents (POME) discharged to the water.

The POME has received considerable attention because of the amount of material generated. POME generation is approximately 60 to 67 percent of the weight of FFB, including water form the process. The largest single source of POME is the centrifugal sludge. The quantity of POME on a wet basis is roughly 2.5 times greater than the amount of crude palm oil generated.

Significant research has been performed on the utilization of palm mill wastes including the POME. All raw effluents receive treatment prior to discharge. Data from individual mills as well as government published sources were used in characterizing these discharges. Some general assumptions were necessary to describe the common practices. In general, it was assumed 5 percent of POME is treated through biogas operation; 95 percent is assumed lagooned after aerobic and anaerobic digestion. Of that POME lagooned, 33 percent is utilized as fertilizer, and 65 percent is not utilized; the remaining 2 percent is assumed to have no effluent or zero discharge. The wastewater discharges, therefore, represent this 65 percent value.

The energy requirements and environmental emissions for the production of palm kernels are shown in Table L-3.

Palm Kernel Oil Processing

The extraction of crude palm kernel oil (CPKO) from palm kernels can be carried out in a variety of ways:

- Mechanical extraction using high-pressure screw pressing
- Solvent extraction with hexane
- Preprocessing followed by solvent extraction

Table L-3

DATA FOR THE PRODUCTION OF PALM KERNELS

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Fresh Fruit Bunches	2,980	lb		2,980	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Biomass	3,800	thousand Btu	3,800	8.85	GJ	8.85
Total Process			3,800			8.85
Transportation Energy						
Single unit truck	6.22	ton-miles		20.02	tonne-km	
Diesel	0.14	gal	22.2	1.17	liter	0.052
Ocean freighter	1,508	ton-miles		4,854	tonne-km	
Diesel	0.29	gal	46	2.39	liter	0.11
Residual	2.58	gal	443	21.5	liter	1.03
Total Transportation			510			1.19
Environmental Emissions						
Atmospheric Emissions						
Carbon Dioxide (non-fossil)	631	lb		631	kg	
Carbon Monoxide	0.11	lb		0.11	kg	
Methane	23.0	lb		23.0	kg	
Nitrogen Oxides	0.27	lb		0.27	kg	
NM Hydrocarbons	0.52	lb		0.52	kg	
Odorous Sulfur	0.15	lb		0.15	kg	
Particulates (unknown)	3.00	lb		3.00	kg	
Sulfur Oxides	1.05	lb		1.05	kg	
Solid Wastes						
Landfilled	19.7	lb		19.7	kg	
Waterborne Wastes						
BOD	0.18	lb		0.18	kg	
COD	1.63	lb		1.63	kg	
Dissolved Solids	5.07	lb		5.07	kg	
Nitrogen	0.10	lb		0.10	kg	
Oil	0.048	lb		0.048	kg	
Suspended Solids	0.73	lb		0.73	kg	

References: L-3, L-5, L-7, L-8, and L-10 through L-21.

Source: Franklin Associates, A Division of ERG

Industry sources have indicated solvent extraction of palm kernel oil accounts for only a minor portion of the CPKO production. Mechanical extraction may be carried out in either a single-or double-press system. In this analysis it was assumed only one-third of all CPKO is produced by way of a double-press system. The remainder was assumed produced from a single-press system (Reference L-4).

The energy and emissions data for the production of CPKO is presented in Table L-4. For every 1,000 pounds of CPKO produced, 1,560 pounds of cake and pellets are produced. Mass partitioning was used to give credit to these coproducts.

Table L-4

DATA FOR THE PROCESSING
OF CRUDE PALM KERNEL OIL

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Palm Kernels	1,064	lb		1,064	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	137	kwh	1,410	302	kwh	3.28
Natural gas	36.1	cu ft	40.4	2.25	cu meters	0.094
Distillate oil	3.83	gal	608	32.0	liter	1.42
Total Process			2,059			4.79
Transportation Energy						
Single unit truck	6.22	ton-miles		20.02	tonne-km	
Diesel	0.14	gal	22.2	1.17	liter	0.052
Ocean freighter	1,508	ton-miles		4,854	tonne-km	
Diesel	0.29	gal	46	2.39	liter	0.11
Residual	2.58	gal	443	21.5	liter	1.03
Total Transportation			510			1.19
Environmental Emissions						
Solid Wastes						
Landfilled	17.2	lb		17.2	kg	
Waterborne Wastes						
Suspended solids	1.84	lb		1.84	kg	

References: L-5, L-7 through L-9, and L-22 through L-24.

Source: Franklin Associates, A Division of ERG

Palm Kernel Oil Refining, Bleaching, and Deodorizing

The purpose for refining is to produce a bland, light colored oil with excellent oxidative stability. This can be achieved by removing trace components such as beta-carotenes, metals, and free fatty acid (FFA). The two most common methods are the alkali or chemical refining route and the physical or steam refining route. The methods differ basically in the way the FFA is removed from the oil.

The chemical refining route is the older of the commercial refining methods. In this system the oil is treated with phosphoric acid and neutralized with a solution of caustic soda. The precipitated impurities are removed and commonly called soapstock. The refined oil is then vacuum dried and mixed with bleaching clay (0.6 to 1.2 percent by weight of the oil input) (Reference L-2). The final step is to deodorize the oil by distillation. The refining loss index for the alkali process ranges from 1.5 to 1.8 times the input FFA.

Drawbacks from the alkali process include the problem of effluent production and the limitation of needing low FFA in the crude oil input. The effluents issue pertains to the production of alkali metal sulphate and dilute sulfuric acid. The alkali method is also considered as restricted to processing crude oils of low FFA. Thus, the greater the incoming FFA, the greater the refinery losses. Typically the FFA levels of crude oils processed by the alkali method are below 0.25 percent (crude palm oil ranges between 3 and 5 percent FFA).

Physical refining, which eliminates the need for effluent plants, involves subjecting the oil to steam distillation of fatty acids in a vacuum under high temperatures. Approximately 85-90 percent of Malaysia refining capacity is through the physical route. Discussion and analysis will therefore focus on physical refining for the processing of crude palm oil.

Physical refining was initially conceived for the treatment of high FFA oils. Because of this situation and the fact that no alkali or acid industry exists in Malaysia, the physical refining route was a natural progression.

Initially the oil is treated with phosphoric acid (85 percent). Next the degummed oil comes in contact with bleaching clay (0.6 to 1.5 percent by weight of the oil) (Reference L-4). This bleaching ratio is considerably higher than that required in the residual/unreacted phosphoric acid and to remove metals and other impurities.

The resulting (degummed and bleached) oil must be deodorized. Because the FFA at this point is still quite high, deodorizing is significantly different than for the alkali process. The deodorization is performed under a vacuum at temperatures of 260° Celsius. The fatty acid distillate is marketed as animal feed. The refining loss index is from 1.1 to 2.8 times the input FFA. An average 93.5 percent oil yield is achieved through the physical refining route.

The energy requirements and environmental emissions for the refining, bleaching, and deodorizing of palm kernel oil are shown in Table L-5.

Table L-5

DATA FOR THE REFINING, BLEACHING AND DEODORIZING OF PALM KERNEL OIL

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude Palm Kernel Oil	1,016	lb		1,016	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	4.3	kwh	44	9.5	kwh	0.10
Distillate oil	3.20	gal	508.2	26.70	liter	1.18
Total Process			552			1.29
Transportation Energy						
Combination truck	18.6	ton-miles		59.9	tonne-km	
Diesel	1.18	gal	187	9.85	liter	0.44
Ocean freighter	1,508	ton-miles		4,854	tonne-km	
Diesel	0.45	gal	71.5	3.75	liter	0.17
Residual	4.53	gal	777	37.8	liter	1.81
Total Transportation			1,036			2.41
Environmental Emissions						
Atmospheric Emissions						
Carbon Monoxide	0.0070	lb		0.0070	kg	
Hydrocarbons	0.0020	lb		0.0020	kg	
Solid Wastes						
Landfilled	20.9	lb		20.9	kg	
Waterborne Wastes						
BOD	0.44	lb		0.44	kg	
COD	0.87	lb		0.87	kg	
Suspended solids	0.54	lb		0.54	kg	
Dissolved solids	1.00	lb		1.00	kg	
Oil	0.057	lb		0.057	kg	

References: L-5

Source: Franklin Associates, A Division of ERG

Glycerine Production

Glycerine is produced by several methods: 1) as a byproduct of soap manufacture, 2) from propylene and chlorine to form allyl chloride, which is converted to dichlorohydrin with hypochlorous acid and then saponified to glycerine with caustic, 3) by isomerization of propylene oxide to allyl alcohol, which is then reacted with peracetic acid, followed by hydrolyzing the glycidol into glycerine, 4) hydrogenation of carbohydrates with a nickel catalyst, and 5) from acrolein and hydrogen peroxide. In this analysis, glycerine is produced as a byproduct of palm oil methyl ester, which is an intermediate in soap production. This production method makes up approximately 75 percent of the total U.S. glycerine production amount (Reference L-25).

Although a number of raw materials (coconut oil, palm oil, palm kernel oil, etc.) can be used to produce glycerine, palm kernel oil has been chosen in this analysis (Reference L-26). Refined palm kernel oil is converted to methyl esters and glycerine by the transesterification of triglycerides. The reaction occurs with excess methanol, a process known as methanolysis, in the presence of a sodium methylate catalyst. The reaction takes place at atmospheric pressure and can be carried out in a batch or continuous process. The yields will be higher (in excess of 99 percent) for the continuous process.

The reaction forms two layers. The bottom layer consists of crude glycerine, soap, methanol, small amounts of methyl ester, and water. The top layer contains the methyl esters.

The first step in refining the glycerine is to distill off the methanol and water. The methanol is dried and recirculated back into the esterification process or used to make sodium methylate. The remaining glycerine mixture is acidulated to separate the fatty acids from the soap. Methyl esters are also separated and the glycerine is dried.

Table L-6 displays the energy requirements and environmental emissions for the production of glycerine.

Table L-6

DATA FOR THE PRODUCTION OF GLYCERINE

	English units (Basis: 1,000 lb)		Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Raw Materials						
Refined Palm Kernel Oil	675	lb		675	kg	
Crude Palm Kernel Oil	232	lb		232	kg	
Methanol	124	lb		124	kg	
Energy Usage						
Process Energy						
Electricity (grid)	5.48	kwh	56.4	12.1	kwh	0.13
Natural gas	2,071	cu ft	2,320	129	cu meters	5.40
Bit./Sbit. Coal	49.1	lb	551	49.1	kg	1.28
Total Process			2,927			6.81
Transportation Energy						
Combination truck	27.1	ton-miles		87.2	tonne-km	
Diesel	0.28	gal	45.2	2.37	liter	0.11
Rail	49.8	ton-miles		160.3	tonne-km	
Diesel	0.12	gal	19.6	1.03	liter	0.046
Total Transportation			64.8			0.15
Environmental Emissions						
Atmospheric Emissions						
NM Hydrocarbons	2.41	lb		2.41	kg	
Methane	0.014	lb		0.014	kg	
Other Organics	0.034	lb		0.034	kg	
Waterborne Wastes						
BOD	0.063	lb		0.063	kg	
COD	0.070	lb		0.070	kg	
Oil	0.012	lb		0.012	kg	
Suspended solids	0.028	lb		0.028	kg	
Dissolved solids	0.068	lb		0.068	kg	

References: L-5, L-27, and L-28.

Source: Franklin Associates, A Division of ERG

Polyether Polyol for Flexible Foam Polyurethanes

The manufacture of polyether polyol begins with the introduction of a potassium hydroxide catalyst to a polyol initiator, such as a triol. Sodium hydroxide data is used in place of potassium hydroxide data, which were not available. The manufacture of sodium hydroxide utilizes a process similar to the manufacture of potassium hydroxide. This solution is reacted with propylene oxide and ethylene oxide to form an intermediate. Water is then added to this intermediate. A solvent is introduced, which absorbs the polyol from the water/catalyst. The density difference between the aqueous & organic phases is used to separate the two phases. Finally, the polyol is purified of solvent, side products and water through distillation (Reference L-28).

Table L-7 presents the data for the production of polyether polyol for use in flexible foam polyurethane. Data for the production of polyether polyol were provided by five leading producers (5 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). Heat was a coproduct for two producers. The energy for exported heat was reported separately as recovered energy.

As of 2002, it is estimated that for all polyurethane applications, there were 7 polyether polyol producers and 9 polyether polyol plants in the U.S. (Reference L-1 and L-29). The polyether polyol data collected represents a majority of the total North American production of polyether polyol for flexible foam polyurethane. The polyether polyol producers who provided data for this module verified that the characteristics of their plants are representative of a majority of the North American production. The average dataset was reviewed and accepted by all polyether polyol data providers.

To assess the quality of the data collected for polyether polyols used in flexible foam polyurethane, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for these polyether polyols include direct measurements, information provided by purchasing and utility records, and engineering estimates. All data submitted for polyether polyols represents the years 2003 and 2005 and represents U.S. production.

Table L-7

DATA FOR THE PRODUCTION OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANE

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Propylene oxide	856	lb			856	kg	
Ethylene oxide	113	lb			113	kg	
Glycerine	26.3	lb			26.3	kg	
Caustic Potash	3.96	lb			3.96	kg	
Water Consumption	54.0	gal			451	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	10.9	kwh		112	24.0	kwh	0.26
Electricity (cogeneration)	48.7	kwh		332	107	kwh	0.77
Natural gas	985	cu ft		1,103	61.5	cu meters	2.57
Recovered Energy	79.0	thousand Btu		79.0	184	MJ	0.18
Total Process				1,469			3.42
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.027	lb			0.027	kg	
Carbon Dioxide	26.1	lb			26.1	kg	
Chlorine	1.0E-05	lb	(1)		1.0.E-05	kg	
Lead	1.0E-07	lb	(1)		1.0.E-07	kg	
Mercury	1.0E-07	lb	(1)		1.0.E-07	kg	
Methane	0.0010	lb	(1)		0.0010	kg	
Nitrogen Oxides	0.063	lb			0.063	kg	
Nitrous Oxide	1.0E-04	lb	(1)		1.0E-04	kg	
NM Hydrocarbons	0.11	lb			0.11	kg	
Other Organics	0.023	lb			0.023	kg	
Particulates (unknown)	0.0010	lb	(1)		0.0010	kg	
PM2.5	0.010	lb	(1)		0.010	kg	
PM10	0.057	lb			0.057	kg	
Sulfur Oxides	2.1E-04	lb			2.1E-04	kg	
Solid Wastes							
Landfilled	0.87	lb			0.87	kg	
Waterborne Wastes (2)							
Ammonia	0.010	lb	(1)		0.010	kg	
BOD	0.28	lb			0.28	kg	
COD	2.96	lb			2.96	kg	
Dissolved Solids	1.00	lb	(1)		1.00	kg	
Hexane	0.10	lb	(1)		0.10	kg	
Metal Ion	1.00	lb	(1)		1.00	kg	
Nitrates	1.00	lb	(1)		1.00	kg	
Suspended Solids	3.6.E-04	lb			3.6E-04	kg	
TOC	0.010	lb	(1)		0.010	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(2) These waterborne emissions may be overstated as 1 or more of the plants providing data were only able to supply waterborne emissions before the effluent was sent to a water treatment plant.

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Source: Franklin Associates, A Division of ERG

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APPENDIX M

METHYLENE DIPHENYLENE DIISOCYANATE (MDI)

INTRODUCTION

This appendix discusses the manufacture of pure and polymeric forms of methylene diphenylene diisocyanate (MDI), which is a precursor for a variety of polyurethanes. Industries that use polyurethanes with MDI as a precursor include automotive, construction, footwear, and appliances. Over 2.2 billion pounds of pure and polymeric MDI were produced in the U.S. and Canada in 2002 (Reference M-1). The material flow for MDI is shown in Figure M-1. The total unit process energy and emissions data (cradle-to-MDI) for MDI are displayed in Table M-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Hydrogen
- Nitric Acid
- Nitrobenzene
- Aniline
- Formaldehyde
- Phosgene
- Methylene diphenylene diisocyanate (PMDI/MDI)

Crude oil production, refining of petroleum products (distillation, desalting and hydrotreating), natural gas production, and natural gas processing (extraction) are discussed in Appendix B. Mixed xylenes production, carbon monoxide production, and methanol production are discussed in Appendix F. Benzene production and pygas production are discussed in Appendix G. Salt mining and sodium hydroxide/chlorine production are discussed in Appendix I. Ammonia production is discussed in Appendix J. Although carbon monoxide data is not shown in this appendix due to confidentiality issues, the transport data is specific to MDI and is represented as .216 ton-miles by petroleum pipeline in Table M-1.

Hydrogen Production

Hydrogen and carbon dioxide are coproducts in the production of syntheses gas. Synthesis gas is primarily produced from natural gas by steam-methane reforming. Natural gases, or other light hydrocarbons, and steam are fed into a primary reformer over a nickel catalyst to produce hydrogen and carbon oxides, generally referred to as synthesis gas. About 70 percent of the hydrocarbon feed is converted to synthesis gas in the primary reformer.

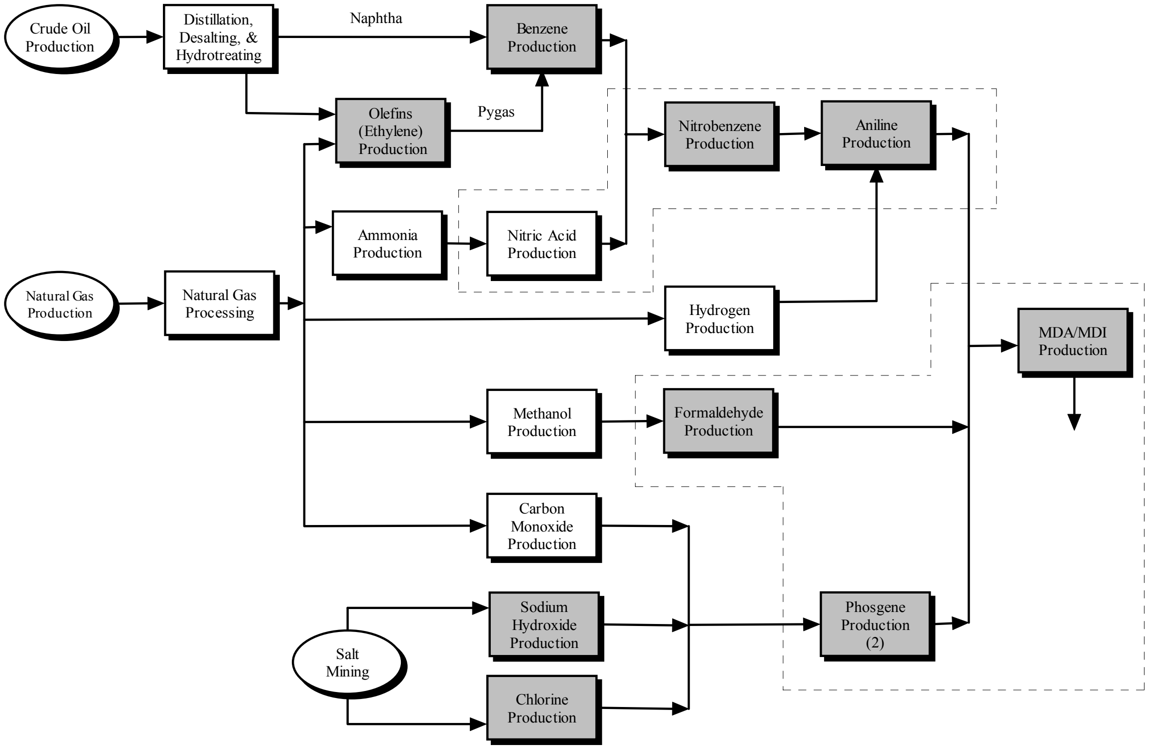

Figure M-1. Flow diagram for the manufacture of methylene diphenylene diisocyanate (MDI). Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted lines are included in an aggregated dataset.

The effluent from the reformers is fed into carbon monoxide shift converters where the carbon monoxide reacts with water to form carbon dioxide and hydrogen. The effluent from the shift converters is cooled, and condensed water is removed. The carbon dioxide and some excess hydrogen are also removed from the synthesis gas as coproducts (Reference M-2).

The ratio of carbon monoxide to hydrogen in the synthesis gas differs depending on the specifications for the synthesis gas, and therefore the amounts of hydrogen and carbon dioxide coproducts differ also. Synthesis gas is a raw material for many different processes, each with specific requirements. Because of this difference in requirements, it is difficult to show a generic or widely applicable material balance for this process.

Table M-1

DATA FOR THE PRODUCTION OF METHYLENE DIPHENYLENE DIISOCYANATE (MDI)

(Cradle-to-MDI)

(page 1 of 4)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Crude oil	340	lb		340	kg	
Natural Gas	203	lb		203	kg	
Salt	472	lb		472	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			4,720			11.0
Petroleum			6,639			15.5
Total Resource			11,359			26.4
Process Energy						
Electricity (grid)	318	kwh	3,378	700	kwh	7.86
Electricity (cogeneration)	136	kwh	- (2)	300	kwh	-
Natural gas	7,581	cu ft	8,490	473	cu meters	19.8
LPG	0.047	gal	5.13	0.40	liter	0.012
Bit./Sbit. Coal	18.4	lb	207	18.4	kg	0.48
Distillate oil	0.82	gal	130	6.85	liter	0.30
Residual oil	2.86	gal	490	23.8	liter	1.14
Gasoline	0.049	gal	6.95	0.41	liter	0.016
Diesel	2.6E-04	gal	0.042	0.0022	liter	9.7E-05
Internal Offgas use (1)						
From Oil	10.3	lb	453	10.3	kg	1.05
From Natural Gas	23.2	lb	626	23.2	kg	1.46
Recovered Energy	900	thousand Btu	900	2,094	MJ	2.10
Total Process			12,887			30.0
Transportation Energy						
Combination truck	41.3	ton-miles		23.3	tonne-km	
Diesel	0.43	gal	68.9	3.62	liter	0.16
Rail	43.4	ton-miles		24.5	tonne-km	
Diesel	0.11	gal	17.1	0.90	liter	0.040
Barge	58.0	ton-miles		32.7	tonne-km	
Diesel	0.046	gal	7.37	0.39	liter	0.017
Residual oil	0.15	gal	26.5	1.29	liter	0.062
Ocean freighter	516	ton-miles		291	tonne-km	
Diesel	0.098	gal	15.6	0.82	liter	0.036
Residual	0.88	gal	151	7.36	liter	0.35
Pipeline-natural gas	111	ton-miles		62.5	tonne-km	
Natural gas	76.4	cu ft	85.6	4.77	cu meter	0.20
Pipeline-petroleum products	159	ton-miles		89.7	tonne-km	
Electricity	3.47	kwh	35.5	7.65	kwh	0.083
Total Transportation			408			0.95

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table M-1

DATA FOR THE PRODUCTION
OF METHYLENE DIPHENYLENE DIISOCYANATE (MDI)
(Cradle-to-MDI)
(page 2 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Particulates (unspecified)	0.093	lb	0.093	kg
Nitrogen Oxides	0.54	lb	0.54	kg
Non-Methane Hydrocarbons	1.05	lb	1.05	kg
Sulfur Oxides	6.34	lb	6.34	kg
Carbon Monoxide	6.66	lb	6.66	kg
Aldehydes (unspecified)	0.014	lb	0.014	kg
Methane	4.37	lb	4.37	kg
Other Organics	0.11	lb	0.11	kg
Ammonia	0.18	lb	0.18	kg
Copper	4.8E-05	lb	4.8E-05	kg
Lead	4.8E-06	lb	4.8E-06	kg
Mercury	1.5E-04	lb	1.5E-04	kg
Chlorine	7.8E-04	lb	7.8E-04	kg
Hydrogen Chloride	3.0E-04	lb	3.0E-04	kg
Carbon Dioxide - Fossil	90.8	lb	90.8	kg
Carbon Tetrachloride	0.010	lb	0.010	kg
Trichloroethane	3.3E-08	lb	3.3E-08	kg
Toluene	0.033	lb	0.033	kg
VOC	0.17	lb	0.17	kg
Particulates (PM2.5)	0.010	lb	0.010	kg
Particulates (PM10)	0.059	lb	0.059	kg
HFC-22	4.8E-04	lb	4.8E-04	kg
HCFC-123	4.0E-05	lb	4.0E-05	kg
HFC-134a	4.0E-05	lb	4.0E-05	kg
Xylenes	0.019	lb	0.019	kg
Hydrogen	7.5E-04	lb	7.5E-04	kg
TOC	0.65	lb	0.65	kg
Formaldehyde	0.0012	lb	0.0012	kg
Benzene	0.021	lb	0.021	kg
Dimethyl Ether	0.0010	lb	0.0010	kg
Ethylbenzene	0.0026	lb	0.0026	kg
Sulfuric Acid	4.8E-06	lb	4.8E-06	kg
Nickel Compounds	4.8E-04	lb	4.8E-04	kg
Perfluorocarbons (PFC)	0.0048	lb	0.0048	kg
Methanol	0.0010	lb	0.0010	kg
Solid Wastes				
Landfilled	19.2	lb	19.2	kg
Burned	3.34	lb	3.34	kg
Waste-to-Energy	0.75	lb	0.75	kg
Waterborne Wastes				
Dissolved Solids	129	lb	129	kg
Suspended Solids	4.10	lb	4.10	kg
BOD	0.72	lb	0.72	kg
COD	1.17	lb	1.17	kg
Phenol/ Phenolic Compounds	0.0013	lb	0.0013	kg
Sulfides	5.1E-04	lb	5.1E-04	kg
Oil	0.065	lb	0.065	kg
Iron	0.28	lb	0.28	kg
Cyanide	1.2E-06	lb	1.2E-06	kg
Alkalinity	0.18	lb	0.18	kg
Chromium (unspecified)	0.0037	lb	0.0037	kg
Chromium (hexavalent)	1.3E-05	lb	1.3E-05	kg
Aluminum	0.13	lb	0.13	kg
Nickel	5.2E-04	lb	5.2E-04	kg
Mercury	1.8E-06	lb	1.8E-06	kg
Lead	0.0010	lb	0.0010	kg
Phosphates	0.0071	lb	0.0071	kg
Zinc	0.0031	lb	0.0031	kg
Ammonia	0.052	lb	0.052	kg
Sulfates	0.16	lb	0.16	kg

Table M-1

DATA FOR THE PRODUCTION OF METHYLENE DIPHENYLENE DIISOCYANATE (MDI)
(Cradle-to-MDI)
(page 3 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
1-Methylfluorene	2.5E-07	lb	2.5E-07	kg
2,4-Dimethylphenol	6.2E-05	lb	6.2E-05	kg
2-Hexanone	1.4E-05	lb	1.4E-05	kg
2-Methylnaphthalene	3.5E-05	lb	3.5E-05	kg
4-Methyl-2-Pentanone	9.3E-06	lb	9.3E-06	kg
Acetone	2.2E-05	lb	2.2E-05	kg
Alkylated benzenes	7.1E-05	lb	7.1E-05	kg
Alkylated fluorenes	4.1E-06	lb	4.1E-06	kg
Alkylated naphthalenes	1.2E-06	lb	1.2E-06	kg
Alkylated phenanthrenes	4.8E-07	lb	4.8E-07	kg
Antimony	8.1E-05	lb	8.1E-05	kg
Arsenic	5.6E-04	lb	5.6E-04	kg
Barium	1.81	lb	1.81	kg
Benzene	0.0037	lb	0.0037	kg
Acid (benzoic)	0.0023	lb	0.0023	kg
Beryllium	2.9E-05	lb	2.9E-05	kg
Boron	0.0070	lb	0.0070	kg
Bromide	0.48	lb	0.48	kg
Cadmium	8.2E-05	lb	8.2E-05	kg
Calcium	7.13	lb	7.13	kg
Chlorides	80.2	lb	80.2	kg
Cobalt	4.9E-05	lb	4.9E-05	kg
Copper	5.0E-04	lb	5.0E-04	kg
Dibenzofuran	4.2E-07	lb	4.2E-07	kg
Dibenzothiophene	3.4E-07	lb	3.4E-07	kg
Ethylbenzene	2.1E-04	lb	2.1E-04	kg
Fluorine	2.1E-06	lb	2.1E-06	kg
Hardness	22.0	lb	22.0	kg
Acid (hexanoic)	4.7E-04	lb	4.7E-04	kg
Lead 210	2.3E-13	lb	2.3E-13	kg
Lithium	1.05	lb	1.05	kg
Magnesium	1.39	lb	1.39	kg
Manganese	0.0022	lb	0.0022	kg
Methyl Chloride	8.9E-08	lb	8.9E-08	kg
Methyl Ethyl Ketone	1.8E-07	lb	1.8E-07	kg
Molybdenum	5.1E-05	lb	5.1E-05	kg
Xylene	6.7E-05	lb	6.7E-05	kg
Naphthalene	4.0E-05	lb	4.0E-05	kg
n-Decane	6.5E-05	lb	6.5E-05	kg
n-Docosane	2.4E-06	lb	2.4E-06	kg
n-Dodecane	1.2E-04	lb	1.2E-04	kg
n-Eicosane	3.4E-05	lb	3.4E-05	kg
n-Hexacosane	1.5E-06	lb	1.5E-06	kg
n-Hexadecane	1.3E-04	lb	1.3E-04	kg
n-Octadecane	3.3E-05	lb	3.3E-05	kg
n-Tetradecane	5.4E-05	lb	5.4E-05	kg
o + p-Xyxlene	4.9E-05	lb	4.9E-05	kg
o-Cresol	6.4E-05	lb	6.4E-05	kg
p-Cresol	6.9E-05	lb	6.9E-05	kg
p-Cymene	2.2E-07	lb	2.2E-07	kg
Pentamethylbenzene	1.7E-07	lb	1.7E-07	kg
Phenanthrene	4.8E-07	lb	4.8E-07	kg
Radium 226	8.0E-11	lb	8.0E-11	kg
Radium 228	4.1E-13	lb	4.1E-13	kg

Table M-1

DATA FOR THE PRODUCTION
OF METHYLENE DIPHENYLENE DIISOCYANATE (MDI)
(Cradle-to-MDI)
(page 4 of 4)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Selenium	1.6E-05	lb	1.6E-05	kg
Silver	0.0047	lb	0.0047	kg
Sodium	22.6	lb	22.6	kg
Strontium	0.12	lb	0.12	kg
Sulfur	0.0059	lb	0.0059	kg
Surfactants	0.0020	lb	0.0020	kg
Thallium	1.7E-05	lb	1.7E-05	kg
Tin	3.9E-04	lb	3.9E-04	kg
Titanium	0.0012	lb	0.0012	kg
Toluene	0.0035	lb	0.0035	kg
Total biphenyls	4.6E-06	lb	4.6E-06	kg
Total dibenzothiophenes	1.4E-08	lb	1.4E-08	kg
Vanadium	6.0E-05	lb	6.0E-05	kg
Xylene	0.0018	lb	0.0018	kg
Yttrium	1.5E-05	lb	1.5E-05	kg
Styrene	1.4E-07	lb	1.4E-07	kg
TOC	0.025	lb	0.025	kg
Chloroform	1.0E-06	lb	1.0E-06	kg
Nitrates	1.0E-08	lb	1.0E-08	kg

References: Tables B-2 through B-5, F-2, F-6, G-2, I-2, I-3, J-2, and M-2 through M-4.

Source: Franklin Associates, A Division of ERG models

Table M-2 provides the energy and emissions data for the production of hydrogen. The data for hydrogen production are estimates of the synthesis gas production. Raw material inputs for hydrogen are based on the conversion of methane to carbon monoxide and hydrogen.

Nitric Acid Production

The raw materials necessary for nitric acid production are ammonia, air, and a platinum-rhodium catalyst. Gaseous ammonia is mixed with air and passed over the catalyst to produce nitric oxides. Reaction water is removed as 2% nitric acid condensate. Secondary air containing recycled nitrogen dioxide is added to the nitrous gas, which is compressed and fed into an absorption column, where acid is formed. Nitrogen dioxide remaining in the gas is absorbed in the nitric acid and must be stripped from the acid by secondary air, which is recycled.

The energy and emissions data for nitric acid production is from a primary European source from 1990. This dataset has been included with the aniline/ nitrobenzene average dataset in Table M-3 to conceal the confidential data of the provider company.

Table M-2

DATA FOR THE PRODUCTION OF HYDROGEN

	English units (Basis: 1,000 lb)		Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Raw Materials						
Methane	593	lb		593	kg	
Energy Usage						
Process Energy						
Natural gas	14,697	cu ft	16,461	917	cu meters	38.3
Total Process			16,461			38.3
Transportation Energy						
Pipeline-natural gas	1.20	ton-miles		3.86	tonne-km	
Natural gas	0.83	cu ft	0.93	2.66	cu meters	2.98
Total Transportation			0.93			2.98
Environmental Emissions						
Atmospheric Emissions						
Total Organic Compounds	4.20	lb		4.20	kg	
Carbon Monoxide	7.60	lb		7.60	kg	
Ammonia	1.10	lb		1.10	kg	
Carbon Dioxide (fossil)	3.40	lb		3.40	kg	
Solid Wastes						
Landfilled	0.20	lb		0.20	kg	
Waterborne Wastes						
Ammonia	0.10	lb		0.10	kg	

References: M-2 through M-4.

Source: Franklin Associates, A Division of ERG

Nitrobenzene Production

Nitrobenzene and other nitroaromatics, such as nitrochlorobenzene and dinitrotoluene, are formed by nitrating the appropriate aromatic hydrocarbon with a mixed acid containing nitric and sulfuric acid. The nitrated aromatic is separated from the acid mixture in a centrifugal separator, neutralized and washed, and finally dried in a drying column. The recovered acid mixture containing nitric acid and nitro compounds is recycled.

The energy and emissions data for nitrobenzene production are from two provider companies and are aggregated with the aniline/nitric acid dataset in Table M-3 to protect the data's confidentiality.

As of 2002 there were 4 nitrobenzene producers and 5 nitrobenzene plants in the U.S. (Reference M-6). The nitrobenzene data collected represents a majority of the total North American nitrobenzene production amount. The nitrobenzene producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American nitrobenzene production. The average dataset was reviewed and accepted by all nitrobenzene data providers.

To assess the quality of the data collected for nitrobenzene, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for nitrobenzene include direct measurements, information provided by purchasing and utility records and engineering estimates. All data submitted for nitrobenzene ranges from 2003-2004 and represents U.S. production.

Aniline Production

Aniline is formed by the hydrogenation of nitrobenzene in the presence of a copper-chromium or copper-silica catalyst, or by vapor phase ammonolysis of phenol and ammonia.

For hydrogenation of nitrobenzene, preheated hydrogen and nitrobenzene are fed into an evaporator, and aniline is formed by vapor phase catalytic reduction. The aniline is dehydrated to remove the water produced during the reaction.

In the ammonolysis process, phenol and ammonia are preheated and fed into an adiabatic, fixed abed reactor and passed over a catalyst to produce aniline and water. The effluent gas is partially condensed, and the liquid and vapor phases separated. The vapor phase containing unreacted ammonia is recycled. Ammonia is stripped from the liquid fraction, and the aniline is dried and distilled. Unreacted phenol is recovered and recycled.

Table M-3 presents the data for the production of nitric acid, nitrobenzene, and aniline. Data for the production of nitrobenzene and aniline were provided by two leading producers (2 plants) in North America to Franklin Associates. Steam/heat is produced as a coproduct during this process. The energy amount for this coproduct is reported separately as recovered energy.

As of 2002 there were 6 aniline producers and 7 aniline plants in the U.S. (Reference M-6). The aniline data collected represents approximately half of the total North American aniline production amount. The aniline producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American aniline production. The average dataset was reviewed and accepted by all aniline data providers.

Table M-3

DATA FOR THE PRODUCTION OF ANILINE
(including nitric acid and nitrobenzene production)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Benzene	621	lb			621	kg	
Hydrogen	45.6	lb			45.6	kg	
Ammonia	149	lb			149	kg	
Oxygen (from air)	559	lb			559	kg	
Water Consumption	141	gal			1,177	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy (1)							
Electricity (grid)	75.4	kwh		776	166	kwh	1.81
Electricity (cogeneration)	36.1	kwh		246	79.6	kwh	0.57
Natural gas	451	cu ft		505	28.2	cu meters	1.18
Recovered Energy	1,308	thousand Btu		1,308	3.05	GJ	3.05
Total Process				219			0.51
Transportation Energy							
Barge	14.8	ton-miles			47.63	tonne-km	
Diesel	0.012	gal		1.88	0.099	liter	0.0044
Residual oil	0.039	gal		6.76	0.33	liter	0.016
Pipeline-petroleum products	0.15	ton-miles			0.483	tonne-km	
Electricity	0.0033	kwh		0.033	0.0072	kwh	7.8E-05
Total Transportation				8.67			0.020
Environmental Emissions							
Atmospheric Emissions							
Acid Mist	1.0E-05	lb	(1)		1.0E-05	kg	
Ammonia	0.0033	lb			0.0033	kg	
Carbon Monoxide	0.011	lb			0.011	kg	
Chlorine	9.7E-05	lb			9.7E-05	kg	
Copper	1.0E-04	lb	(1)		1.0E-04	kg	
HFCs/HCFCs	0.010	lb	(1)		0.010	kg	
Lead	1.0E-06	lb	(1)		1.0E-06	kg	
Mercury	1.0E-06	lb	(1)		1.0E-06	kg	
Metal Ion	0.0010	lb	(1)		0.0010	kg	
Nitrogen Oxides	0.84	lb			0.84	kg	
NM Hydrocarbons	0.0072	lb			0.0072	kg	
Other Organics	0.010	lb	(1)		0.010	kg	
PM2.5	0.010	lb	(1)		0.010	kg	
PM10	0.045	lb			0.045	kg	
Sulfur Oxides	1.0E-05	lb	(1)		1.0E-05	kg	
Solid Wastes							
Burned	0.50	lb			0.50	kg	
Waste-to-Energy	1.56	lb			1.56	kg	
Waterborne Wastes (2)							
Total Organic Carbon	0.010	lb	(1)		0.010	kg	

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(1) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(2) Waterborne emissions collected for nitrobenzene and aniline included those sent to deepwell disposal. Emissions sent to deepwell disposal are not included in the table as they are not released to a water source. The following emissions were reported as being sent to deepwell disposal: toluene, phenol, 2-DNP, aniline, and nitrobenzene.

References: M-5 and M-7

Source: Franklin Associates, A Division of ERG

To assess the quality of the data collected for aniline, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for aniline include direct measurements, information provided by purchasing and utility records, and engineering estimates. All data submitted for aniline ranges from 2003-2004 and represents U.S. production.

Formaldehyde Production

Formaldehyde is most commonly produced by oxidation of methanol, in the presence of either a silver or ferric molybdate catalyst. Along with the silver catalyst, methanol, air, and water are preheated and fed into the reactor vessel. The heat from the reaction gas is recovered by generating steam, and the gases are then sent to an absorption tower.

The process for the metal oxide catalyst differs from the silver catalyst process in that the metal oxide reaction occurs at lower temperatures and requires a much greater excess of air in the feed. Heat recovered from the reaction gases is used to preheat the feed, and the excess steam is exported.

The formaldehyde is stripped from the reaction gases with water and then distilled. A solution containing 60 percent urea can also be used during the stripping process.

Data for the production of formaldehyde was collected from one confidential source in the United States. This data was aggregated with phosgene, MDA, and PMDI/MDI and is included in Table M-4.

As of 2001 there were 16 formaldehyde producers and 43 formaldehyde plants in the U.S. (Reference M-6). Although the formaldehyde data collected represents only a small portion of the total North American formaldehyde production amount, the formaldehyde producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American formaldehyde production.

To assess the quality of the data collected for formaldehyde, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for formaldehyde include direct measurements, information provided by purchasing and utility records, and engineering estimates. All data submitted for formaldehyde represents 2007 U.S. production.

Phosgene Production

Phosgene (also called carbonyl chloride, carbon oxychloride, or chloroformyl chloride) is produced by the reaction of carbon monoxide and chlorine in the presence of an activated charcoal catalyst. Careful production, handling, and trace recovery must be maintained because of phosgene's toxicity. Chlorine gas and carefully purified carbon monoxide are mixed with a slight excess of carbon monoxide to insure complete conversion of chlorine. The reaction is exothermic and is carried out in relatively simple tubular heat exchangers. The product gas is condensed and the phosgene removed in an absorption column. Any non-condensed phosgene is removed in a caustic scrubber.

Phosgene data was collected with the formaldehyde, MDA and PMDI/MDI energy and emissions and is included in Table M-4.

Methylene Diphenylene Diisocyanate (PMDI/MDI) Production

Methylene diphenylene isocyanate (MDI) formation consists of two steps. In the first, 4,4-methylenedianiline (MDA) is created as an intermediate by the condensation of aniline and formaldehyde in the presence of an acid. In the final step, MDA is phosgenated to produce MDI. A mixture of MDI, its dimer and trimer is formed, and referred to as polymeric MDI (PMDI). Pure MDI is distilled from the reaction mixture. The market split is approximately 80 percent polymeric MDI and 20 percent pure MDI (Reference M-6). Polyurethanes commonly utilize the PMDI for rigid foams, while the pure MDI is more commonly used in thermoplastic and cast elastomer applications (Reference M-8).

Table M-4 presents the data for the production of formaldehyde, phosgene, MDA, and PMDI/MDI. Data for the production of phosgene, MDA, PMDI/MDI were provided by four leading producers (4 plants) in North America to Franklin Associates. A large amount of hydrogen chloride is produced as a coproduct during this process. A mass basis was used to partition the credit for each product. The coproduct amount is not shown due to confidentiality issues. Once collected, the data for each plant is reviewed individually. At that time, coproduct allocation is performed for the individual plant. After coproduct allocation is complete, the data of all plants are averaged using yearly production amounts. Confidentiality issues prohibit the revealing of each plant's individual HCl coproduct amount. An average of the coproduct could be provided, but this would not allow for precise reproduction of the dataset.

As of 2003 there were 4 PMDI/MDI producers and 5 PMDI/MDI plants in the U.S. (Reference M-6). The PMDI/MDI data collected represents a majority of the total North American PMDI/MDI production amount. The PMDI/MDI producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American PMDI/MDI production. The average dataset was reviewed and accepted by all PMDI/MDI data providers.

To assess the quality of the data collected for PMDI/MDI, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for PMDI/MDI include direct measurements, information provided by purchasing and utility records, and engineering estimates. All data submitted for PMDI/MDI represents the year 2003 and represents U.S. production.

Table M-4

DATA FOR THE PRODUCTION OF PURE AND POLYMERIC METHYLENE DIPHENYLENE DIISOCYANATE (MDI)
(including formaldehyde, phosgene and MDA production)

	English units (Basis: 1,000 lb)			Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Raw Materials (1)							
Aniline	480	lb			480	kg	
Methanol	65.6	lb			65.6	kg	
Chlorine	378	lb			378	kg	
Caustic	150	lb			150	kg	
Carbon Monoxide	58.2	lb			58.2	kg	
Water Consumption	160	gal			1,335	liter	
Energy Usage							
Process Energy							
Electricity (grid)	48.7	kwh		501	107	kwh	1.17
Electricity (cogeneration)	37.1	kwh		253	81.8	kwh	0.59
Natural gas	1,856	cu ft		2,079	116	cu meters	4.84
Recovered Energy	177	thousand Btu		177	412	MJ	0.41
Total Process				2,656			6.18
Transportation Energy							
Combination truck	0.40	ton-miles			1.30	tonne-km	
Diesel	0.0042	gal		0.67	0.035	liter	0.0016
Rail	3.25	ton-miles			10.47	tonne-km	
Diesel	0.0081	gal		1.28	0.067	liter	0.0030
Pipeline-petroleum products	0.045	ton-miles			0.145	tonne-km	
Electricity	9.9E-04	kwh		0.010	0.0022	kwh	2.3E-05
Total Transportation				1.97			0.0046
Environmental Emissions							
Atmospheric Emissions							
Aldehydes	1.0E-04	lb	(2)		1.0E-04	kg	
Ammonia	0.0024	lb			0.0024	kg	
Carbon Dioxide	10	lb	(2)		10.0	kg	
Carbon Monoxide	0.58	lb			0.58	kg	
Carbon Tetrachloride	0.010	lb			0.010	kg	
Chlorine	1.0E-04	lb			1.0E-04	kg	
Dimethyl ether	0.0010	lb	(2)		0.0010	kg	
Hydrochloric Acid	1.0E-04	lb	(2)		1.0E-04	kg	
Methanol	0.0010	lb	(2)		0.0010	kg	
NM Hydrocarbons	0.014	lb			0.014	kg	
Nitrogen Oxides	0.0010	lb	(2)		0.0010	kg	
Other Organics	0.11	lb			0.11	kg	
Particulates (unknown)	0.0010	lb	(2)		0.0010	kg	
PM2.5	0.0010	lb	(2)		0.0010	kg	
PM10	0.014	lb			0.014	kg	
Sulfur Oxides	1.0E-06	lb	(2)		1.0E-06	kg	
Solid Wastes							
Landfilled	1.38	lb			1.38	kg	
Burned	1.45	lb			1.45	kg	
Waterborne Wastes (3)							
Ammonia	0.0011	lb			0.0011	kg	
BOD	0.0045	lb			0.0045	kg	
Chloroform	1.0E-06	lb	(2)		1.0E-06	kg	
COD	0.010	lb	(2)		0.010	kg	
Copper	1.0E-06	lb	(2)		1.0E-06	kg	
Cyanide	1.0E-06	lb	(2)		1.0E-06	kg	
Dissolved Solids	10.0	lb	(2)		10.0	kg	
Lead	1.0E-07	lb	(2)		1.0E-07	kg	
Nickel	1.0E-05	lb	(2)		1.0E-05	kg	
Nitrates	1.0E-08	lb	(2)		1.0E-08	kg	
Oil	0.010	lb	(2)		0.010	kg	
Phenol	1.0E-04	lb	(2)		1.0E-04	kg	
Phosphates	0.0071	lb			0.0071	kg	
Suspended Solids	0.0083	lb			0.0083	kg	
TOC	0.020	lb			0.020	kg	

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(1) Raw materials for the production of formaldehyde also include oxygen from air and water.

(2) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

(3) Waterborne emissions collected for phosgene/MDA/MDI included those sent to deepwell disposal. Emissions sent to deepwell disposal are not included in the table as they are not released to a water source. The following emissions were reported as being sent to deepwell disposal: MDA, aniline, and caustic.

References: M-7 and M-9

Source: Franklin Associates, A Division of ERG

REFERENCES

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M-2. **Reigel's Handbook of Industrial Chemistry.** Tenth Edition. Edited by James A. Kent. Kluwar Academic / Plenum Publishers. New York. 2003.

M-3. **Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources.** Fifth Edition. U.S. Environmental Protection Agency. July 1995.

M-4. Franklin Associates estimate.

M-5. Information and data collected from APC member and non-member companies producing nitrobenzene and aniline. 2003-2004.

M-6. Chemical profiles information taken from the website: http://www.the-innovation-group.com/welcome.htm

M-7. Information and data collected from APC member and non-member companies producing phosgene, MDA, and PMDI/MDI. 2003.

M-8. Isocyanates information compiled from the website: http://www.levitt-safety.com/WhatsNew/DesignatedSubstances/isocyanates.htm

M-9. Information and data collected from a confidential source producing formaldehyde. 2007.

M-10 Information and data collected from a confidential source producing nitric acid. 1990.

APPENDIX N

TOLUENE DIISOCYANATE (TDI)

INTRODUCTION

This appendix discusses the manufacture of toluene diisocyanate (TDI), which is a precursor for a variety of polyurethanes, mostly flexible foams. Examples of uses of polyurethanes that have TDI as a precursor are furniture, automotive, and carpet underlayment. Over 1.1 billion pounds of TDI were produced in the U.S. and Canada in 2002 (Reference N-1). The material flow for TDI is shown in Figure N-1. The total unit process energy and emissions data (cradle-to-TDI) for TDI are displayed in Table N-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Toluene
- Sulfur
- Sulfuric Acid
- Soda Ash
- Dinitrotoluene
- Toluene diamine (TDA)
- Toluene diisocyanate (TDI)

Crude oil production, refining of petroleum products (distillation, desalting, and hydrotreating), natural gas production, and natural gas processing (extraction) are discussed in Appendix B. Mixed xylenes production and carbon monoxide production are discussed in Appendix F. Salt mining and sodium hydroxide/chlorine production are discussed in Appendix I. Ammonia production is discussed in Appendix J. Nitric acid production and phosgene production are discussed in Appendix M. Although carbon monoxide data is not shown in this appendix due to confidentiality issues, the transport data is specific to TDI and is represented as 2.92 ton-miles by petroleum pipeline in Table N-1.

Toluene Production

Approximately 95 percent of toluene is produced by the catalytic reforming of light petroleum distillate (naphtha). The remainder is produced either from pyrolysis gas or as a coproduct of styrene from ethylbenzene (Reference N-2). Data for toluene in this analysis represents only the reforming process.

In the reforming process, naphtha is fed through a catalyst bed at elevated temperatures and pressures. The most common type of reforming process is platforming, in which a platinum-containing catalyst is used. Products obtained from the platforming process include aromatic compounds (benzene, toluene, xylene), chemical hydrogen, light gas, and liquefied petroleum gas. The aromatics content of the reformate varies and is normally less than 45 percent.

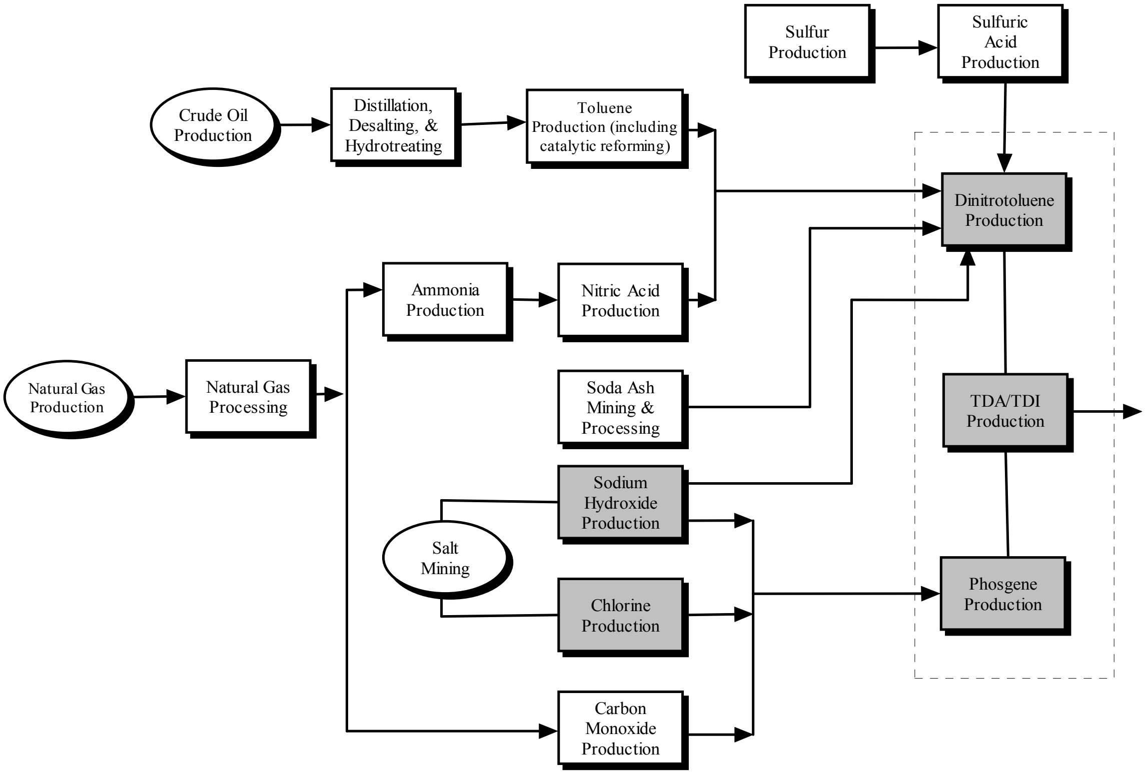

Figure N-1. Flow diagram for the manufacture of toluene diisocyanate (TDI). Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis. Boxes within the dotted rectangle are included in an aggregate dataset.

The reformate from the platforming process undergoes solvent extraction and fractional distillation to produce pure benzene, toluene and other coproducts.

The energy requirements and environmental emissions for the production of toluene are shown in Table N-2. These data are calculated from a straight average of two catalytic reformer datasets from Europe in the early 1990s.

Sulfur Production

Sulfur exists in nature as elemental sulfur and is also found in ores such as pyrite (FeS2). Sulfur is also recovered from hydrogen sulfide (H2S), a component of petroleum and natural gas. The Frasch process (sulfur obtained from limestone) is no longer used in the United States (Reference N-11). The U.S. now produces its sulfur using the Claus process (from natural gas and petroleum). A description of the Claus sulfur production process follows. Sulfur production data are shown in Table N-3.

Table N-1

DATA FOR THE PRODUCTION OF TOLUENE DIISOCYANATE (TDI)
(Cradle-to-TDI)
(page 1 of 3)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials (1)						
Crude oil	318	lb		318	kg	
Natural Gas	149	lb		149	kg	
Salt	425	lb		425	kg	
Soda Ash	4.03	lb		4.03	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas			3,462			8.06
Petroleum			6,222			14.5
Total Resource			9,684			22.5
Process Energy						
Electricity (grid)	267	kwh	2,839	588	kwh	6.61
Electricity (cogeneration)	187	kwh	- (2)	412	kwh	-
Natural gas	9,653	cu ft	10,812	603	cu meters	25.2
LPG	0.043	gal	4.67	0.36	liter	0.011
Bit./Sbit. Coal	17.2	lb	193	17.2	kg	0.45
Distillate oil	0.77	gal	122	6.43	liter	0.28
Residual oil	2.95	gal	506	24.6	liter	1.18
Gasoline	0.039	gal	5.57	0.33	liter	0.013
Recovered Energy	337	thousand Btu	337	784	MJ	0.78
Total Process			14,146			32.9
Transportation Energy						
Combination truck	38.8	ton-miles		21.9	tonne-km	
Diesel	0.41	gal	64.7	3.4	liter	0.15
Rail	29.6	ton-miles		16.7	tonne-km	
Diesel	0.074	gal	11.7	0.61	liter	0.027
Barge	25.7	ton-miles		14.5	tonne-km	
Diesel	0.021	gal	3.26	0.17	liter	0.0076
Residual oil	0.068	gal	11.7	0.57	liter	0.027
Ocean freighter	1,222	ton-miles		689	tonne-km	
Diesel	0.23	gal	36.9	1.94	liter	0.086
Residual	2.09	gal	359	17.43	liter	0.83
Pipeline-natural gas	73.7	ton-miles		41.5	tonne-km	
Natural gas	50.8	cu ft	56.9	3.17	cu meter	0.13
Pipeline-petroleum products	145	ton-miles		81.9	tonne-km	
Electricity	3.17	kwh	32.4	6.98	kwh	0.075
Total Transportation			576			1.34

(1) Does not include oxygen taken from the air.

(2) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table N-1

DATA FOR THE PRODUCTION
OF TOLUENE DIISOCYANATE (TDI)
(Cradle-to-TDI)
(page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Aldehydes	0.013	lb	0.013	kg
Ammonia	0.39	lb	0.39	kg
Benzene	9.2E-06	lb	9.2E-06	kg
Carbon Dioxide (fossil)	28.2	lb	28.2	kg
Carbon Monoxide	5.57	lb	5.57	kg
Carbon Tetrachloride	7.8E-05	lb	7.8E-05	kg
CFCs	3.7E-08	lb	3.7E-08	kg
Chlorine	8.1E-04	lb	8.1E-04	kg
HFC-22	0.010	lb	0.010	kg
Hydrocarbons (NM)	0.78	lb	0.78	kg
Hydrogen Chloride	0.0011	lb	0.0011	kg
Lead	1.0E-07	lb	1.0E-07	kg
Mercury	1.4E-04	lb	1.4E-04	kg
Methane	3.46	lb	3.46	kg
Nitrogen Oxides	0.57	lb	0.57	kg
ODCB	0.0010	lb	0.0010	kg
Other Organics	1.0E-04	lb	1.0E-04	kg
Particulates (unknown)	0.48	lb	0.48	kg
Phosgene	1.0E-05	lb	1.0E-05	kg
PM2.5	0.0010	lb	0.0010	kg
PM10	0.020	lb	0.020	kg
Sulfur Oxides	4.38	lb	4.38	kg
TDA	1.0E-05	lb	1.0E-05	kg
TDI	1.0E-04	lb	1.0E-04	kg
TOC	0.81	lb	0.81	kg
Toluene	0.049	lb	0.049	kg
Trichloroethane	3.0E-08	lb	3.0E-08	kg
VOC	0.11	lb	0.11	kg
Solid Wastes				
Landfilled	14.8	lb	14.8	kg
Burned	1.30	lb	1.30	kg
Waste-to-Energy	34.3	lb	34.3	kg
Waterborne Wastes				
1-Methylfluorene	2.0E-07	lb	2.0E-07	kg
2,4-Dimethylphenol	5.0E-05	lb	5.0E-05	kg
2-Hexanone	1.2E-05	lb	1.2E-05	kg
2-Methylnapthalene	2.8E-05	lb	2.8E-05	kg
4-Methyl-2-Pentanone	7.5E-06	lb	7.5E-06	kg
Acetone	1.8E-05	lb	1.8E-05	kg
Acid (unspecified)	2.5E-04	lb	2.5E-04	kg
Alkylated benzenes	6.2E-05	lb	6.2E-05	kg
Alkylated fluorenes	3.6E-06	lb	3.6E-06	kg
Alkylated naphthalenes	1.0E-06	lb	1.0E-06	kg
Alkylated phenanthrenes	4.2E-07	lb	4.2E-07	kg
Alkalinity	0.14	lb	0.14	kg
Aluminum	0.11	lb	0.11	kg
Ammonia	0.056	lb	0.056	kg
Antimony	7.1E-05	lb	7.1E-05	kg
Arsenic	4.5E-04	lb	4.5E-04	kg
Barium	1.57	lb	1.57	kg
Benzene	0.0030	lb	0.0030	kg
Benzoic acid	0.0018	lb	0.0018	kg
Beryllium	2.4E-05	lb	2.4E-05	kg
BOD	0.70	lb	0.70	kg
Boron	0.0056	lb	0.0056	kg
Bromide	0.38	lb	0.38	kg
Cadmium	6.7E-05	lb	6.7E-05	kg
Calcium	5.70	lb	5.70	kg
Chlorides	64.0	lb	64.0	kg
Chloroform	1.0E-06	lb	1.0E-06	kg
Chromium (unspecified)	0.0032	lb	0.0032	kg
Chromium (hexavalent)	1.1E-05	lb	1.1E-05	kg

Table N-1

DATA FOR THE PRODUCTION OF TOLUENE DIISOCYANATE (TDI)
(Cradle-to-TDI)
(page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Cobalt	3.9E-05	lb	3.9E-05	kg
COD	1.11	lb	1.11	kg
Copper	4.2E-04	lb	4.2E-04	kg
Cyanide	3.0E-05	lb	3.0E-05	kg
Dibenzofuran	3.4E-07	lb	3.4E-07	kg
Dibenzothiophene	2.7E-07	lb	2.7E-07	kg
Dissolved Solids	98.5	lb	98.5	kg
Ethylbenzene	1.7E-04	lb	1.7E-04	kg
Fluorine	1.8E-06	lb	1.8E-06	kg
Hardness	17.6	lb	17.6	kg
Hexanoic acid	3.7E-04	lb	3.7E-04	kg
Iron	0.24	lb	0.24	kg
Lead	8.7E-04	lb	8.7E-04	kg
Lead 210	1.8E-13	lb	1.8E-13	kg
Lithium	0.69	lb	0.69	kg
Magnesium	1.11	lb	1.11	kg
Manganese	0.0018	lb	0.0018	kg
Mercury	1.6E-06	lb	1.6E-06	kg
Methylchloride	7.1E-08	lb	7.1E-08	kg
Methyl Ethyl Ketone	1.4E-07	lb	1.4E-07	kg
Molybdenum	4.1E-05	lb	4.1E-05	kg
m-Xylene	5.4E-05	lb	5.4E-05	kg
Naphthalene	3.2E-05	lb	3.2E-05	kg
n-Decane	5.2E-05	lb	5.2E-05	kg
n-Docosane	1.9E-06	lb	1.9E-06	kg
n-Dodecane	9.8E-05	lb	9.8E-05	kg
n-Eicosane	2.7E-05	lb	2.7E-05	kg
n-Hexacosane	1.2E-06	lb	1.2E-06	kg
n-Hexadecane	1.1E-04	lb	1.1E-04	kg
Nickel	4.2E-04	lb	4.2E-04	kg
n-Octadecane	2.6E-05	lb	2.6E-05	kg
n-Tetradecane	4.3E-05	lb	4.3E-05	kg
o + p-Xylene	3.9E-05	lb	3.9E-05	kg
o-Cresol	5.1E-05	lb	5.1E-05	kg
ODCB	1.0E-04	lb	1.0E-04	kg
Oil	0.050	lb	0.050	kg
p-Cresol	5.5E-05	lb	5.5E-05	kg
p-Cymene	1.8E-07	lb	1.8E-07	kg
Pentamethylbenzene	1.3E-07	lb	1.3E-07	kg
Phenanthrene	4.1E-07	lb	4.1E-07	kg
Phenol	8.6E-04	lb	8.6E-04	kg
Phosphates	0.0010	lb	0.0010	kg
Radium 226	6.4E-11	lb	6.4E-11	kg
Radium 228	3.3E-13	lb	3.3E-13	kg
Selenium	1.4E-05	lb	1.4E-05	kg
Silver	0.0037	lb	0.0037	kg
Sodium	18.1	lb	18.1	kg
Sodium Hydroxide	1.00	lb	1.00	kg
Strontium	0.097	lb	0.097	kg
Sulfates	0.13	lb	0.13	kg
Sulfides	0.0011	lb	0.0011	kg
Sulfur	0.0047	lb	0.0047	kg
Surfactants	0.0016	lb	0.0016	kg
Suspended Solids	3.60	lb	3.60	kg
Thallium	1.5E-05	lb	1.5E-05	kg
Tin	3.3E-04	lb	3.3E-04	kg
Titanium	0.0011	lb	0.0011	kg
TOC	0.010	lb	0.010	kg
Toluene	0.0028	lb	0.0028	kg
Total biphenyls	4.0E-06	lb	4.0E-06	kg
Total dibenzothiophenes	1.2E-08	lb	1.2E-08	kg
Vanadium	4.8E-05	lb	4.8E-05	kg
Xylene (unspecified)	0.0014	lb	0.0014	kg
Yttrium	1.2E-05	lb	1.2E-05	kg
Zinc	0.0027	lb	0.0027	kg

References: Tables B-2 through B-5, F-3, F-6, I-2, I-3b, J-2, and N-2 through N-6.

Source: Franklin Associates, A Division of ERG models

Table N-2

DATA FOR THE PRODUCTION OF TOLUENE

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Naphtha (from refinery)	1,000	lb		1,000	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	10.8	kwh	111	23.9	kwh	0.26
Natural gas	394	cu ft	441	24.6	cu meters	1.03
Distillate oil	0.60	gal	95.2	5.00	liter	0.22
Residual oil	5.80	gal	995	48.4	liter	2.32
Total Process			1,643			3.83
Transportation Energy						
Barge	7.50	ton-miles		24.14	tonne-km	
Diesel	0.0060	gal	0.95	0.050	liter	0.0022
Residual oil	0.020	gal	3.42	0.17	liter	0.0080
Total Transportation			4.38			0.010
Environmental Emissions						
Atmospheric Emissions						
Carbon Dioxide (fossil)	45.2	lb		45.2	kg	
Carbon Monoxide	0.0051	lb		0.0051	kg	
Nitrogen Oxides	0.062	lb		0.062	kg	
Particulates	0.020	lb		0.020	kg	
Sulfur Oxides	0.44	lb		0.44	kg	
Solid Wastes						
Landfilled	0.022	lb		0.022	kg	
Waterborne Wastes						
BOD	0.70	lb		0.70	kg	
COD	1.08	lb		1.08	kg	
Dissolved solids	0.11	lb		0.11	kg	
Oil	0.018	lb		0.018	kg	
Sulfides	0.0033	lb		0.0033	kg	

References: N-3 through N-6.

Source: Franklin Associates, A Division of ERG

Table N-3

DATA FOR THE PRODUCTION OF SULFUR

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	140	kwh	1,441	309	kwh	3.35
Natural Gas	2,163	cu ft	2,423	135	cu meters	5.64
LPG	0.14	gal	15.1	1.17	liter	0.035
Distillate Oil	0.20	gal	31.8	1.67	liter	0.074
Residual Oil	3.39	gal	582	28.3	liter	1.35
Gasoline	0.086	gal	12.2	0.72	liter	0.028
Total Process			4,504			10.5
Transportation Energy						
Combination Truck	24.2	ton-miles		77.9	tonne-km	
Diesel	0.25	gal	40.4	2.12	liter	0.094
Rail	1.33	ton-miles		4.28	tonne-km	
Diesel	0.0033	gal	0.52	0.028	liter	0.0012
Barge	74.0	ton-miles		238.1	tonne-km	
Diesel	0.059	gal	9.40	0.49	liter	0.022
Residual Ooil	0.20	gal	33.8	1.64	liter	0.079
Ocean Freighter	1,521	ton-miles		4895	tonne-km	
Diesel	0.29	gal	45.9	2.41	liter	0.11
Residual	2.60	gal	446	21.7	liter	1.04
Pipeline-Natural Gas	133	ton-miles		428.0	tonne-km	
Natural Gas	91.8	cu ft	103	5.73	cu meter	0.24
Pipeline-Petroleum Products	203	ton-miles		653	tonne-km	
Electricity	4.43	kwh	45.3	9.76	kwh	0.11
Total Transportation			724			1.68
Environmental Emissions						
Atmospheric Emissions						
Aldehydes (unspecified)	0.086	lb		0.086	kg	
Ammonia	0.0026	lb		0.0026	kg	
Chlorine	1.0E-04	lb		1.0E-04	kg	
HCl	7.6E-05	lb		7.6E-05	kg	
Hydrocarbons (unspecified)	16.1	lb		16.1	kg	
Lead	7.1E-07	lb		7.1E-07	kg	
Particulates (unspecified)	2.53	lb		2.53	kg	
Sulfur Oxides	0.86	lb		0.86	kg	
Solid Wastes						
Landfilled	53.2	lb		53.2	kg	
Waterborne Wastes						
Acid (unspecified)	5.6E-07	lb		5.6E-07	kg	
Ammonia	9.0E-04	lb		9.0E-04	kg	
BOD	0.0069	lb		0.0069	kg	
Chromium (unspecified)	2.2E-06	lb		2.2E-06	kg	
COD	0.033	lb		0.033	kg	
Dissolved Solids	0.47	lb		0.47	kg	
Iron	2.1E-04	lb		2.1E-04	kg	
Lead	1.0E-06	lb		1.0E-06	kg	
Metal Ion (unspecified)	0.012	lb		0.012	kg	
Oil	0.030	lb		0.030	kg	
Phenol/Phenolics	3.9E-05	lb		3.9E-05	kg	
Suspended Solids	0.0063	lb		0.0063	kg	
Zinc	1.5E-05	lb		1.5E-05	kg	

References: N-15 through N-17.

Source: Franklin Associates, A Division of ERG

Recovery of sulfur from sour natural gas and crude oil via the Claus process accounts for the total amount of the sulfur produced in the United States. Approximately 79 percent of the sulfur produced via Claus recovery is obtained from hydrogen sulfide recovered from petroleum refining, and the remaining 21 percent is recovered from natural gas sweetening (Reference N-11). The following data includes data for the production of sulfur from petroleum refining only.

Hydrogen sulfide is recovered from refinery gases by absorption in a solvent or by regenerative chemical absorption (Reference N-12). Hydrogen sulfide concentrations in the gas from the absorption unit vary. For this analysis, an industry average H2S gas concentration of 85 percent is used (References N-13 and N-12). This concentrated hydrogen sulfide stream is treated by the Claus process to recover the sulfur. The Claus process is based upon the reaction of hydrogen sulfide with sulfur dioxide according to the exothermic reaction (Reference N-12):

$$2H2S + SO2 \rightarrow 3S + 2H2O \qquad \text{(Reaction 1)}$$

Sulfur dioxide for the reaction is prepared by oxidation of hydrogen sulfide with air or oxygen in a furnace using either the partial combustion process (once-through process) or the split-stream process. The partial combustion method is used when the H2S concentration is greater than 50 percent and the hydrocarbon concentration is less than 2 percent. The split stream process is used when there is an H2S concentration of 20 to 50 percent and a hydrocarbon concentration of less than 5 percent.

In the partial combustion method, the hydrogen sulfide-rich gas stream is burned with a fuel gas in an oxygen-limited environment to oxidize one-third of the H2S to SO2 according to the reaction (Reference N-14):

$$2H2S + 2O2 \rightarrow SO2 + S + 2H2O \qquad \text{(Reaction 2)}$$

Sulfur is removed from the burner and the H2S/SO2 mixture moves to the catalytic converter chambers.

In the split stream process, one-third of the hydrogen sulfide is split off and completely oxidized to SO_2 according to the reaction:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \qquad \text{(Reaction 3)}$$

The remaining two-thirds of the H_2S is mixed with the combustion product and enters the catalytic converter chambers.

The H_2S and SO_2 mixture from either process is passed through one or more catalyst beds and is converted to sulfur, which is removed by condensers between each bed. For this analysis, an H_2S concentration of 85 percent has been assumed; therefore, it is also assumed that the partial combustion process is used.

Although efficiencies of 96 to 99 percent sulfur recovery have been demonstrated for the Claus process, recovery is usually not over 96 percent and is limited by thermodynamic considerations (References N-12 and N-14). For this analysis, a sulfur recovery efficiency of 95 percent is assumed.

The energy generated from burning hydrogen sulfide to produce SO_2 is usually recovered and used directly to reheat the process stream in secondary and tertiary condensers, or recovered as steam for use in other processes (Reference N-14). Heat released from cooling the exothermic reaction to form sulfur is also recovered.

Sulfuric Acid Production

All sulfuric acid produced in the U.S. is produced by the contact process (Reference N-20). The sulfur input streams used by contact plants can be of three different forms: (1) elemental sulfur, (2) spent sulfuric acid or hydrogen sulfides, and (3) metal sulfide ores or smelter gas. Contact plants that use elemental sulfur account for 81 percent of sulfuric acid production (Reference N-18).

There are three basic steps in the contact process. The first step oxidizes (burns) sulfur to sulfur dioxide (SO_2). The second step catalytically oxidizes sulfur dioxide to sulfur trioxide (SO_3). The third step dissolves the sulfur trioxide into a 98 percent solution of sulfuric acid. The third step can also produce sulfuric acid by adding sulfur trioxide directly to water. However, when sulfur trioxide is added directly to water, the reaction is slow and tends to form a mist.

During sulfuric acid production, the burning of sulfur produces heat, which in turn is used to generate steam. This steam is usually used in adjacent processing plants and supplies energy to the sulfuric acid plant. The exported steam is given a credit and shown as recovered energy.

Process data for sulfuric acid production are shown in Table N-4.

Table N-4

DATA FOR THE PRODUCTION OF SULFURIC ACID

	English units (Basis: 1,000 lb)			**SI units (Basis: 1,000 kg)**		
Raw Materials						
Sulfur	330	lb		330	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	30.0	kwh	309	66.1	kwh	0.72
Recovered Energy	850	thousand Btu	850	1,977	MJ	1.98
Total Process			-541			-1.26
Transportation Energy						
Combination Truck	7.50	ton-miles		24.14	tonne-km	
Diesel	0.079	gal	12.5	0.66	liter	0.029
Total Transportation			12.5			0.03
Environmental Emissions						
Atmospheric Emissions						
Nitrogen Oxides	0.050	lb		0.050	kg	
Particulates (unspecified)	1.00	lb		1.00	kg	
Sulfur Oxides	2.59	lb		2.59	kg	
Solid Wastes						
Landfilled	0.50	lb		0.50	kg	
Waterborne Wastes						
Acid (unspecified)	0.30	lb		0.30	kg	
BOD	0.10	lb		0.10	kg	
Suspended Solids	0.30	lb		0.30	kg	

References: N-5, N-19, and N-21.

Source: Franklin Associates, A Division of ERG

Soda Ash Mining & Processing

Soda ash used in the U.S. is naturally occurring and is obtained from trona and alkaline brines in the Green River basin in Wyoming and Searles Lake in California. The soda ash is mined using two different methods, underground trona mining and solution mining. 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 used by one of the six major soda ash producers in the U.S. (Reference N-23). Soda ash from solution mining is for the most part used for the manufacture of caustic soda. The data in this module are based on underground trona mining.

After mining, trona is crushed, screened and then calcined in rotary, gas-fired kilns. The mineral is then dissolved in water and filtered. The resulting soda ash solution (sodium carbonate) is evaporated and dried (Reference N-20). Airborne particulates generated from mining and drying operations are reduced by control equipment such as bag filters and wet scrubbers. Airborne carbon dioxide is generated from calcining operations. Solid wastes and water effluents generated during soda ash mining and production are recycled to the soda ash treatment processes, held in on-site evaporation ponds, or are returned to mine-shaft voids. Due to the onsite treatment of solid and waterborne wastes, this module assumes that negligible solid wastes and water emissions are produced from soda ash production and released to the environment (References N-5 and N-20).

Soda ash can also be produced synthetically via the Solvay process. The Solvay process uses salt, coke, limestone, with ammonia as a catalyst. Synthetic soda ash is more expensive to produce than natural soda ash and also has high concentrations of calcium chloride and sodium chloride in the process effluent. This method of soda ash production is not currently used in the U.S.

U.S. production provides nearly all of the soda ash required by U.S. manufacturers. Approximately 45 percent of the total soda ash manufactured is used in glass manufacturing. Soda ash mining and processing data are shown in Table N-5.

Dinitrotoluene (DNT) Production

Nitroaromatics, including nitrobenzene, nitrochlorobenzene, and dinitrotoluene, are formed by nitrating the appropriate aromatic hydrocarbon with a mixed acid containing nitric and sulfuric acid. In the first stage of the nitration process a mixture of the ortho-, meta-, and para-nitrotoluene isomers is formed. The ortho- and para-nitrotoluene isomers are separated from the acid mixture in a centrifugal separator. After the isomers are separated, they are reacted with nitric acid to produce either 2,4-DNT or a mixture of 2,4-DNT and 2,6-DNT. The recovered acid mixture containing nitric acid and nitro compounds is recycled (Reference N-8).

Sulfuric acid is separated and recycled back into the production of nitroaromatics. Since the sulfuric acid does not leave the process as part of the product, it is treated as a catalyst. Only the make-up sulfuric acid is included in the LCI.

Data for the production of DNT was collected from one confidential source in the United States. This data was aggregated with phosgene, TDA, and TDI and is included in Table N-6.

Table N-5

DATA FOR THE MINING & PROCESSING OF SODA ASH

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	41.1	kwh	423	90.6	kwh	0.98
Natural gas	797	cu ft	893	49.8	cu meters	2.08
Coal	108	lb	1,213	108	kg	2.82
Distillate oil	0.067	gal	10.6	0.067	liter	0.025
Residual oil	0.19	gal	32.6	1.59	liter	0.076
Total Process			2,572			5.99
Transportation Energy						
Combination truck	7.50	ton-miles		24.14	tonne-km	
Diesel	0.079	gal	12.5	0.66	liter	0.029
Total Transportation			12.5			0.029
Environmental Emissions						
Atmospheric Emissions						
Carbon Dioxide (fossil)	415	lb		415	kg	
Particulates (unspecified)	96.5	lb		96.5	kg	

References: N-5, N-20, and N-22.

Source: Franklin Associates, A Division of ERG

Toluene Diamine (TDA) Production

Toluene Diamine (TDA) is produced by the hydrogenation of dinitrotoluene. The catalytic hydrogenation of dinitrotoluene to toluene diamine is a standard aromatic synthesis process. The isomer ratio for TDA depends on the DNT isomer ratio used. Water, toluidine, and ortho-TDA can be removed by distillation or will be separated after phosgenation with the TDI residue (Reference N-8).

Because confidential datasets cannot be shown individually, the datasets for DNT, phosgene, TDA, and TDI were combined into one data table. TDA data was collected from two sources and are included with the TDI energy and emissions in Table N-6. The TDA producers verified that the characteristics of their plants are representative of a majority of North American TDA production. The average DNT/phosgene/TDA/TDI dataset was reviewed and accepted by all DNT/phosgene/TDA/TDI data providers. The data submitted for TDA represents U.S. production in the year 2003.

Toluene Diisocyanate (TDI) Production

Toluene diisocyanate (TDI) is made by phosgenation of toluene diamine (TDA). The diamine mixture is dissolved in chlorobenzenes and reacted with excess phosgene to produce the TDI. After phosgenation, the mixture is stripped from the solvent and separated by distillation (Reference N-9). The excess phosgene is recycled. Most of the TDI used in flexible polyurethane foams is a mixture of the 2,4- and 2,6- isomers. The 80:20 mixture of 2,4-TDI and 2,6-TDI is today the most important commercial product, but other mixtures are available.

Table N-6 presents the data for the production of DNT, phosgene, TDA, and TDI. Data for the production of phosgene, TDA, and TDI were provided by three leading producers (3 plants) in North America to Franklin Associates. Heat was exported as a coproduct for some producers. The energy amount for the exported heat was reported separately as recovered energy. A large amount of hydrogen chloride is produced as a coproduct during this process. A mass basis was used to partition the credit for each product. The coproduct amount is not shown due to confidentiality issues. Once collected, the data for each plant is reviewed individually. At that time, coproduct allocation is performed for the individual plant. After coproduct allocation is complete, the data of all plants are averaged using yearly production amounts. Confidentiality issues prohibit the revealing of each plant's individual HCl coproduct amount. An average of the coproduct could be provided, but this would not allow for precise reproduction of the dataset.

As of 2002 there were 5 TDI producers and 6 TDI plants in the U.S. (Reference N-1 and N-2). The TDI data collected represents approximately half of the total North American TDI production amount. The TDI producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American TDI production. The average dataset was reviewed and accepted by all TDI data providers.

To assess the quality of the data collected for TDI, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for TDI include direct measurements, information provided by purchasing and utility records, and engineering estimates. All data submitted for TDI represents the year 2003 and represents U.S. production.

Table N-6

DATA FOR THE PRODUCTION OF TOLUENE DIISOCYANATE (TDI)
(Includes Dinitrotoluene, Phosgene and TDA)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Raw Materials							
Carbon Monoxide	192	lb			192	kg	
Chlorine	462	lb			462	kg	
Sodium Hydroxide	22.6	lb			22.6	kg	
Toluene	308	lb			308	kg	
Nitric Acid	431	lb			431	kg	
Sulfuric Acid	8.26	lb			8.26	kg	
Soda Ash	4.03	lb			4.03	kg	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	29.5	kwh		303	65.0	kwh	0.71
Electricity (cogeneration)	116	kwh		- (1)	256	kwh	-
Natural gas	3,991	cu ft		4,470	249	cu meters	10.4
Recovered Energy	337	thousand Btu		337	784	MJ	0.78
Total Process				4,436			10.3
Transportation Energy							
Ocean freighter	753	ton-miles			2,422	tonne-km	
Diesel	0.14	gal		22.7	1.19	liter	0.053
Residual	1.29	gal		221	10.7	liter	0.51
Pipeline-petroleum products	0.36	ton-miles			1.16	tonne-km	
Electricity	0.0078	kwh		0.080	0.017	kwh	1.9E-04
Total Transportation				244			0.57
Environmental Emissions							
Atmospheric Emissions							
Ammonia	0.049	lb			0.049	kg	
Carbon Monoxide	0.010	lb			0.010	kg	
Chlorine	2.8E-04	lb			2.8E-04	kg	
HFC-22	0.010	lb	(2)		0.010	kg	
Hydrochloric Acid	0.0010	lb	(2)		0.0010	kg	
Lead	1.0E-07	lb	(2)		1.0E-07	kg	
Mercury	1.0E-07	lb	(2)		1.0E-07	kg	
NM Hydrocarbons	0.024	lb			0.024	kg	
Nitrogen Oxides	0.12	lb			0.12	kg	
o-Dichlorobenzene	0.0010	lb	(2)		0.0010	kg	
Other Organics	1.0E-04	lb	(2)		1.0E-04	kg	
Particulates (unknown)	0.0057	lb			0.0057	kg	
PM2.5	0.0010	lb	(2)		0.0010	kg	
PM10	0.011	lb			0.011	kg	
Phosgene	1.0E-05	lb	(2)		1.0E-05	kg	
TDA	1.0E-05	lb	(2)		1.0E-05	kg	
TDI	1.0E-04	lb	(2)		1.0E-04	kg	
VOC	1.0E-04	lb	(2)		1.0E-04	kg	
Solid Wastes							
Landfilled	0.14	lb			0.14	kg	
Burned	0.70	lb			0.70	kg	
Waste-to-Energy	34.3	lb			34.3	kg	
Waterborne Wastes							
Ammonia	1.0E-04	lb	(2)		1.0E-04	kg	
BOD	0.050	lb			0.050	kg	
Chloroform	1.0E-06	lb	(2)		1.0E-06	kg	
COD	0.17	lb			0.17	kg	
Copper	1.0E-06	lb	(2)		1.0E-06	kg	
Cyanide	3.0E-05	lb			3.0E-05	kg	
Dissolved solids	1.00	lb	(2)		1.00	kg	
Nickel	1.0E-06	lb	(2)		1.0E-06	kg	
o-Dichlorobenzene	1.0E-04	lb	(2)		1.0E-04	kg	
Phosphates	0.0010	lb	(2)		0.0010	kg	
Sodium Hydroxide	1.00	lb	(2)		1.00	kg	
Suspended Solids	0.037	lb			0.037	kg	
TOC	0.010	lb	(2)		0.010	kg	
Nitrate	0.010	lb	(2)		0.010	kg	

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(1) Fuel use for electricity from cogeneration is shown within the natural gas amount. The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

(2) This emission was reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude.

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Source: Franklin Associates, A Division of ERG

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