FINAL REPORT

LIFE CYCLE INVENTORY OF PLASTIC FABRICATION PROCESSES: INJECTION MOLDING AND THERMOFORMING

SUBMITTED TO:

RIGID PLASTIC PACKAGING GROUP (RPPG)

SUBMITTED BY:

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PREFACE

This gate-to-gate LCI study of plastic fabrication methods was conducted for the Rigid Plastic Packaging Group (RPPG) of the Plastics Division of the American Chemistry Council (ACC). Ashley Carlson, Director of Packaging was the project coordinator for the Plastics Division of the ACC. The report was made possible through the cooperation of RPPG/ACC member companies and non-member companies who provided data on injection molding and thermoforming processes for plastics fabrication.

Eastern Research Group, Franklin Associates Division, carried out the work as an independent contractor for this project. Rebe Feraldi was the primary analyst collecting and compiling the LCI data and authoring the report. Beverly Sauer, Senior Chemical Engineer was Project Manager and provided technical and editorial review. Sarah Cashman and Lori Snook contributed to research and report preparation tasks.

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.

September, 2011

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CHAPTER 1. STUDY SCOPE & LCI METHODOLOGY

OVERVIEW

Franklin Associates developed a methodology for performing resource and environmental profile analyses (REPA), now known as life cycle inventories (LCI). This methodology has been documented for the United States 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: 2006, Environmental management – Life cycle assessment – Principles and framework
- ISO 14044: 2006, Environmental management – Life cycle assessment – Requirements and guidelines

This LCI quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from two plastic fabrication processes: injection molding and thermoforming. Figure 1 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.

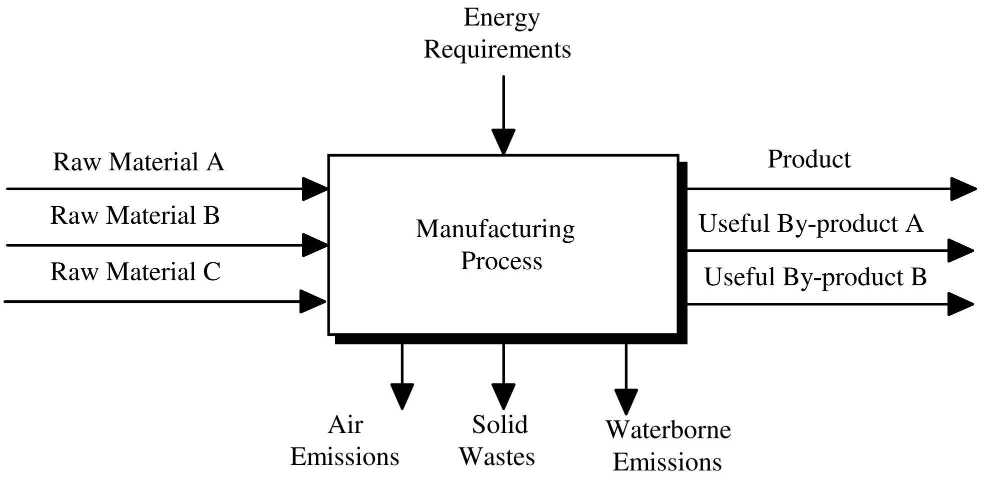

Figure 1. "Black Box" Concept for Developing LCI Data

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.

The system boundaries for the injection molding and thermoforming data sets developed in this project are gate-to-gate; that is, the analysis begins and ends with the fabrication step so that these datasets may be linked with the resin/precursor data, use, and end-of-life data in order to create full life cycle inventories for a variety of plastic products. Example cradle-to-gate LCI results for virgin plastic thermoformed and injection molded parts are also provided, to illustrate the contribution of the converting step to the total cradle-to-gate results for a plastic product.

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.

STUDY GOAL AND INTENDED AUDIENCE

The intent of the study was to develop unit process data sets for two rigid plastic product fabrication methods using primary data from plastic converters. The data quality goal for this study was to use data that most accurately represents current U.S. rigid plastic fabrication processes. The quality of individual data sets vary in terms of representativeness, measured values or estimates, etc.; however, all 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. Environmental profiles presented in this report for the fabrication processes were developed using the data provided by participating companies for this study.

The original goal of the study was to collect a large number of data sets covering a variety of resin types and product configurations so that additional analysis could be conducted to identify relationships between converting process energy requirements and product parameters such as resin type, part size or configuration, etc.; however, the number of data sets collected was insufficient to support development of parameterized dependencies.

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

The converting data sets developed in the project, together with virgin resin data and recycled resin data developed under separate projects for the Plastics Division of the American Chemistry Council, can be combined to model a wide variety of injection molded and thermoformed plastic products. By making these data sets publicly available through the U.S. LCI Database, ACC has provided valuable resources to support consistent, transparent modeling of plastic products by any interested party.

STUDY SCOPE AND SYSTEM BOUNDARIES

This project developed unit process data for the fabrication of rigid plastic products by two different methods: (1) injection molding of resin and (2) converting resin into sheet, then thermoforming sheet to form a rigid container.

Functional Unit

Typically a unit based upon the function of the investigated products is chosen as the basis for an LCI study. For the plastic fabrication processes, we use a functional unit of 1,000 pounds of product output. Results are also presented for metric units.

System Boundaries

This study presents unit process data sets (LCI data modules) for the following two rigid plastic fabrication methods: 1) injection molding of thermoplastics, and 2) thermoplastic sheet formation and subsequent thermoforming of thermoplastics. These data sets can be used together with LCI data on virgin and recycled plastic resins to construct LCI models for a wide range of thermoformed and injection molded plastic products. Each LCI data module includes the following information:

Elementary inputs and outputs (to and from nature)
- Water inputs required
- Raw material inputs required
- Air emission outputs
- Waterborne emission outputs
- Water output

Intermediate inputs and outputs (to and from the technosphere)
- Energy product inputs required
- Economic goods (material) input required
- Solid waste outputs to be managed
- Wastewater outputs to be treated
- Economic goods (material) output

Each converting data set includes incoming transportation steps. The energy used to heat, cool, and/or light non-manufacturing space is not included in the system boundaries of this LCI. The amount of energy used to heat, cool, and/or light the non-manufacturing space of the plastic fabrication facilities is expected to vary widely depending on the location (i.e., surrounding climate) and configuration of the plant. The data forms completed by RPPG members provided sufficient information to disaggregate and remove the energy consumed by reporting facilities for their non-manufacturing space.

Production of the resins and/or chemical precursors of the fabricated product, transportation of the finished rigid plastic product to a retailer, and use of that product by consumers are not included in the study. Environmental burdens associated with end-of-life management of the rigid plastic products are also not considered in this analysis. However, cradle-to-gate data for fabricated plastic products are provided to illustrate the contribution of the converting process to the LCI results for production of thermoformed and injection molded plastic products.

Detailed process flow diagrams and LCI results, along with brief descriptions of processes are found in Chapter 2 for injection molding and in Chapter 3 for thermoforming.

System Components Not Included

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

Capital Equipment: The materials and energy inputs as well as waste outputs associated with the manufacture of capital equipment are excluded from this analysis. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. In general, these types of capital equipment are used to produce large quantities of product output over a useful life of many years. Thus, energy and emissions associated with the production of these facilities and equipment generally become negligible.

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: Miscellaneous materials that comprise less than one percent by weight of the net process inputs are typically not included in the assessment unless inventory data for their production are readily available or there is reason to believe the materials would make significant contributions to energy use or environmental impacts. For example, in this study, the weight of inks and labels are less than 0.25 percent of material inputs and are not included in the analysis. Omitting miscellaneous materials and additives helps keep the scope of the study focused and manageable within budget and time constraints. While there are energy and emissions associated with production of materials that are used in very low quantities, the amounts would have to be disproportionately high per pound of material for such small additives to have a significant effect on overall life cycle results for the systems studied. This cut-off assumption is based on past LCA studies that demonstrate that materials which comprise less than one percent of system weight have a negligible effect on total LCA results. The intent of this project was to develop converting data sets that are applicable to a broad range of products. Average material inputs for colorants, printing, labeling, and packaging based on the LCI surveys are reported in the tables, but modeling of specific thermoformed or injection molded product systems should use product-specific input data whenever possible.

DATA SOURCES AND DATA QUALITY

Overview

Data necessary for conducting the inventory and for presenting the gate-to-gate environmental profiles for the two fabrication methods are separated into two categories: foreground process-related data and the background data required for material and energy inputs to the foreground processes. The accuracy of the study is directly related to the quality of input data. Quality of input data is dependent on both data sources and methodological considerations. This section discusses the data sources used and data quality considerations given to both the foreground and background process data compiled for this analysis.

Data Sources

Foreground inventory data is primary data compiled specifically for this analysis. Survey participants are members of the Rigid Plastics Packaging Group (RPPG) of the Plastics Division of the American Chemistry Council (ACC).

For background data used to develop cradle-to-gate environmental profiles of fabricated plastic products, data from a number of published sources were utilized for this report. The data sources used to characterize upstream processes associated with plastic fabrication are listed under the relevant sections.

Data Quality

ISO standard 14044:2006 states that "Data quality requirements shall be specified to enable the goal and scope of the LCA to be met." The data quality requirements listed include time-related representativeness, geographical coverage, technology coverage, completeness, and more.

The data quality goal for this study was to use data that most accurately represents current U.S. fabrication of rigid plastic products by means of injection molding or thermoforming. The quality of individual data sets 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.

The data quality goal for this study was to use data that most accurately represents current U.S. rigid plastic fabrication processes. The development of methodology for the collection of data is essential to obtaining quality data. All process data sets used in this study were thoroughly reviewed for accuracy and currency for this analysis.

Geographic Scope

The geographic scope of this study is rigid plastic products fabricated in North America; however, this does include raw material sourced from other regions of the world (this primarily applies to crude oil imports). The main sources of data and information for geography-dependent process (e.g., energy production) are drawn from US specific reports and databases. Primary data specific to the fabrication operations is collected from North American companies.

Technology Coverage

Primary data is collected for the mix of technologies currently used by plastic fabricators in the US. In addition to process data, the LCI survey form also requested information for assessing the age and representativeness of the technology used by the facility/ies providing the process data.

Temporal Coverage

For the primary data collected, annual production data was collected for the most current full calendar year (2009 - 2010).

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 specific fuel requirements at the fabrication steps may be drawn and connected in sequence for the cradle-to-gate inventory. These datasets include energy requirements and environmental emissions for the production and combustion of process fuels. 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 and other fuels are required in order to produce electricity and primary fuels, there is a complex and technically infinite set of interdependent steps involved in fuel modeling. An input-output modeling matrix is used for these calculations.

In 2003, Franklin Associates updated our fuels and energy database for inclusion in the U.S. LCI database. Emissions for fuels extraction and processing were updated in 2011. This fuels and energy database, which is published in the U.S LCI Database, is used in this analysis.

Electricity Grid Fuel Data

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 United States national average fuel consumption by electrical utilities is used.

Transportation Data

This LCI include transportation requirements between manufacturing steps. For upstream processes (such as crude oil extraction, fuels production, etc.) the transportation modes and distances are based on average industry data. For incoming transport at the fabrication steps, the transportation requirements are based on the weighted averages for transportation modes and distances compiled in the primary data collection.

Water Data

Water consumption data for the investigated fabrication methods are from the primary sources (collected for this study). In the environmental profile results, water consumption data for upstream processes are from primary data collection for associated product systems when possible. When primary data has not been available, water consumption is modeled using values reported in literature. In some cases, consumptive use data may not be available. The ecoinvent database[1], a European LCI database with data for many unit processes, includes water in the life cycle inventory as an input, and does not record water released to the environment (i.e. as an emission) or water consumed. However, ecoinvent is currently one of the most comprehensive LCI sources on water for upstream processes; many other available databases do not report water input/use as an inventory item. Therefore, when primary data or literature values are not available, ecoinvent data are utilized for the water calculations. When utilizing ecoinvent, the data is adapted to represent consumptive use to the extent possible (i.e., incorporating volumes of fresh water removed from the environment and not internally recirculated).

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

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[1] Ecoinvent Centre (2010), ecoinvent data v2.2. ecoinvent reports No. 1-25, Swiss Centre for Life Cycle Inventories. Retrieved from the SimaPro LCA software v7.2.3.

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. 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 model fabricated plastic products, 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. For many chemical processes, the data sets are based on actual plant data reported by plant personnel. 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.

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 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 fabrication step for a plastic component changes the amounts of resin inputs to that process, and so on back to the quantities of crude oil and natural gas extracted.

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.

Assumptions & Limitations

Although the foreground processes in this analysis were populated with primary data and the background processes come from reliable databases and secondary data, most analyses still have limitations. Further, it is necessary to make a number of assumptions when modeling, which could influence the final results of a study. Key limitations and assumptions of this analysis are described in this section.

Geographic Scope. 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. Transportation of crude oil used for petroleum fuels and plastic resins is modeled based on the current mix of domestic and imported crude oil used.

Water Use. Details on sources and quality of water consumption data have been discussed. However, it should be mentioned in this section on limitations that there is currently a lack of water use data on a unit process level for life cycle inventories. In addition, water use data that are available from different sources do not use a consistent method of distinguishing between consumptive use and non-consumptive use of water or clearly identifying the water sources used (freshwater versus saltwater, groundwater versus surface water). A recent article in the International Journal of Life Cycle Assessment summarized the status and deficiencies of water use data for LCA, including the statement, "To date, data availability on freshwater use proves to be a limiting factor for establishing meaningful water footprints of products."[2] The article goes on to define the need for a standardized reporting format for water use, taking into account water type and quality as well as spatial and temporal level of detail. To address many of the inconsistencies in LCA water reporting, the International Standardization Organization is in preliminary stages of developing a water footprint standard (14046**,** *Water footprint – Requirements and guidelines),* which is slated to be completed in 2012.[3]

LCI METHODOLOGY

The accuracy of the study is directly related to 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.

Data Collection/Verification

The process of gathering data is an iterative one. The Rigid Plastic Packaging Group of the Plastics Division of the ACC contacted member companies fabricating rigid plastic products by means of injection molding and/or thermoforming. The companies that agreed to participate in this analysis by collecting process data were contacted, and worksheets and instructions developed specifically for the investigated processes and this project were provided to assist in gathering the necessary process data. Upon receipt of the completed worksheets, the data were evaluated for completeness and reviewed for any material inputs that were additions or changes. 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 was performed for any coproducts at the plant. Then, the datasets for each process were aggregated into a single set of data for that process by weighting the facility's data by its plant production amount percentage. 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.

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[2] Koehler, Annette. "Water use in LCA: managing the planet's freshwater resources." Int J Life Cycle Assess (2008) 13:451-455.

[3] ISO considers potential standard on water footprint. Viewed at: http://www.iso.org/iso/iso-focus-plus_index/iso-focusplus_online-bonus-articles/isofocusplus_bonus_water-footprint.htm.

Confidentiality

Franklin Associates takes care to protect data that is considered confidential by individual data providers. In order to protect confidential data sets provided by individual injection molding and thermoforming facilities, only weighted average data sets can be shown for each type of facility.

Objectivity

Each unit process in the life cycle study 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. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. 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.

Material Requirements

Once the LCI study boundaries have been defined and 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 of fabricated plastic, 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 each process studied. Energy requirements and environmental emissions are determined for each process and expressed in terms of the standard unit of output.

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, gallons of diesel fuel, or kilowatt-hours (kWh) of electricity. The fuel used to transport raw materials to each process is included as a part of the LCI energy requirements. Transportation energy requirements 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 volume or mass units to an equivalent energy 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).

The energy 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
- Biomass

Also included in the LCI energy profile are the energy values for all transportation steps and all fossil fuel-derived raw materials.

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.

Atmospheric Emissions: These emissions include substances classified by regulatory agencies as pollutants, as well as selected non-regulated 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 cradle-to-gate inventory results. 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. The emissions discussion in the results focuses on greenhouse gas emissions, expressed in pounds of carbon dioxide equivalents.

Waterborne Emissions: As with atmospheric emissions, waterborne emissions include all substances classified as pollutants. 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.

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. These include industrial process- and fuel-related wastes, as well as the material components that are disposed. Examples of industrial process wastes are residuals from chemical processes and manufacturing scrap that is not recycled or sold. Examples of fuel-related solid wastes are ash generated by burning coal to produce electricity, or particulates from fuel combustion that are collected in air pollution control devices.

Because this analysis is limited to plastic converting unit processes and cradle-to-gate results for fabricated plastic products, postconsumer wastes are not included. Only industrial wastes from processes and fuel-production throughout the fabrication processes 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.[4] 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, the method used to account for the energy contained in material feedstocks, and the methodology used to allocate environmental burdens for postconsumer recycled content and end-of-life recovery of materials for recycling. 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.

Allocation Procedures

For processes that produce more than one useful output, this LCA follows the allocation guidelines in ISO 14044: 2006. The preferred hierarchy for handling allocation as outlined in ISO 14044, Section 4.3.4.2 is (1) avoid allocation where possible, either by further subdivision of processes or by system expansion, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. PAS 2050 also uses this hierarchy.

No single allocation method is suitable for every scenario. The method used for handling product allocation will vary from one system to another but choosing parameters is not arbitrary. ISO 14044, Section 4.3.4.2 states that “the inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics.”

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 parametric bases for various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic. For the processes in this analysis where allocation cannot be avoided,

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[4] International Standards Organization. ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

simple mass and enthalpy relationships have been chosen as the common parametric basis for allocation. However, these allocation methods are not selected as a default choice, but made on a case by case basis after due consideration of the chemistry and production mode of the investigated system.

When the co-product is heat or steam or a co-product sold for use as a fuel, the energy content of the exported heat, steam, or fuel is treated as an energy credit for that process. When the co-product is a material, the process inputs and emissions are allocated to the primary product and co-product material(s) on a mass basis. Allocation based on economic value can also be used to partition process burdens among useful co-products; however, this approach is less preferred under ISO life cycle standards, 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.

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 2. 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 (EMR) 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.

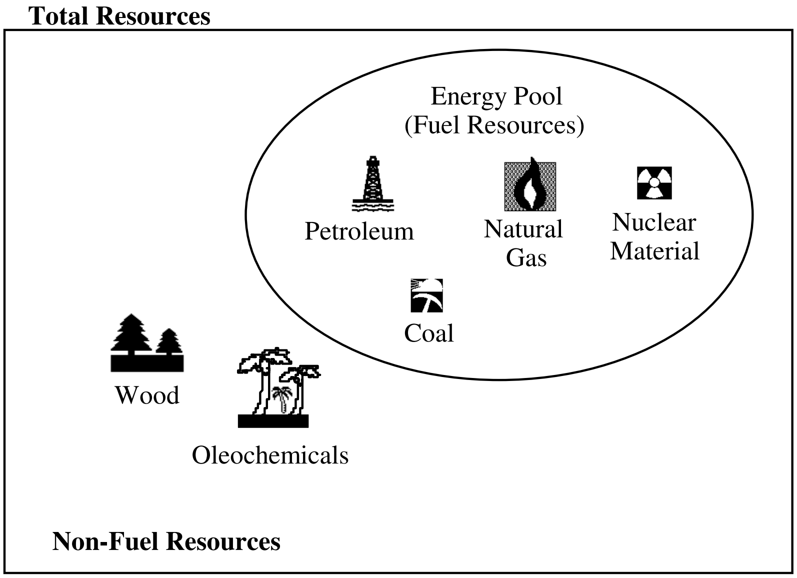

Figure 2. Illustration of the Energy of Material Resource Concept

EMR is the energy content of the fuel materials *input* as raw materials or feedstocks. EMR 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 EMR 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.

In North America, energy content is most often quoted as higher heating value (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]

The materials which are primarily used as fuels can change over time and with location. In industrially developed countries, the material resources whose primary use is for fuel have

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[5] Worrell, Ernst, Dian Phylipsen, Dan Einstein, and Nathan Martin. (2000). 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. (2006). Gas Usage & Value. PennWell Books. p. 76. Figure 4-1.

traditionally been petroleum, natural gas, coal, and nuclear material. While some wood is burned for energy, the primary use for wood in such as context is as a material input 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 current primary consumption is as raw materials for products such as soaps, surfactants, cosmetics, etc. Because biomass has not been a common fuel source in industry in developed countries, the feedstock energy of biomass material inputs has not traditionally been reported by Franklin Associates.

However, with the increasing use of biomass as feedstock for biofuels, for example, corn-derived ethanol and soy-derived biodiesel, as well as the growing efforts to use cellulosic biomass as fuel feedstocks, it is worth tracking energy of material resource for biomass resources as well as fossil resources. In this analysis, biomass EMR is included in the cradle-to-product LCI energy results for wood-derived packaging material.

PRACTICAL APPLICATION OF THE LCI DATA

The unit process tables at the beginning of Chapter 1 and Chapter 2 contain gate-to-gate process data for injection molding and thermoforming, respectively. The cradle-to-gate LCI results for plastic products shown in this report are fully "rolled-up" data sets; that is, they include the burdens for all the processes required to produce the material and energy inputs for the fabricated plastic. Fully rolled-up datasets include not only the direct burdens for the fabrication step but also the upstream burdens for the production and combustion of all fuels used in the processes as well as the production of all materials (including plastic resin) used in the process and the production and combustion of fuel required to deliver materials used in the process. The advantage of using rolled-up data sets is that all the related data have been aggregated into a single data set. However, an important disadvantage of using rolled-up data sets is that the contributing data are "locked in" to the aggregated total so that it is generally not possible to directly adjust the total end results to reflect any subsequent changes in any individual contributing data sets (for example, a reduction in natural gas use at the fabrication step or a change in the mix of fuels used to produce the grid electricity used in the fabrication step).

When life cycle practitioners construct models for product systems, they normally construct the models by linking **unit process** data sets (such as the data sets shown in Table 1. LCI Unit Process Data for Injection Molding and Table 14. LCI Unit Process Data for Thermoforming), rather than using fully rolled-up data sets like the remaining data in this report. In unit process modeling, the quantities of material inputs and fuel inputs to each unit process are linked to data sets for the production of those materials and for production and combustion of fuels. (This is the approach that was used in this analysis to construct the fully rolled-up datasets.) In the unit process modeling approach, the linked data will automatically adjust for changes in any contributing process or fuel-related dataset. In a full cradle-to-grave plastic **product** LCI, the data sets for the resin used in the product (as well as any other material inputs) are combined with the data for product fabrication, use, and end-of-life management. The full cradle-to-grave model of a fabricated plastic product will depend on the specific resin inputs, the product application, and the allocation method chosen for postconsumer recycling, if any, in the product system.

CHAPTER 2. INJECTION MOLDING

INTRODUCTION

This chapter describes the injection molding plastic fabrication process and presents LCI results for 1,000 pounds of fabricated plastic in terms of energy requirements, solid wastes, and atmospheric and waterborne emissions. The production and combustion of fuels used for process and transportation energy and generation of U.S. grid electricity were modeled using data sets developed by Franklin for the U.S. LCI Database. The data for virgin PP and LDPE are the ACC resin data revised in 2011.

INJECTION MOLDING UNIT PROCESS

Injection molding is one of the primary fabrication techniques for rapidly creating large quantities of plastic articles ranging from disposable food containers to high precision engineering components. A variety of resins may be used in injection molding but typically include: polypropylene (PP), general purpose polystyrene (GPPS), polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), and nylon (also known as polyamide, or PA). This plastic fabrication method is distinguished from others by using injection and a hollow mold form to shape the final article. Injection molded parts can have a higher heat index than some other plastic fabrication techniques.

There are two main parts to an injection molding machine: 1) the injection unit and the molding unit. In the injection unit, plastic is loaded into a hopper and pushed through a heated chamber by a screw to bring the resin to a semifluid state. The molten plastic is then injected through a nozzle into the clamped molding unit. The mold is cooled to return the material to a solid state. Cooling is typically achieved by circulating water through chambers within the molding plate. The mold then unclamps and ejects the part for finishing. Finishing steps may include printing and packaging.

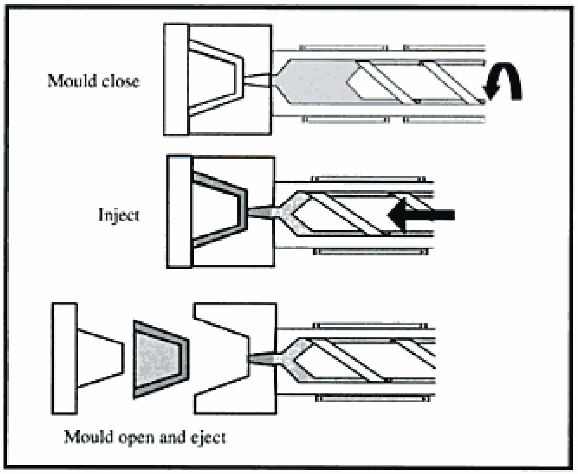

Figure 3. Main Stages of the Injection Molding Process per Hannay 2002[7]

The wall thickness of the injection molded article is determined by the space between the mold and mold core at the molding unit. There may be a single cavity in the mold and this allows scrap to be clamped off and re-ground for internal recycling. A mold may have several cavities through which molten resin runs in a continuous stream. Because the surface of the plastic contracts as it is cooled on the mold, the final part can have high dimensional accuracy. Creating the mold that determines the part's final shape is a very important component of designing injection molding machinery. The machinery may be fitted with interchangeable molds so that one line is capable of producing various shapes and sizes of final parts. As long as the prompt scrap clamped off of the molding unit is clean, it may be reground and returned immediately as feedstock material.

Injection molding machinery may be hydraulic, electric, or a hybrid-type, incorporating both hydraulic and electric components. Historically, the majority of machines have been hydraulic, but an all-electric type was introduced in the 1980s. At the injection unit, the screw acts as the driving force for feeding the resin material through the cycle. The injection unit may be continuously operated as a non-reciprocating screw via electric screw drive technology or as a separate accumulator and piston as in a hydraulic system. The electric screw driver type machinery is generally more expensive than hydraulic reciprocating screws but useful for applications requiring high precision. Hybrid injection molding machines have both electric and hydraulic components. Existing literature on LCI of injection molding indicates that the choice of machine type has a large influence on the specific energy consumption (SEC) of the overall process.[8] This previous work also indicates that all-electric machines have the lowest average SEC and that it is constant regardless of the throughput rate; whereas, both hybrid and hydraulic machines' SEC decreases with increasing throughput. However, other sources indicate that the level of insulation at the injection cylinder can significantly reduce the cost of heat loss.[9]

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[7] Hannay F. 2002. Rigid Plastics Packaging-Materials, Processes, and Applications. Smithers Rapra Publishing.

[8] Thiriez A, Gutowski T. (2006). An environmental analysis of injection molding, Electronics and the Environment, Proceedings of the 2006 IEEE International symposium on.

[9] Bryce DM. (1996). Plastic Injection Molding: Manufacturing Process Fundamentals.

Other parameters having an influence on SEC for injection molding include both the characteristics of the part being produced and other aspects of the equipment with which it is produced. The part's physical characteristics influencing overall energy requirements are the resin type, the weight of the part, and the shape of the part, which determines the percentage of material input that becomes prompt scrap. The part's resin type determines the processing temperatures required for heating and cooling, and these aspects can determine the optimal cycle time. The rotational speed of the screw and the equipment's mold clamping pressure can also play a big role in minimizing the cycle time. Of course, plant management and operational characteristics, which determine machine downtimes and frequency of start-ups, vary among facilities and can also significantly influence SEC.

Of the total mass of molded product generated by facilities providing data for this analysis, 52 percent is produced from hydraulic machinery, 34 percent from hybrid machinery, and only 15 percent from all-electric machines; 59 percent are made of polypropylene (PP) resin, 35 percent are made of linear low-density polyethylene (LLDPE), and the remainder of high-density polyethylene (HDPE) and/or other resin types. Of the product parts generated by participating facilities, 76.0 percent are small-sized rigid plastic parts from 0.05 to 15 grams each, 21.4 percent are medium-sized parts 15 to 50 grams, 2.5 percent are large-sized parts 50 to 150 grams each, and less than 0.05 percent are jumbo-sized parts weighing more than 150 grams apiece.

The average participating facility produces over 100 varieties of parts and produces annually about 450 pounds of parts per square foot of manufacturing floor space. In terms of process energy consumption, the average participating facility consumes most of their electricity at the molding step; only about 15 percent of electricity is consumed at the printing step. The opposite is true for natural gas consumption; nearly all natural gas consumption for manufacturing is consumed at the printing step and only about three percent at the molding step. The amount of incoming corrugated box material is equivalent to that coming out of the process as it is purchased to be used as shipping packaging for finished products. An average of 45.0 pounds of rigid plastic part scrap is produced for every 1,000 pounds of injection molded parts produced; this scrap is sold for recycling. The remaining solid waste generated from the facilities surveyed in this analysis is landfilled. For every 1,000 pounds of injection molded plastic, 15.8 pounds of solid waste is sent to landfill. Of this solid waste, an average of 84 percent by mass is process waste such as contaminated resin scrap, hydraulic oil, and/or inks; while, 16 percent is packaging waste from incoming materials. Table 1 displays the weighted industry average material and energy inputs for the injection molding unit process:

Table 1. LCI Unit Process Data for Injection Molding

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)			
Outputs to Technosphere								
Rigid Plastic Part	1,000	lb			1,000	kg		
Corrugate for Shipping	101	lb			101	kg		
Rigid Plastic Scrap	45.0	lb			45.0	kg		
Inputs from Technosphere (to Product)								
Virgin Resin	1,034	lb			1,034	kg		
Colorant	19.4	lb			19.4	kg		
Inputs from Technosphere (to Process)								
Lubricating Oil	1.30	lb			1.30	kg		
Corrugate for Shipping	101	lb			101	kg		
Process Water Consumption	80.3	gal			670	liter		
Energy Usage				**Total Energy Thousand Btu**				**Total Energy GigaJoules**
Process Energy								
Electricity (grid)	812	kwh		8,357	1,790	kwh		19.5
Natural gas	54.0	cu ft		60.5	3.37	cu meters		0.14
LPG	0.10	gal		10.8	0.83	liter		0.025
Gasoline	0.010	gal		1.42	0.083	liter		0.0033
Diesel	0.0010	gal		0.16	0.0083	liter		3.7E-04
Total Process				8,417				19.6
Incoming Materials Transportation Energy								
Combination truck	8.75	ton-miles			28.2	tonne-km		
Diesel	0.092	gal		14.6	0.77	liter		0.034
Rail	527	ton-miles			1,695	tonne-km		
Diesel	1.31	gal		207	10.9	liter		0.48
Total Transportation				222				0.52
Environmental Emissions								
Atmospheric Emissions								
Particulates	0.0067	lb			0.0067	kg		
Volatile organic carbons	0.043	lb			0.043	kg		
2-propanol	0.10	lb	*		0.10	kg	*	
Ethanol	1.00	lb	*		1.00	kg	*	
Ethyl acetate	0.10	lb	*		0.10	kg	*	
Methyl ethyl ketone	0.10	lb	*		0.10	kg	*	
Toluene	0.010	lb	*		0.010	kg	*	
Ethanol	0.010	lb	*		0.010	kg	*	
Methanol	0.0010	lb	*		0.0010	kg	*	
m-xylene	0.0010	lb	*		0.0010	kg	*	
o-xylene	1.0E-04	lb	*		1.0E-04	kg	*	
p-xylene	1.0E-04	lb	*		1.0E-04	kg	*	
Benzene, ethyl-	1.0E-04	lb	*		1.0E-04	kg	*	
Methane, dichloro-, HCC-30	0.0010	lb	*		0.0010	kg	*	
Propane	0.0010	lb	*		0.0010	kg	*	
Alcohols, C12-14, ethoxylated	0.10	lb	*		0.10	kg	*	
Solid Wastes								
Landfilled	15.8	lb			15.8	kg		

* 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.

Source: Franklin Associates, A Division of ERG

CRADLE-TO-GATE LCI RESULTS FOR INJECTION MOLDED PLASTIC PARTS

For injection molding, the cradle-to-gate results tables and figures break out results by four main process steps: (1) production of the virgin resin inputs, (2) production of other material inputs, (3) transportation energy required for incoming materials, and (4) required processing energy input. The virgin resin data results are for ACC virgin resin data updated in 2010. Because 94 percent of products fabricated by facilities surveyed for this analysis are made of PP or LLDPE, only results for injection molding of these resins are shown in this report. In the previous section, Table 1 shows the industrial average for mass of colorant material input to 1,000 pounds of plastic parts produced by injection molding. However, not all molded products are pigmented, and the material composition of colorant for polymers can vary widely in the industry. Colorants may be organic or inorganic, natural or synthetic, and have different toxicity properties depending on their composition. Because of this wide variability and the fact that no representative LCI data for colorants used in this application are available, the production of colorant is not included in the cradle-to-gate LCI results.

Other material inputs to the injection molding facility include corrugated fiber boxes used for shipping finished parts, and lubricating oil used to maintain processing equipment. Corrugated fiber boxes are modeled using data adapted from the LCI of converted corrugated boxes published by the Corrugated Packaging Alliance (CPA) in 2009.[10] LCI data for refined petroleum are used as a proxy for production of lubricating oil.

Throughout the cradle-to-gate LCI results shown in the remainder of this chapter, the results for corrugated packaging (included in the results for "Other Materials") correspond to the *average* amount of corrugated packaging reported in Table 1. The amount of corrugated packaging used for *specific* injection molded products is expected to vary, depending on part size, configuration, number of parts per box, etc. When using the generic injection molding data set to model specific product systems, actual packaging requirements should be used whenever possible.

Process energy is the energy used to extract, refine, and deliver electricity and/or fuels for combustion required at the injection molding step. Transportation energy is the energy for the production and consumption of fuels used to deliver incoming materials to the injection molding step. The production and combustion of fuels used for process and transportation energy and generation of U.S. grid electricity were modeled using LCI data sets developed by Franklin for the U.S. LCI Database.

Energy Results

Energy consumption for production of rigid plastic parts produced by injection molding are shown by energy category and process step for PP parts in Table 2 and Figure 4 and for LLDPE parts in Table 3 and Figure 5.

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[10] CPA (2010). Life Cycle Assessment of U.S. Industry-Average Corrugated Product, Final Report, Prepared for the Corrugated Packaging Alliance, A Joint Initiative of the American Forest & Paper Association, the Fibre Box Association, and the Association of Independent Corrugated Converters. Prepared by PE Americas and Five Winds International, December 30, 2009.

Table 2. Cradle-to-Gate Cumulative Energy Demand for Injection Molded PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	**TOTAL (1)**	**% TOTAL (1)**
Nuclear	0.42	0.069	0.0022	1.77	**2.26**	**5%**
Coal	1.10	0.19	0.0059	6.24	**7.54**	**17%**
Natural Gas	22.2	0.14	0.011	1.66	**24.0**	**53%**
Petroleum	9.59	0.25	0.24	0.49	**10.6**	**23%**
Hydro	0.048	0.0073	2.6E-04	0.20	**0.26**	**1%**
Biomass	0.0010	0.77	5.6E-06	0.0044	**0.78**	**2%**
TOTAL (1)	**33.4**	**1.43**	**0.26**	**10.4**	**45.4**	
% TOTAL (1)	**73%**	**3%**	**1%**	**23%**		

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

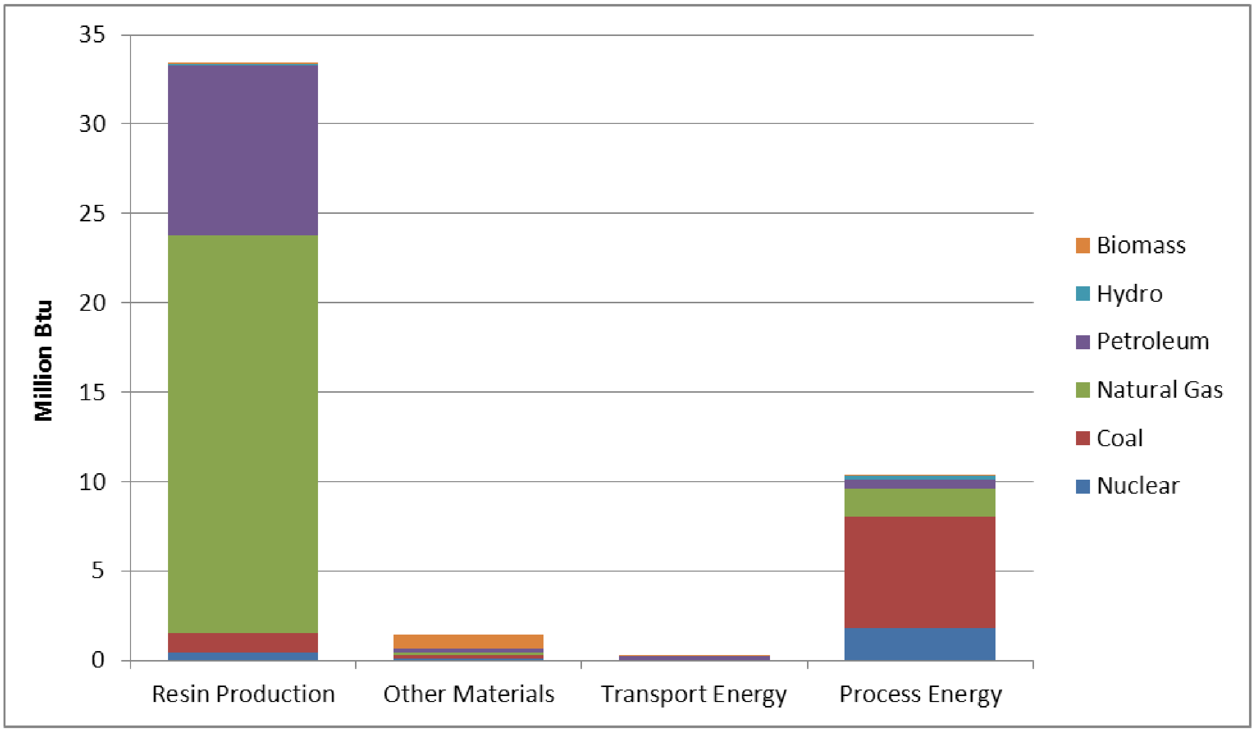

Figure 4. Cradle-to-Gate Cumulative Energy Demand for Injection Molded PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

Table 3. Cradle-to-Gate Cumulative Energy Demand for Injection Molded LLDPE Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	**TOTAL (1)**	**% TOTAL (1)**
Nuclear	0.34	0.069	0.0022	1.77	**2.17**	**5%**
Coal	0.89	0.19	0.0059	6.24	**7.32**	**16%**
Natural Gas	27.6	0.14	0.011	1.66	**29.4**	**64%**
Petroleum	4.83	0.25	0.24	0.49	**5.81**	**13%**
Hydro	0.039	0.0073	2.6E-04	0.20	**0.25**	**1%**
Biomass	8.4E-04	0.77	5.6E-06	0.0044	**0.78**	**2%**
TOTAL (1)	**33.6**	**1.43**	**0.26**	**10.4**	**45.7**	
% TOTAL (1)	**74%**	**3%**	**1%**	**23%**		

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

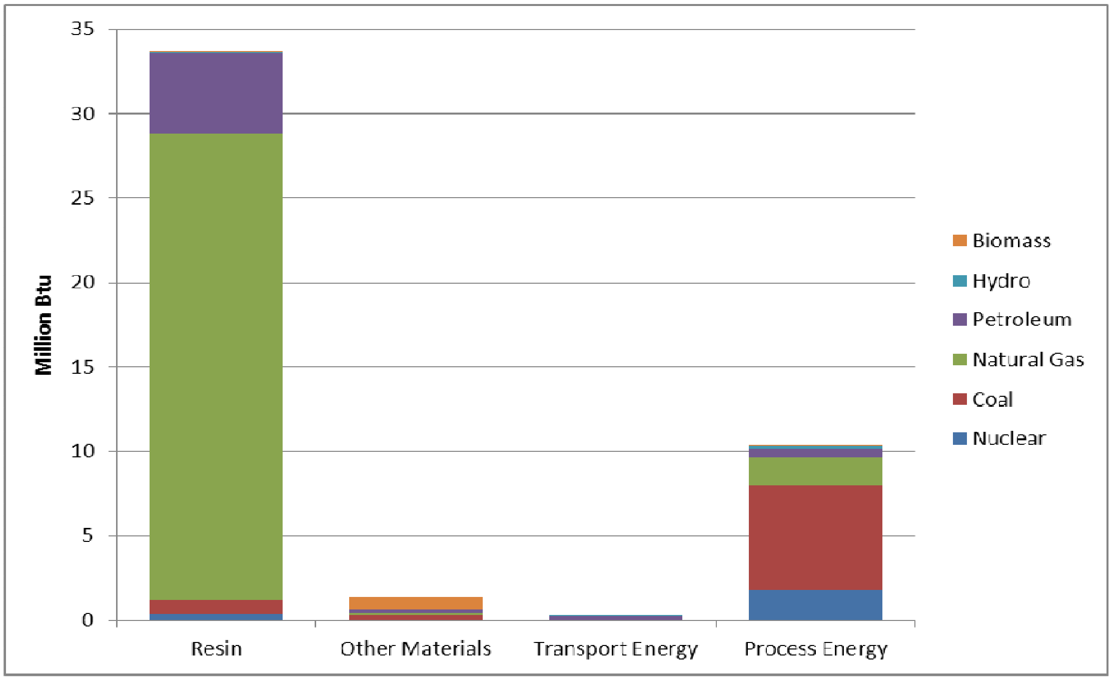

Figure 5. Cradle-to-Gate Cumulative Energy Demand for Injection Molded LLDPE Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

Much of the energy demand for production of virgin resin and other materials is energy of material resources (EMR). EMR is not an expended energy but 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 or corrugated fiber. Use of these material resources as a material input removes them as fuel resources from the energy pool; however, some of this energy remains embodied in the material produced. A detailed description of EMR methodology can be found in Chapter 1: LCI PRACTITIONER METHODOLOGY VARIATION. Table 4/Figure 6 and Table 5/Figure 7 show the relative amounts of EMR (embodied) versus non-EMR (expended) energy demand for injection molded PP and LLDPE, respectively.

Table 4. EMR vs. Non-EMR Cradle-to-Gate Energy Demand for Injection Molded PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	**TOTAL (1)**	**% TOTAL (1)**
Expended Energy	11.5	0.69	0.26	10.4	**22.8**	**50%**
Natural Gas EMR	14.5	0.016	0	0	**14.5**	**32%**
Petroleum EMR	7.46	0.026	0	0	**7.49**	**16%**
Biomass EMR	0	0.70	0	0	**0.70**	**2%**
TOTAL (1)	**33.4**	**1.43**	**0.26**	**10.4**	**45.4**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

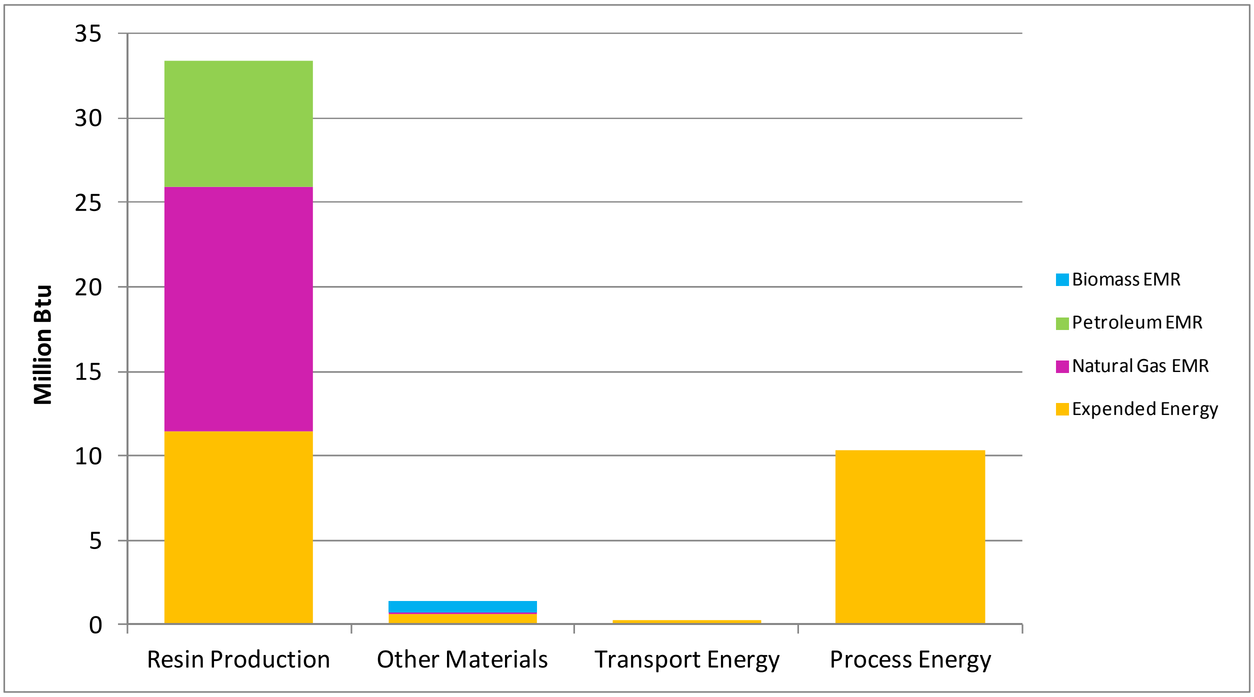

Figure 6. EMR vs. Non-EMR Cradle-to-Gate Energy Demand for Injection Molded PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

Table 5. EMR vs. Non-EMR Cradle-to-Gate Energy Demand for Injection Molded LLDPE Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	**TOTAL (1)**	**% TOTAL (1)**
Expended Energy	11.1	0.69	0.26	10.4	**22.4**	**49%**
Natural Gas EMR	18.7	0.016	0	0	**18.8**	**41%**
Petroleum EMR	3.80	0.026	0	0	**3.83**	**8%**
Biomass EMR	0	0.70	0	0	**0.70**	**2%**
TOTAL (1)	**33.6**	**1.43**	**0.26**	**10.4**	**45.7**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

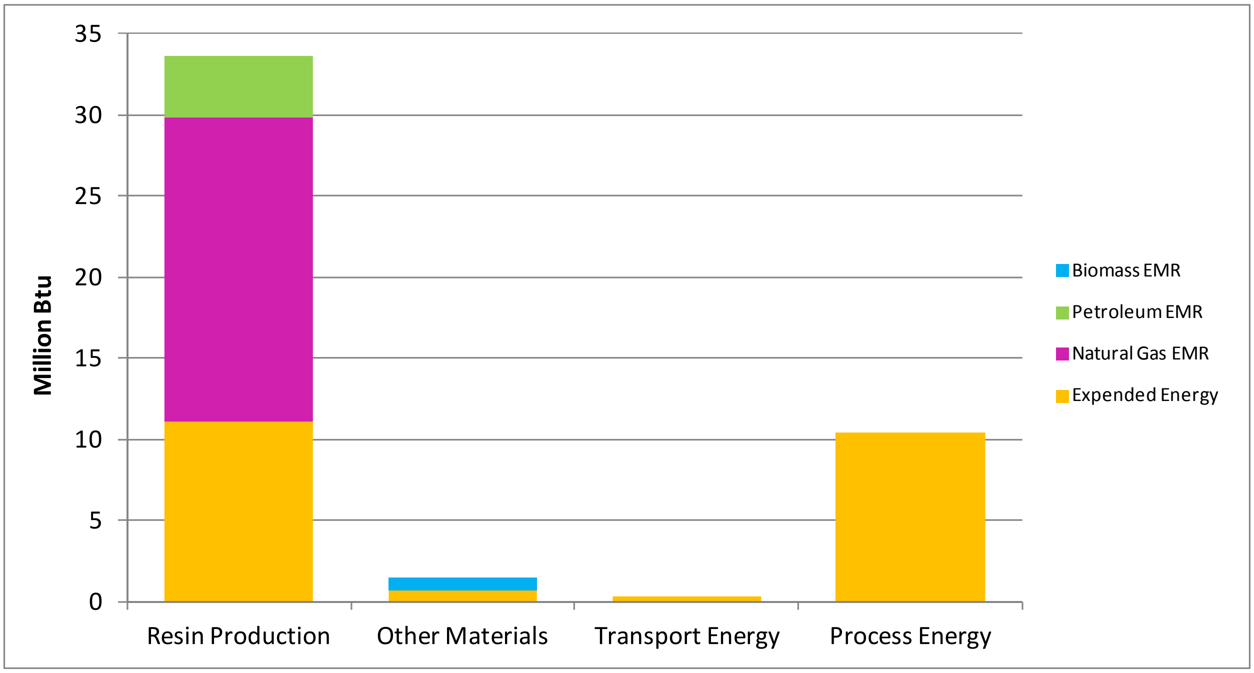

Figure 7. EMR vs. Non-EMR Cradle-to-Gate Energy Demand for Injection Molded LLDPE Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

The cradle-to-gate results show that total energy requirements for the fabrication step of producing rigid plastic parts by injection molding are only about a third of that of virgin materials production steps. As shown in Table 6 and Figure 8, the bulk (97 percent) of energy requirements for the fabrication unit process (i.e., gate-to-gate process) are in providing electricity for injection molding machinery and two percent of energy requirements are for delivery of materials by rail. The largest share of rail transport is required for delivery of incoming virgin resin materials.

Table 6. Unit Process Energy Demand for Injection Molding
(Million Btu of energy per 1,000 pounds of fabricated plastic)

	Electricity Inputs	Natural Gas Inputs	Diesel Inputs	LPG Inputs	Gasoline Inputs	Rail Transport	Truck Transport	**TOTAL (1)**	**% TOTAL (1)**
Nuclear	1.77	1.6E-04	1.5E-06	9.3E-05	1.3E-05	0.0021	1.5E-04	**1.77**	**17%**
Coal	6.24	4.3E-04	3.9E-06	2.5E-04	3.3E-05	0.0055	4.0E-04	**6.24**	**59%**
Natural Gas	1.60	0.060	7.3E-06	4.6E-04	6.2E-05	0.011	7.4E-04	**1.67**	**16%**
Petroleum	0.48	2.2E-04	1.5E-04	0.0094	0.0013	0.22	0.015	**0.73**	**7%**
Hydro	0.20	1.9E-05	1.7E-07	1.1E-05	1.5E-06	2.4E-04	1.7E-05	**0.20**	**2%**
TOTAL (1)	**10.3**	**0.061**	**1.6E-04**	**0.010**	**0.0014**	**0.24**	**0.017**	**10.6**	
% TOTAL (1)	**97%**	**<1%**	**<1%**	**<1%**	**<1%**	**2%**	**<1%**		

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

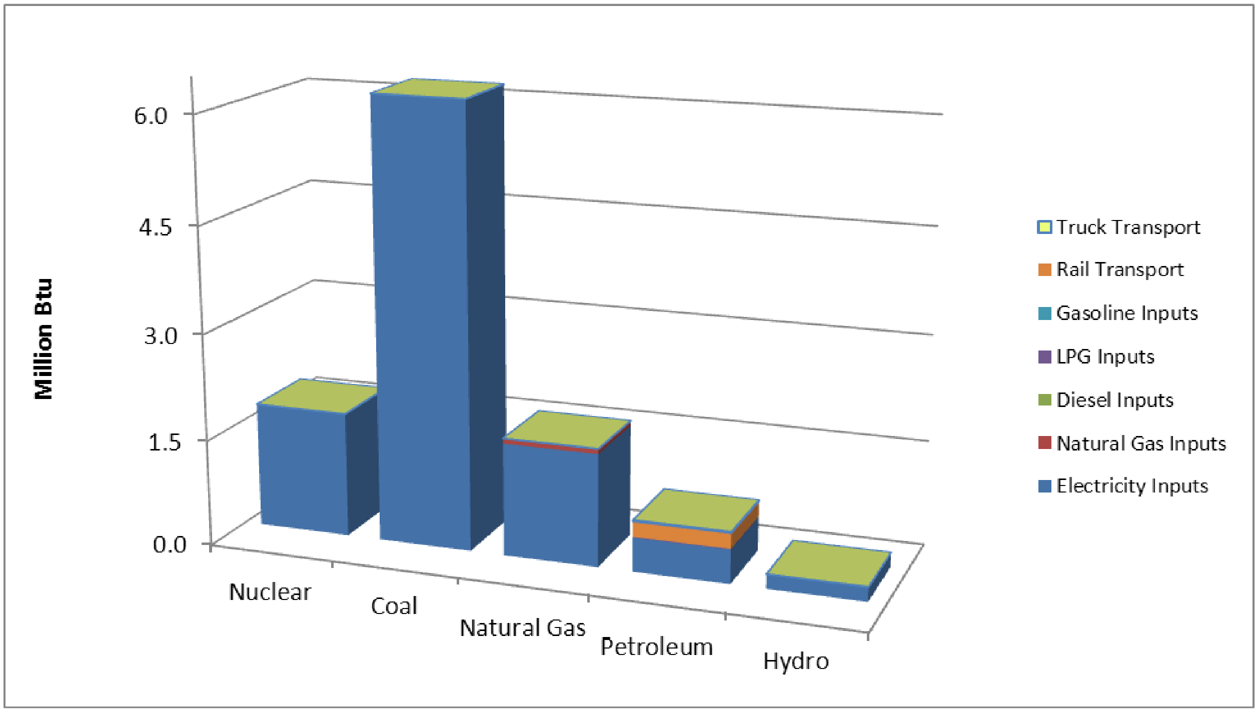

Figure 8. Unit Process Energy Demand for Injection Molding
(Million Btu of energy per 1,000 pounds of fabricated plastic)

Water Use Results

Consumptive water use for cradle-to-gate production of rigid plastic parts produced by the injection molding fabrication method is shown by process step in Table 7 and Figure 9.

Table 7. Cradle-to-Gate Water Use for Injection Molded PP or LLDPE Plastic Parts (Gallons of water per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	**TOTAL (1)**
PP	1,093	198	9.25	0.55	**1,300**
% TOTAL (1)	**84%**	**15%**	**1%**	**<1%**	
LLDPE	952	198	9.25	0.55	**1,160**
% TOTAL (1)	**82%**	**17%**	**1%**	**<1%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

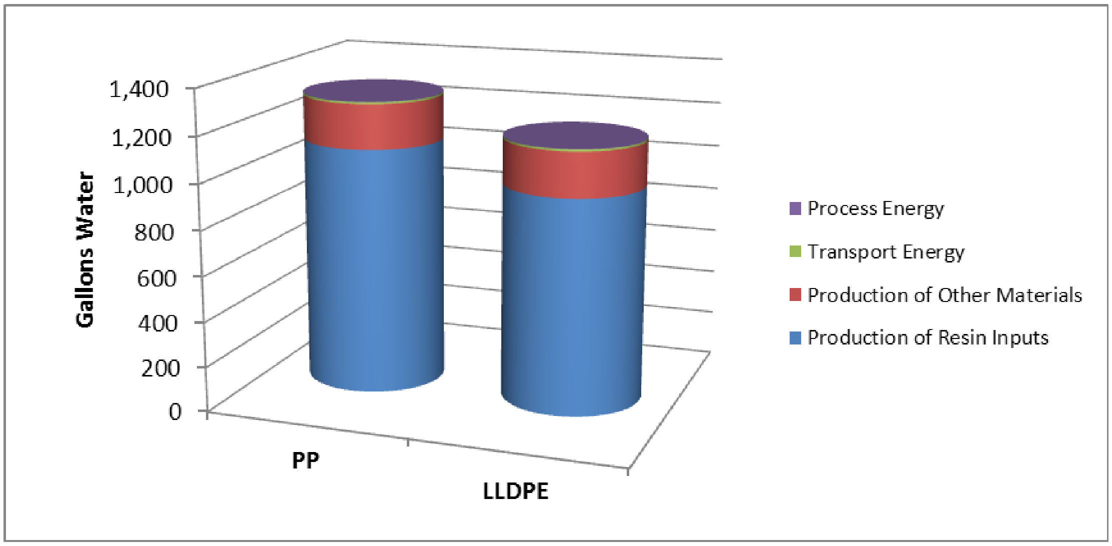

Figure 9. Cradle-to-Gate Water Use for Injection Molded PP or LLDPE Plastic Parts (Gallons of water per 1,000 pounds of fabricated plastic)

The cradle-to-gate results show that the bulk of water is consumed in production of the virgin resin inputs. At the fabrication step, water consumed during production of other materials and incoming process water are the next largest contributing aspects to total water consumption. The ‘process energy’ and ‘transport energy’ columns show water consumption associated with the steps to extract, process, and deliver the fuels used for process and transportation steps, including water consumption associated with electricity generation.

Solid Waste Results

Solid waste generation for cradle-to-gate production of rigid plastic parts produced by the injection molding fabrication method is shown by process step in Table 8 and Figure 10.

Table 8. Cradle-to-Gate Solid Waste Generation for Injection Molded PP or LLDPE Plastic Parts (Pounds of solid waste per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	Process Wastes	**TOTAL (1)**
PP	130	19.3	0.95	182	15.8	**348**
% TOTAL (1)	**37%**	**6%**	**0%**	**52%**	**5%**	
LLDPE	116	19.3	0.95	182	15.8	**334**
% TOTAL (1)	**35%**	**6%**	**0%**	**55%**	**5%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

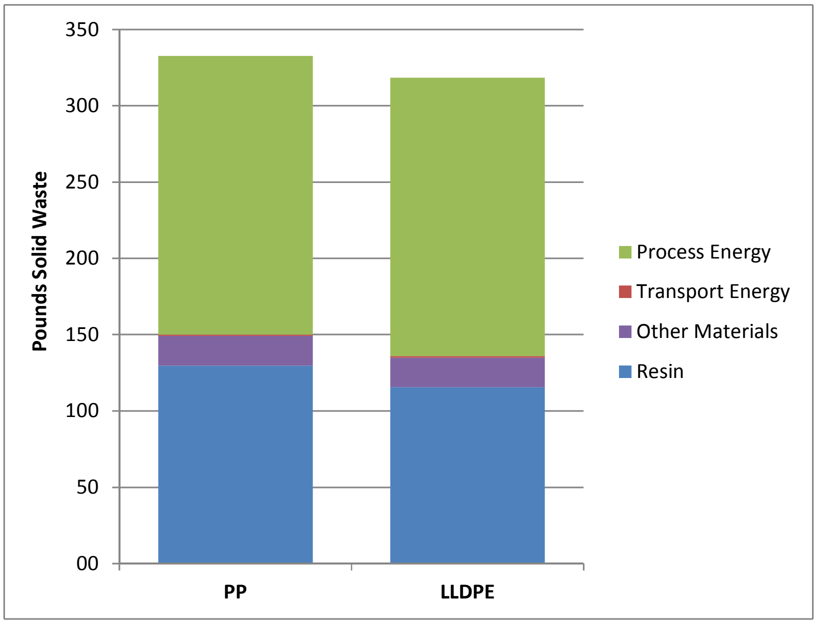

Figure 10. Cradle-to-Gate Solid Waste Generation for Injection Molded PP or LLDPE Plastic Parts (Pounds of solid waste per 1,000 pounds of fabricated plastic)

The cradle-to-gate results for solid waste generation indicate that over half of total generation occurs during the production and combustion of fuels required for operations at the injection molding facility. The next largest portion of solid waste is that generated during the production of the virgin resin material inputs. Scrap that is put to some use on-site or by an off-site user is not included in the total solid waste generation inventory. Also, because this is a cradle-to-gate LCI analysis (i.e., extends only through production of the fabricated plastic part) no postconsumer wastes are modeled. The disposition of a fabricated plastic product depends on the product application (packaging, durable product, etc.), its composition, access to recycling programs, and other product-specific factors that are outside the scope of a generic cradle-to-gate LCI.

Atmospheric and Waterborne Emissions

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels required for injection molding of rigid PP and LLDPE parts. The emissions tables in this section present emission quantities based upon the best data available. However, in the many unit processes included in the system models, some emissions data have been collected as reported from the industrial sources, some are estimated from EPA emission factors, and some have been calculated based on reaction chemistry or other information.

Atmospheric and waterborne emissions for each production of either PP or LLDPE injection molded plastic parts include emissions from (1) production of the virgin resin inputs, (2) production of other material inputs such as lubricating oil and corrugated shipping packaging, (3) production and combustion of fuels during transportation of incoming materials, (4) production and combustion of required processing fuels and production of the required electricity at the injection molding facility, and from (5) non-fuel combustion emissions at the injection molding facility itself occurring during processing and operation. Non-fuel related emissions at the injection molding facility are mostly particulate matter and volatile organic carbons from the injection molding and printing processes. The majority of atmospheric emissions are fuel-related, particularly in the case of greenhouse gas emissions, which are the focus of this discussion.

Greenhouse Gas (GHG) Emissions. The atmospheric emissions that typically contribute the majority of the total greenhouse gas impacts for product systems are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Greenhouse gas impacts are reported as carbon dioxide equivalents (CO_2 eq). Global warming potential (GWP) factors are used to convert emissions of individual greenhouse gases to the basis of CO_2 eq. The GWP of each greenhouse gas represents the relative global warming contribution of a pound of that substance compared to a pound of carbon dioxide. For each type of injection molded plastic (PP and LLDPE) the weight of each greenhouse gas emitted is multiplied by its GWP, then the CO_2 eq for all the individual GHGs are added to arrive at the total CO_2 eq. GHG results for production of injection molded plastic parts are shown for PP in and for LLDPE in Table 9 and Figure 11.

The GWP factors that are most widely used are those from the International Panel on Climate Change (IPCC) Second Assessment Report (SAR), published in 1996. The IPCC SAR 100-year global warming potentials (GWP) are 21 for methane and 310 for nitrous oxide. Two subsequent updates of the IPCC report with slightly different GWPs have been published since the SAR; however, some reporting standards that were developed at the time of the SAR continue to use the SAR GWP factors.[11] In addition to GHG results based on IPCC SAR GWP factors, the tables in this report also show GHG results using IPCC 2007 GWP factors, which are 25 for methane and 298 for nitrous oxide. The total CO_2 eq using the 2007 factors is slightly higher than the CO_2 eq calculated using 1996 SAR factors.

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[11] The United Nations Framework Convention on Climate Change reporting guidelines for national inventories continue to use GWPs from the IPPC Second Assessment Report (SAR). For this reason, the U.S. EPA also uses GWPs from the IPCC SAR, as described on page ES-1 of EPA 430-R-08-005 **Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006** (April 15, 2008).

Table 9. Cradle-to-Gate GHGs for Injection Molded PP or LLDPE Plastic Parts
(Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	Facility Emissions	**TOTAL (1)**
PP	1,908	146	41.0	1,420	0.0087	**3,514**
% TOTAL (1)	**54%**	**4%**	**1%**	**40%**	**<1%**	
LLDPE	1,952	146	41.0	1,420	0.0087	**3,559**
% TOTAL (1)	**55%**	**4%**	**1%**	**40%**	**<1%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

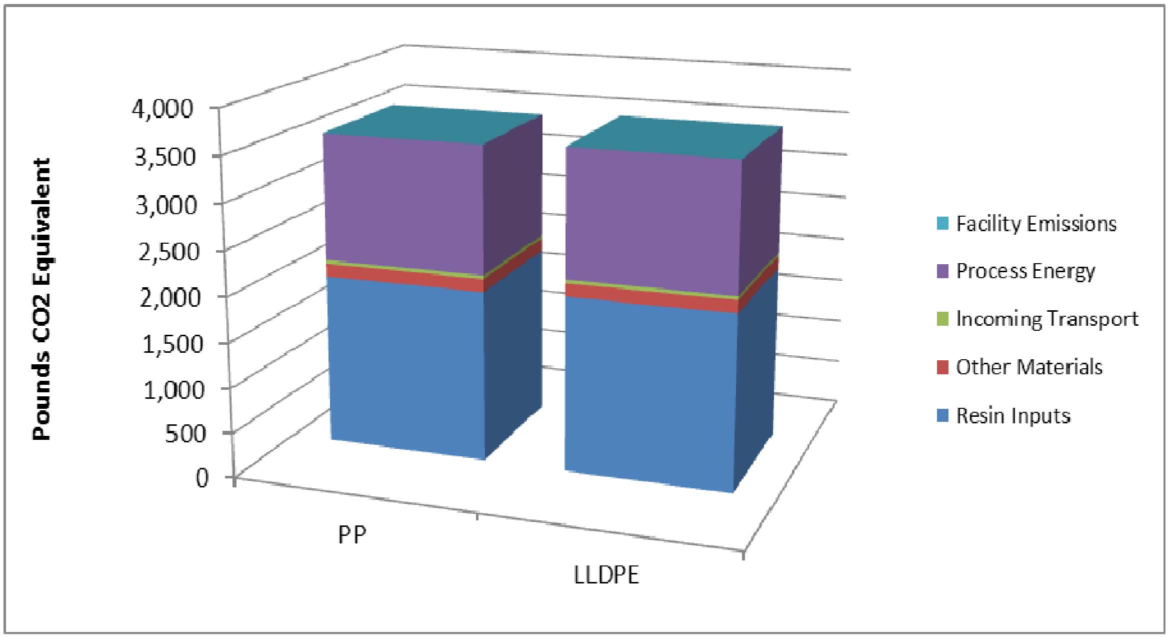

Figure 11. Cradle-to-Gate GHGs for Injection Molded PP or LLDPE Plastic Parts
(Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

The results show that over half of the GHG emissions are associated with production of virgin resin, which requires a substantial amount of fuels combustion as well as some fugitive emissions of carbon dioxide and methane released during the extraction, transport, and processing of natural gas and crude oil feedstocks for resin production. The other significant contribution to GHG emissions is the production of electricity and the production and combustion of process fuels used at the injection molding facility. The only GHG emission reported to be directly emitted at the facility from injection molding processing is methylene chloride from solvents and cleaners. Table 10/Figure 12 and Table 11/Figure 13 show the global warming potential (GWP) of each of the main GHGs from cradle-to-gate plastic fabrication for PP and LLDPE, respectively. This breakout by GHG shows that carbon dioxide emissions are the largest contributors to the global warming potential (GWP) of the GHGs; methane emissions have the second largest contribution and nitrous oxide emissions the third largest contribution. Several other emissions from the cradle-to-gate plastic fabrication systems are GHGs (e.g., sulfur hexafluoride, CFCs, and HCFCs) but their cumulative amounts and associated contribution to the overall GWP is less than one percent. Non-fuel related GHGs emitted at the injection molding facility are incorporated in the 'other' GHGs category.

Table 10. Cradle-to-Gate GWP by GHG for Injection Molded PP Plastic Parts
(Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	Process Emissions	**TOTAL (1)**	**% TOTAL (1)**
Fossil CO2	1,500	139	38.8	1,337	0	**3,015**	**86%**
Methane	400	5.93	1.91	74.1	0	**482**	**14%**
Nitrous Oxide	6.88	0.79	0.30	8.81	0	**16.8**	**<1%**
Others	0.16	0.10	0.0038	9.4E-04	0.0087	**0.27**	**<1%**
TOTAL (1)	**1,908**	**146**	**41.0**	**1,420**	**0.0087**	**3,514**	**100%**
% TOTAL (1)	**54%**	**4%**	**1%**	**40%**	**<1%**	**100%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

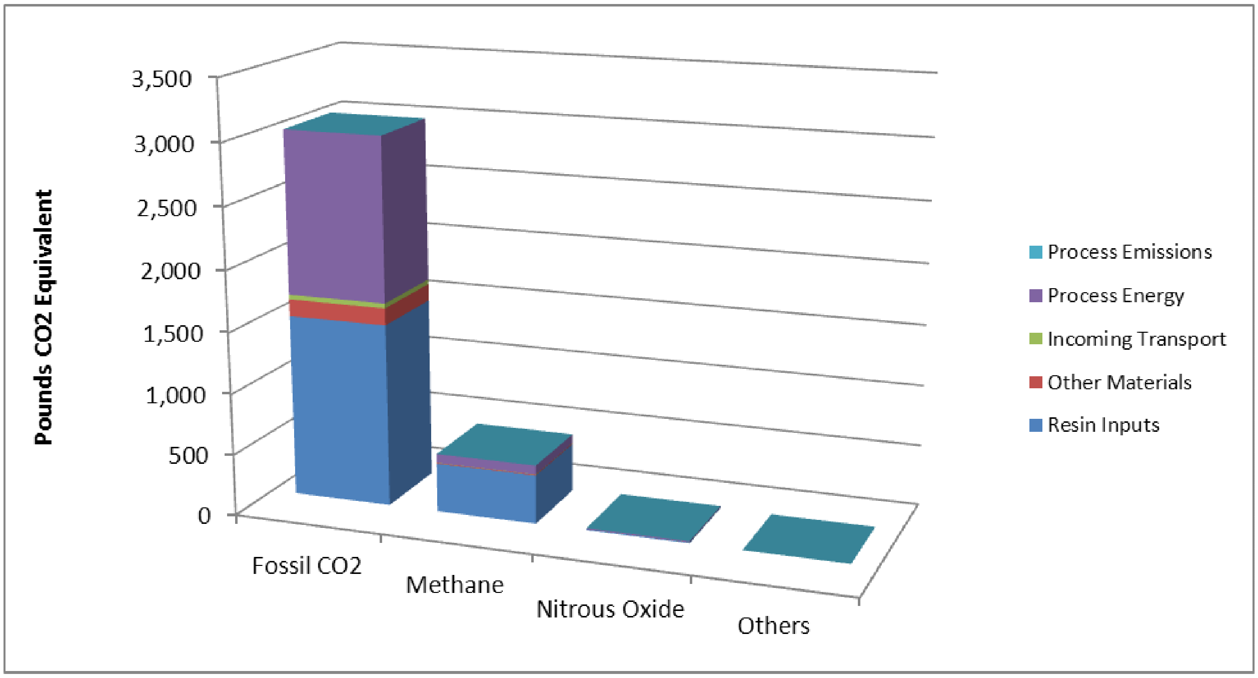

Figure 12. Cradle-to-Gate GWP by GHG for Injection Molded PP Plastic Parts
(Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

Table 11. Cradle-to-Gate GWP by GHG for Injection Molded LLDPE Plastic Parts (Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	Process Emissions	**TOTAL (1)**	**% TOTAL (1)**
Fossil CO2	1,498	139	38.8	1,337	0	**3,013**	**85%**
Methane	443	5.93	1.91	74.1	0	**525**	**15%**
Nitrous Oxide	10.9	0.79	0.30	8.81	0	**20.8**	**1%**
Others	0.098	0.14	0.0038	9.3E-04	0.0087	**0.25**	**<1%**
TOTAL (1)	**1,952**	**146**	**41.0**	**1,420**	**0.0087**	**3,559**	
% TOTAL (1)	**55%**	**4%**	**1%**	**40%**	**<1%**		

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

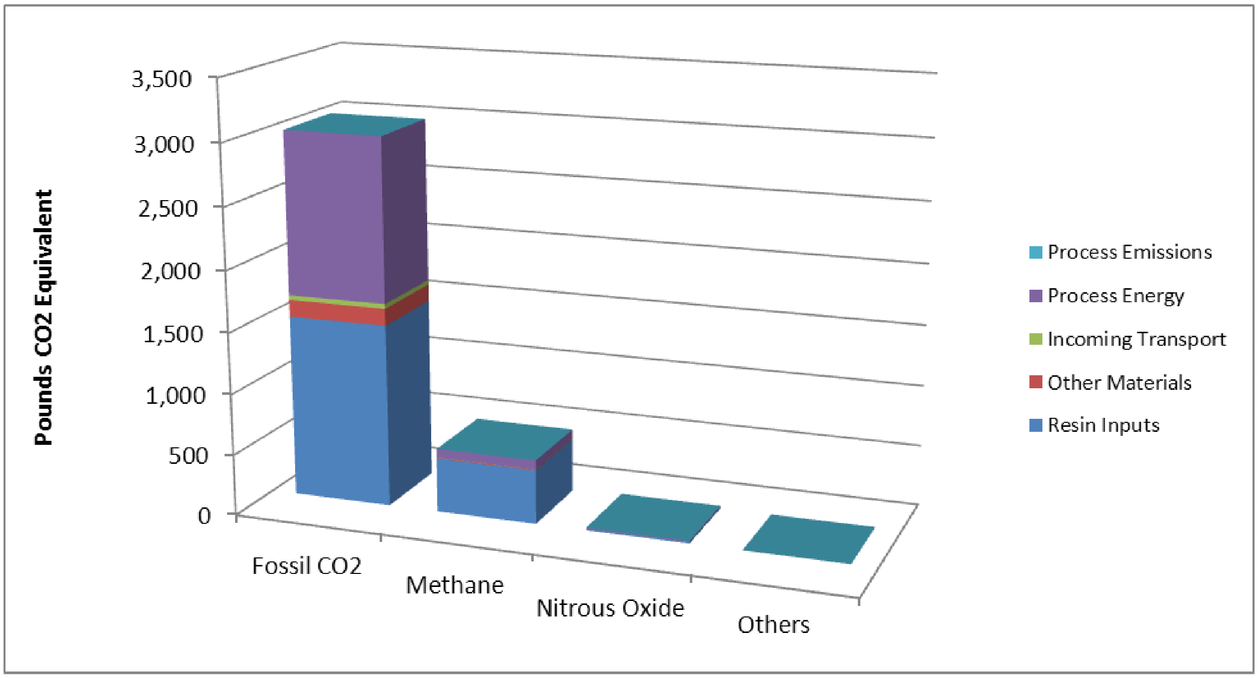

Figure 13. Cradle-to-Gate GWP by GHG for Injection Molded LLDPE Plastic Parts (Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

Other Atmospheric and Waterborne Emissions. Tables showing the full list of atmospheric and waterborne emissions for cradle-to-gate injection molded plastic parts are shown in Table 12 and Table 13, respectively.

Table 12. Cradle-to-Gate Atmospheric Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 1 of 4)

		PP Part	LLDPE Part
1-Butanol	lb	3.0E-17	3.0E-17
1-Pentanol	lb	2.4E-17	2.4E-17
1-Pentene	lb	1.8E-17	1.8E-17
1-Propanol	lb	3.3E-15	3.3E-15
1,4-Butanediol	lb	6.4E-16	6.4E-16
2-Aminopropanol	lb	2.0E-17	2.0E-17
2-Butene, 2-methyl-	lb	4.0E-21	4.0E-21
2-Chloroacetophenone	lb	3.5E-09	3.5E-09
2-Methyl-1-propanol	lb	6.6E-17	6.6E-17
2-Nitrobenzoic acid	lb	3.5E-17	3.5E-17
2-Propanol	lb	0.10	0.10
2,4-D	lb	8.6E-13	8.6E-13
4-Methyl-2-pentanone	lb	8.4E-05	8.4E-05
5-methyl Chrysene	lb	6.7E-09	6.4E-09
Acenaphthene	lb	1.5E-07	1.5E-07
Acenaphthylene	lb	7.6E-08	7.3E-08
Acetaldehyde	lb	6.4E-04	6.4E-04
Acetic acid	lb	2.6E-10	2.6E-10
Acetic acid, methyl ester	lb	4.5E-15	4.5E-15
Acetone	lb	6.0E-04	6.0E-04
Acetonitrile	lb	1.8E-13	1.8E-13
Acetophenone	lb	7.5E-09	7.4E-09
Acid gases	lb	7.8E-19	7.8E-19
Acidity, unspecified	lb	3.3E-12	3.3E-12
Acids, unspecified	lb	1.4E-11	1.4E-11
Acrolein	lb	0.0010	0.0010
Acrylic acid	lb	2.6E-14	2.6E-14
Actinides, radioactive, unspecified	Bq	3.7E-08	3.7E-08
Aerosols, radioactive, unspecified	Bq	4.2E-07	4.2E-07
Alachlor	lb	6.2E-13	6.2E-13
Alcohols, c12-14, ethoxylated	lb	0.10	0.10
Aldehydes, unspecified	lb	0.0013	0.0013
alpha-Pinene	lb	0.0019	0.0019
Aluminium	lb	2.1E-08	2.1E-08
Aluminum	lb	4.6E-17	1.0E-04
Ammonia	lb	0.012	0.0065
Ammonium carbonate	lb	1.2E-13	1.2E-13
Ammonium chloride	lb	8.4E-04	8.1E-04
Ammonium, ion	lb	1.2E-16	1.2E-16
Aniline	lb	2.8E-16	2.8E-16
Anthracene	lb	6.4E-08	6.1E-08
Anthranilic acid	lb	2.6E-17	2.6E-17
Antimony	lb	6.9E-06	6.2E-06
Antimony-124	Bq	5.5E-11	5.5E-11
Antimony-125	Bq	3.5E-10	3.5E-10
Argon-41	Bq	2.9E-04	2.9E-04
Arsenic	lb	1.3E-04	1.3E-04
Arsenic trioxide	lb	3.7E-19	3.7E-19
Arsine	lb	3.1E-17	3.1E-17
Barium	lb	6.6E-06	6.6E-06
Barium-140	Bq	2.3E-08	2.3E-08
Bentazone	lb	5.2E-13	5.2E-13
Benzal chloride	lb	3.1E-20	3.1E-20
Benzaldehyde	lb	8.6E-14	8.6E-14
Benzene	lb	0.11	0.13
Benzene, 1-methyl-2-nitro-	lb	3.1E-17	3.1E-17
Benzene, 1,2-dichloro-	lb	6.6E-16	6.6E-16
Benzene, 1,2,4-trichloro-	lb	5.2E-05	5.2E-05
Benzene, 1,3,5-trimethyl-	lb	7.7E-19	7.7E-19
Benzene, chloro-	lb	1.1E-08	1.1E-08
Benzene, ethyl-	lb	0.013	0.016
Benzene, hexachloro-	lb	2.5E-12	2.5E-12
Benzene, pentachloro-	lb	4.7E-14	4.7E-14
Benzo(a)anthracene	lb	2.4E-08	2.3E-08
Benzo(a)pyrene	lb	4.9E-08	4.8E-08
Benzo(b)fluoranthene	lb	4.5E-17	4.5E-17
Benzo(b,j,k)fluoranthene	lb	3.3E-08	3.2E-08
Benzo(ghi)perylene	lb	8.2E-09	7.9E-09
Benzyl chloride	lb	3.5E-07	3.5E-07
Beryllium	lb	7.1E-06	6.8E-06
Bicyclo[3.1.1]heptane, 6,6-dimethyl-2-methylene-	lb	0.0011	0.0011
Biphenyl	lb	5.2E-07	5.0E-07
Boron	lb	4.4E-10	4.4E-10
Boron trifluoride	lb	4.1E-21	4.1E-21
Bromine	lb	5.0E-11	5.0E-11
Bromoform	lb	2.0E-08	1.9E-08
Bromoxynil	lb	7.0E-13	7.0E-13
BTEX, unspecified ratio	lb	1.1E-11	1.1E-11
Butadiene	lb	1.8E-06	1.9E-06
Butane	lb	6.5E-09	6.5E-09
Butene	lb	1.3E-10	1.3E-10
Butyrolactone	lb	1.5E-16	1.5E-16
Cadmium	lb	2.5E-05	2.5E-05
Calcium	lb	7.8E-10	7.8E-10
Carbon-14	Bq	0.0028	0.0028
Carbon dioxide	lb	0.14	0.14
Carbon dioxide, biogenic	lb	154	154
Carbon dioxide, fossil	lb	3,010	3,007
Carbon dioxide, land transformation	lb	0.0020	0.0020
Carbon disulfide	lb	7.2E-08	7.1E-08
Carbon monoxide	lb	7.57	4.41
Carbon monoxide, biogenic	lb	2.9E-09	2.9E-09
Carbon monoxide, fossil	lb	1.00	1.04
Carbonyl sulfide	lb	3.4E-11	3.4E-11
Cerium-141	Bq	5.5E-09	5.5E-09
Cesium-134	Bq	1.8E-08	1.8E-08
Cesium-137	Bq	4.0E-08	4.0E-08
Chloramine	lb	1.3E-16	1.3E-16
Chloride	lb	1.9E-12	1.9E-12

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 12. Cradle-to-Gate Atmospheric Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 2 of 4)

		PP Part	LLDPE Part
CFCs and HCFCs, unspecified	lb	3.7E-12	3.7E-12
Chlorine	lb	1.6E-04	1.6E-04
Chloroacetic acid	lb	8.1E-14	8.1E-14
Chloroform	lb	1.3E-04	1.3E-04
Chlorosilane, trimethyl-	lb	3.6E-11	3.6E-11
Chlorosulfonic acid	lb	2.5E-16	2.5E-16
Chlorpyrifos	lb	2.3E-13	2.3E-13
Chromium	lb	9.4E-05	9.2E-05
Chromium-51	Bq	3.5E-10	3.5E-10
Chromium VI	lb	2.4E-05	2.3E-05
Chromium, ion	lb	1.3E-12	1.3E-12
Chrysene	lb	3.0E-08	2.9E-08
Clomazone	lb	1.2E-13	1.2E-13
Cobalt	lb	6.5E-05	5.7E-05
Cobalt-58	Bq	6.0E-10	6.0E-10
Cobalt-60	Bq	7.1E-09	7.1E-09
Copper	lb	8.3E-07	8.1E-07
Cumene	lb	8.8E-09	8.8E-09
Cyanide	lb	1.3E-06	1.2E-06
Cyanoacetic acid	lb	2.0E-16	2.0E-16
Cyclohexane	lb	4.5E-15	4.5E-15
D-limonene	lb	8.6E-05	8.6E-05
Dibenz(a,h)anthracene	lb	1.4E-17	1.4E-17
Diethanolamine	lb	3.0E-21	3.0E-21
Diethylamine	lb	1.3E-16	1.3E-16
Dimethyl malonate	lb	2.5E-16	2.5E-16
Dimethyl sulfide	lb	0.0018	0.0018
Dinitrogen monoxide	lb	0.056	0.069
Dioxins, measured as 2,3,7,8-tetra-chlorodibenzo-p-dioxin	lb	8.9E-08	8.9E-08
Dipropylamine	lb	7.4E-17	7.4E-17
Ethane	lb	1.1E-08	1.1E-08
Ethane, 1,1-difluoro-, HFC-152a	lb	5.8E-14	5.8E-14
Ethane, 1,1,1-trichloro-, HCFC-140	lb	1.0E-08	9.9E-09
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	lb	1.5E-11	1.5E-11
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	lb	1.2E-15	1.2E-15
Ethane, 1,2-dibromo-	lb	6.0E-10	6.0E-10
Ethane, 1,2-dichloro-	lb	2.0E-08	2.0E-08
Ethane, 1,2-dichloro-1,1,2-trifluoro-, HCFC-123	lb	8.8E-14	8.8E-14
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	lb	1.7E-12	1.7E-12
Ethane, chloro-	lb	2.1E-08	2.1E-08
Ethane, hexafluoro-, HFC-116	lb	9.6E-10	9.6E-10
Ethanol	lb	1.01	1.01
Ethene	lb	7.1E-10	7.1E-10
Ethene, chloro-	lb	3.6E-11	3.6E-11
Ethene, tetrachloro-	lb	1.4E-05	1.3E-05
Ethyl acetate	lb	0.10	0.10
Ethyl cellulose	lb	9.3E-14	9.3E-14
Ethylamine	lb	8.0E-17	8.0E-17
Ethylene diamine	lb	3.5E-16	3.5E-16
Ethylene dibromide	lb	2.2E-06	1.2E-06
Ethylene oxide	lb	4.5E-12	4.5E-12
Ethyne	lb	3.9E-11	3.9E-11
Fluoranthene	lb	2.2E-07	2.1E-07
Fluorene	lb	2.8E-07	2.7E-07
Fluoride	lb	4.1E-05	4.0E-05
Fluorine	lb	3.7E-08	3.7E-08
Fluosilicic acid	lb	1.8E-09	1.8E-09
Formaldehyde	lb	0.0012	0.0013
Formamide	lb	4.4E-17	4.4E-17
Formic acid	lb	1.3E-12	1.3E-12
Furan	lb	1.4E-09	0.0010
Glyphosate	lb	4.1E-11	4.1E-11
Glyphosate-trimesium	lb	3.4E-12	3.4E-12
Heat, waste	MJ	14.9	14.9
Helium	lb	5.1E-10	5.1E-10
Heptane	lb	1.3E-09	1.3E-09
Hexamethylene diamine	lb	7.0E-18	7.0E-18
Hexane	lb	7.0E-06	7.0E-06
Hydrazine, methyl-	lb	8.5E-08	8.4E-08
Hydrocarbons, aliphatic, alkanes, cyclic	lb	7.5E-13	7.5E-13
Hydrocarbons, aliphatic, alkanes, unspecified	lb	1.6E-08	1.6E-08
Hydrocarbons, aliphatic, unsaturated	lb	2.6E-09	2.6E-09
Hydrocarbons, aromatic	lb	1.2E-08	1.2E-08
Hydrocarbons, chlorinated	lb	9.3E-12	9.3E-12
Hydrocarbons, unspecified	lb	0.056	0.056
Hydrogen	lb	0.0054	0.0041
Hydrogen-3, Tritium	Bq	0.012	0.012
Hydrogen bromide	lb	2.3E-14	2.3E-14
Hydrogen chloride	lb	0.37	0.35
Hydrogen cyanide	lb	1.1E-12	1.1E-12
Hydrogen fluoride	lb	0.045	0.044
Hydrogen iodide	lb	2.5E-17	2.5E-17
Hydrogen peroxide	lb	6.9E-14	6.9E-14
Hydrogen sulfide	lb	7.2E-08	7.2E-08
Indeno(1,2,3-cd)pyrene	lb	1.8E-08	1.8E-08
Iodine	lb	2.4E-11	2.4E-11
Iodine-129	Bq	2.3E-06	2.3E-06
Iodine-131	Bq	5.5E-05	5.5E-05
Iodine-133	Bq	3.1E-08	3.1E-08
Iodine-135	Bq	8.2E-09	8.2E-09
Iron	lb	6.6E-06	6.6E-06
Isocyanic acid	lb	9.2E-13	9.2E-13
Isophorone	lb	2.9E-07	2.9E-07
Isoprene	lb	5.0E-11	5.0E-11
Isopropylamine	lb	3.1E-17	3.1E-17
Kerosene	lb	4.0E-04	3.9E-04
Krypton-85	Bq	4.9E-04	4.9E-04

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 12. Cradle-to-Gate Atmospheric Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 3 of 4)

		PP Part	LLDPE Part
Krypton-85m	Bq	2.32	2.32
Krypton-87	Bq	7.8E-05	7.8E-05
Krypton-88	Bq	1.0E-04	1.0E-04
Krypton-89	Bq	4.1E-05	4.1E-05
Lactic acid	lb	5.8E-17	5.8E-17
Lanthanum-140	Bq	1.9E-09	1.9E-09
Lead	lb	1.5E-04	1.4E-04
Lead-210	Bq	1.1E-05	1.1E-05
Lead compounds	lb	9.1E-19	9.1E-19
m-Xylene	lb	0.0010	0.0010
Magnesium	lb	0.0033	0.0032
Manganese	lb	2.7E-04	2.6E-04
Manganese-54	Bq	1.8E-10	1.8E-10
Mercaptans, unspecified	lb	1.1E-04	1.1E-04
Mercury	lb	2.9E-05	2.8E-05
Metals, unspecified	lb	0.0023	0.0023
Methacrylic acid, methyl ester	lb	1.0E-08	9.9E-09
Methane	lb	2.22	2.15
Methane, biogenic	lb	3.4E-09	3.4E-09
Methane, bromo-, Halon 1001	lb	8.0E-08	7.9E-08
Methane, bromochlorodifluoro-, Halon 1211	lb	8.9E-13	8.9E-13
Methane, bromotrifluoro-, Halon 1301	lb	4.1E-12	4.1E-12
Methane, chlorodifluoro-, HCFC-22	lb	1.0E-06	1.1E-05
Methane, chlorotrifluoro-, CFC-13	lb	1.1E-05	5.9E-06
Methane, dichloro-, HCC-30	lb	0.0011	0.0011
Methane, dichlorodifluoro-, CFC-12	lb	2.9E-09	2.9E-09
Methane, dichlorofluoro-, HCFC-21	lb	8.9E-18	8.9E-18
Methane, fossil	lb	17.0	18.8
Methane, monochloro-, R-40	lb	2.7E-07	2.6E-07
Methane, tetrachloro-, CFC-10	lb	2.4E-06	2.4E-06
Methane, tetrafluoro-, CFC-14	lb	9.6E-09	9.6E-09
Methane, trichlorofluoro-, CFC-11	lb	3.9E-13	3.9E-13
Methane, trifluoro-, HFC-23	lb	2.8E-15	2.8E-15
Methanesulfonic acid	lb	2.0E-16	2.0E-16
Methanol	lb	0.013	0.013
Methyl acetate	lb	8.2E-18	8.2E-18
Methyl acrylate	lb	2.9E-14	2.9E-14
Methyl amine	lb	1.4E-16	1.4E-16
Methyl borate	lb	1.0E-17	1.0E-17
Methyl ethyl ketone	lb	0.10	0.10
Methyl formate	lb	1.2E-16	1.2E-16
Methyl lactate	lb	6.4E-17	6.4E-17
Methyl mercaptan	lb	2.2E-04	2.2E-04
Methyl methacrylate	lb	1.8E-16	1.8E-16
Metolachlor	lb	1.2E-12	1.2E-12
Metribuzin	lb	3.0E-13	3.0E-13
Molybdenum	lb	2.9E-11	2.9E-11
Monoethanolamine	lb	1.6E-09	1.6E-09
Naphthalene	lb	2.3E-05	2.2E-05
Nickel	lb	5.7E-04	4.8E-04
Niobium-95	Bq	2.2E-11	2.2E-11
Nitrate	lb	1.5E-11	1.5E-11
Nitric oxide	lb	1.6E-13	1.6E-13
Nitrobenzene	lb	4.0E-16	4.0E-16
Nitrogen	lb	2.2E-09	2.2E-09
Nitrogen dioxide	lb	2.0E-05	2.0E-05
Nitrogen oxides	lb	7.66	7.01
Nitrogen, total	lb	2.7E-13	2.7E-13
Nitrous oxide	lb	5.5E-04	5.5E-04
NMVOC, non-methane VOC, unspecified	lb	1.34	1.06
Noble gases, radioactive, unspecified	Bq	20.6	20.6
o-Xylene	lb	1.0E-04	1.0E-04
Octane	lb	2.0E-12	2.0E-12
Odorous sulfur	lb	4.2E-14	4.2E-14
Organic acids	lb	3.1E-06	3.0E-06
Organic substances, unspecified	lb	0.014	0.014
Oxygen	lb	1.2E-08	1.2E-08
Ozone	lb	9.1E-10	9.1E-10
p-Xylene	lb	1.0E-04	1.0E-04
PAH, polycyclic aromatic hydrocarbons	lb	7.6E-06	8.0E-06
Palladium	lb	2.0E-23	2.0E-23
Particulates, < 10 um	lb	1.36	0.76
Particulates, < 2.5 um	lb	0.23	0.17
Particulates, > 10 um	lb	9.1E-07	9.1E-07
Particulates, > 2.5 um, and < 10um	lb	0.21	0.22
Particulates, unspecified	lb	1.24	1.19
Pendimethalin	lb	6.7E-12	6.7E-12
Pentane	lb	8.2E-09	8.2E-09
Phenanthrene	lb	8.2E-07	7.9E-07
Phenol	lb	1.0E-04	1.0E-04
Phenol, 2,4-dichloro-	lb	5.3E-17	5.3E-17
Phenol, pentachloro-	lb	6.6E-11	6.6E-11
Phenols, unspecified	lb	3.1E-05	2.7E-05
Phosphate	lb	4.8E-15	4.8E-15
Phosphine	lb	2.3E-17	2.3E-17
Phosphorus	lb	3.4E-10	3.4E-10
Phthalate, dioctyl-	lb	3.7E-08	3.6E-08
Platinum	lb	3.4E-17	3.4E-17
Plutonium-238	Bq	2.9E-13	2.9E-13
Plutonium-alpha	Bq	6.9E-12	6.9E-12
Polonium-210	Bq	1.8E-05	1.8E-05
Polychlorinated biphenyls	lb	3.0E-12	3.0E-12
Polycyclic organic matter, unspecified	lb	2.9E-05	1.5E-05
Potassium	lb	0.0012	0.0012
Potassium-40	Bq	2.2E-06	2.2E-06
Propanal	lb	1.9E-07	1.9E-07
Propane	lb	0.0010	0.0010
Propene	lb	1.2E-04	1.2E-04

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 12. Cradle-to-Gate Atmospheric Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)

(Page 4 of 4)

		PP Part	LLDPE Part
Propionic acid	lb	1.0E-11	1.0E-11
Propylamine	lb	1.4E-17	1.4E-17
Propylene oxide	lb	7.1E-07	7.1E-07
Protactinium-234	Bq	3.6E-07	3.6E-07
Pyrene	lb	1.0E-07	9.6E-08
Radioactive species, other beta emitters	Bq	1.4E-05	1.4E-05
Radioactive species, unspecified	Bq	1.7E+07	1.7E+07
Radionuclides (Including Radon)	lb	0.022	0.022
Radium-226	Bq	1.4E-05	1.4E-05
Radium-228	Bq	4.7E-06	4.7E-06
Radon-220	Bq	6.3E-05	6.3E-05
Radon-222	Bq	47.5	47.5
Rhodium	lb	1.9E-23	1.9E-23
Ruthenium-103	Bq	4.7E-12	4.7E-12
Scandium	lb	4.4E-12	4.4E-12
Selenium	lb	4.0E-04	3.9E-04
Silicon	lb	2.3E-09	2.3E-09
Silicon tetrafluoride	lb	2.4E-14	2.4E-14
Silver	lb	2.0E-13	2.0E-13
Silver-110	Bq	4.7E-11	4.7E-11
Sodium	lb	2.7E-05	2.7E-05
Sodium chlorate	lb	2.8E-13	2.8E-13
Sodium dichromate	lb	3.1E-13	3.1E-13
Sodium formate	lb	2.7E-14	2.7E-14
Sodium hydroxide	lb	2.6E-13	2.6E-13
Strontium	lb	2.3E-11	2.3E-11
Styrene	lb	4.5E-05	4.5E-05
Sulfate	lb	6.7E-09	6.7E-09
Sulfur dioxide	lb	12.9	13.0
Sulfur hexafluoride	lb	7.6E-12	7.6E-12
Sulfur oxides	lb	2.34	1.51
Sulfur trioxide	lb	3.4E-15	3.4E-15
Sulfur, total reduced	lb	0.0092	0.0092
Sulfuric acid	lb	1.2E-13	1.2E-13
Sulfuric acid, dimethyl ester	lb	2.4E-08	2.4E-08
t-Butyl methyl ether	lb	1.9E-08	1.9E-08
t-Butylamine	lb	1.6E-16	1.6E-16
Tar	lb	1.7E-18	1.7E-18
Tellurium	lb	1.7E-13	1.7E-13
Terpenes	lb	0.0066	0.0066
Thallium	lb	1.6E-12	1.6E-12
Thorium	lb	1.4E-13	1.4E-13
Thorium-228	Bq	6.3E-07	6.3E-07
Thorium-230	Bq	1.4E-06	1.4E-06
Thorium-232	Bq	6.6E-07	6.6E-07
Thorium-234	Bq	3.6E-07	3.6E-07
Tin	lb	1.2E-10	1.2E-10
Tin oxide	lb	7.9E-20	7.9E-20
Titanium	lb	2.2E-10	2.2E-10
TOC, Total Organic Carbon	lb	2.2E-04	2.2E-04
Toluene	lb	0.17	0.21
Toluene, 2-chloro-	lb	1.6E-16	1.6E-16
Toluene, 2,4-dinitro-	lb	1.4E-10	1.4E-10
Trichloroethane	lb	2.4E-09	2.4E-09
Trifluralin	lb	6.7E-12	6.7E-12
Trimethylamine	lb	1.5E-17	1.5E-17
Tungsten	lb	4.9E-13	4.9E-13
Uranium	lb	1.7E-13	1.7E-13
Uranium-234	Bq	4.4E-06	4.4E-06
Uranium-235	Bq	7.7E-07	7.7E-07
Uranium-238	Bq	6.7E-06	6.7E-06
Uranium alpha	Bq	2.0E-05	2.0E-05
Used air	lb	2.7E-05	2.7E-05
Vanadium	lb	2.0E-10	2.0E-10
Vinyl acetate	lb	3.8E-09	3.8E-09
VOC, volatile organic compounds	lb	1.08	1.25
Water	lb	1.5E-05	1.5E-05
Xenon-131m	Bq	4.1E-04	4.1E-04
Xenon-133	Bq	0.015	0.015
Xenon-133m	Bq	1.8E-05	1.8E-05
Xenon-135	Bq	0.0060	0.0060
Xenon-135m	Bq	0.0037	0.0037
Xenon-137	Bq	1.1E-04	1.1E-04
Xenon-138	Bq	8.6E-04	8.6E-04
Xylene	lb	0.095	0.12
Zinc	lb	8.2E-06	7.1E-06
Zinc-65	Bq	9.1E-10	9.1E-10
Zinc oxide	lb	1.6E-19	1.6E-19
Zirconium	lb	2.0E-13	2.0E-13
Zirconium-95	Bq	8.9E-10	8.9E-10

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 13. Cradle-to-Gate Waterborne Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 1 of 4)

		PP Part	LLDPE Part
1-Butanol	lb	1.7E-13	1.7E-13
1-Pentanol	lb	5.8E-17	5.8E-17
1-Pentene	lb	4.4E-17	4.4E-17
1,4-Butanediol	lb	2.5E-16	2.5E-16
2-Aminopropanol	lb	5.0E-17	5.0E-17
2-Hexanone	lb	5.2E-06	5.3E-06
2-Methyl-1-propanol	lb	1.6E-16	1.6E-16
2-Methyl-2-butene	lb	9.7E-21	9.7E-21
2-Propanol	lb	4.6E-13	4.6E-13
2,4-D	lb	3.7E-14	3.7E-14
4-Methyl-2-pentanone	lb	2.6E-06	2.7E-06
Acenaphthene	lb	4.9E-14	4.9E-14
Acenaphthylene	lb	7.8E-15	7.8E-15
Acetaldehyde	lb	9.5E-13	9.5E-13
Acetic acid	lb	1.4E-11	1.4E-11
Acetone	lb	6.2E-06	6.6E-06
Acetonitrile	lb	1.7E-16	1.7E-16
Acetyl chloride	lb	4.6E-17	4.6E-17
Acidity, unspecified	lb	5.5E-05	5.5E-05
Acids, unspecified	lb	1.2E-10	1.2E-10
Acrylate, ion	lb	6.1E-14	6.1E-14
Acrylonitrile	lb	4.1E-16	4.1E-16
Actinides, radioactive, unspecified	Bq	3.5E-06	3.5E-06
Alachlor	lb	2.7E-14	2.7E-14
Aldehydes (unspecified)	lb	2.3E-19	2.3E-19
Aluminium	lb	1.2E-06	1.2E-06
Aluminum	lb	0.055	0.056
Americium-241	Bq	6.2E-08	6.2E-08
Ammonia	lb	0.017	0.013
Ammonia, as N	lb	3.8E-04	3.8E-04
Ammonium, ion	lb	1.8E-04	1.7E-04
Aniline	lb	6.8E-16	6.8E-16
Anthracene	lb	3.9E-15	3.9E-15
Antimony	lb	3.0E-05	3.0E-05
Antimony-122	Bq	1.4E-08	1.4E-08
Antimony-124	Bq	1.0E-06	1.0E-06
Antimony-125	Bq	9.9E-07	9.9E-07
Antimony compounds	lb	1.1E-19	1.1E-19
AOX, Adsorbable Organic Halogen as Cl	lb	4.1E-04	4.1E-04
Arsenic	lb	2.3E-12	2.3E-12
Arsenic, ion	lb	1.7E-04	1.7E-04
Barite	lb	1.8E-08	1.8E-08
Barium	lb	0.67	0.67
Barium-140	Bq	5.9E-08	5.9E-08
Bentazone	lb	2.2E-14	2.2E-14
Benzene	lb	0.0011	0.0011
Benzene, 1-methyl-4-(1-methylethyl)-	lb	6.2E-08	6.5E-08
Benzene, 1,2-dichloro-	lb	7.5E-14	7.5E-14
Benzene, chloro-	lb	1.5E-12	1.5E-12
Benzene, ethyl-	lb	7.2E-05	7.2E-05
Benzene, pentamethyl-	lb	4.6E-08	4.9E-08
Benzenes, alkylated, unspecified	lb	7.8E-05	7.9E-05
Benzo(a)anthracene	lb	3.3E-15	3.3E-15
Benzo(b)fluoranthene	lb	3.7E-15	3.7E-15
Benzoic acid	lb	8.0E-04	8.1E-04
Beryllium	lb	9.2E-06	9.2E-06
Biphenyl	lb	5.1E-06	5.1E-06
BOD5, Biological Oxygen Demand	lb	0.42	0.41
Borate	lb	6.4E-15	6.4E-15
Boron	lb	0.0025	0.0025
Bromate	lb	3.0E-10	3.0E-10
Bromide	lb	0.14	0.14
Bromine	lb	4.6E-09	4.6E-09
Butene	lb	4.8E-14	1.0E-04
Butyl acetate	lb	2.2E-13	2.2E-13
Butyrolactone	lb	3.7E-16	3.7E-16
Cadmium	lb	1.8E-11	1.8E-11
Cadmium, ion	lb	2.8E-05	2.8E-05
Calcium, ion	lb	2.11	2.11
Carbon-14	Bq	3.1E-06	3.1E-06
Carbon disulfide	lb	1.6E-15	1.6E-15
Carbonate	lb	8.9E-10	8.9E-10
Carboxylic acids, unspecified	lb	2.3E-08	2.3E-08
Cerium-141	Bq	2.4E-08	2.4E-08
Cerium-144	Bq	7.2E-09	7.2E-09
Cesium	lb	5.6E-12	5.6E-12
Cesium-134	Bq	3.6E-06	3.6E-06
Cesium-136	Bq	4.2E-09	4.2E-09
Cesium-137	Bq	4.4E-04	4.4E-04
Chloramine	lb	1.1E-15	1.1E-15
Chlorate	lb	2.3E-09	2.3E-09
Chloride	lb	24.5	24.6
Chlorinated solvents, unspecified	lb	1.3E-12	1.3E-12
Chlorine	lb	7.7E-11	7.7E-11
Chloroacetic acid	lb	3.6E-12	3.6E-12
Chloroacetyl chloride	lb	6.6E-17	6.6E-17
Chloroform	lb	3.5E-15	3.5E-15
Chlorosulfonic acid	lb	6.1E-16	6.1E-16
Chlorpyrifos	lb	9.8E-15	9.8E-15
Chromium	lb	0.0012	0.0012
Chromium-51	Bq	4.5E-06	4.5E-06
Chromium VI	lb	9.7E-07	9.7E-07
Chromium, ion	lb	1.6E-04	1.6E-04
Chrysene	lb	1.9E-14	1.9E-14
Clomazone	lb	5.1E-15	5.1E-15
Cobalt	lb	1.8E-05	1.8E-05
Cobalt-57	Bq	1.3E-07	1.3E-07
Cobalt-58	Bq	2.0E-05	2.0E-05
Cobalt-60	Bq	3.1E-05	3.1E-05
COD, Chemical Oxygen Demand	lb	0.46	0.41

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 13. Cradle-to-Gate Waterborne Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
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		PP Part	LLDPE Part
Copper	lb	6.9E-05	8.5E-05
Copper, ion	lb	2.7E-04	2.5E-04
Cresol	lb	2.1E-17	2.1E-17
Cumene	lb	1.5E-08	1.5E-08
Curium alpha	Bq	8.2E-08	8.2E-08
Cyanide	lb	4.6E-08	4.8E-08
Cyclohexane	lb	4.6E-17	1.0E-04
Decane	lb	2.3E-05	2.3E-05
Detergent, oil	lb	4.0E-04	4.0E-04
Detergents, unspecified	lb	1.9E-14	1.9E-14
Dibenzofuran	lb	1.2E-07	1.2E-07
Dibenzothiophene	lb	1.1E-07	1.1E-07
Dichromate	lb	1.1E-12	1.1E-12
Diethylamine	lb	3.2E-16	3.2E-16
Dimethylamine	lb	1.7E-15	1.7E-15
Dioxins, measured as 2,3,7,8-tetra-chlorodibenzo-p-dioxin	lb	1.2E-19	1.2E-19
Dipropylamine	lb	1.8E-16	1.8E-16
Dissolved organics	lb	2.7E-17	2.7E-17
Dissolved solids	lb	9.74	9.70
DOC, Dissolved Organic Carbon	lb	4.4E-06	4.4E-06
Docosane	lb	6.6E-07	6.9E-07
Dodecane	lb	4.4E-05	4.4E-05
Eicosane	lb	1.2E-05	1.2E-05
Ethane, 1,2-dichloro-	lb	3.6E-13	3.6E-13
Ethanol	lb	4.3E-13	4.3E-13
Ethene	lb	4.1E-11	4.1E-11
Ethene, chloro-	lb	6.9E-13	6.9E-13
Ethyl acetate	lb	3.7E-16	3.7E-16
Ethylamine	lb	1.9E-16	1.9E-16
Ethylene diamine	lb	8.4E-16	8.4E-16
Ethylene oxide	lb	2.4E-12	2.4E-12
Fluoranthene	lb	3.9E-15	3.9E-15
Fluorene	lb	1.9E-06	1.9E-06
Fluorene, 1-methyl-	lb	7.0E-08	7.4E-08
Fluorenes, alkylated, unspecified	lb	4.5E-06	4.6E-06
Fluoride	lb	0.0029	0.0028
Fluorine	lb	2.4E-07	2.4E-07
Fluosilicic acid	lb	3.2E-09	3.2E-09
Formaldehyde	lb	6.4E-11	6.4E-11
Formamide	lb	1.1E-16	1.1E-16
Formate	lb	4.9E-14	4.9E-14
Formic acid	lb	3.1E-17	3.1E-17
Furan	lb	1.4E-16	1.4E-16
Glutaraldehyde	lb	2.2E-12	2.2E-12
Glyphosate	lb	1.8E-12	1.8E-12
Glyphosate-trimesium	lb	1.4E-13	1.4E-13
Haloalkanes	lb	1.2E-13	1.2E-13
Heat, waste	MJ	0.0033	0.0033
Hexadecane	lb	4.8E-05	4.8E-05

		PP Part	LLDPE Part
Hexane	lb	2.4E-18	2.4E-18
Hexanoic acid	lb	1.7E-04	1.7E-04
Hydrocarbons, aliphatic, alkanes, unspecified	lb	7.2E-10	7.2E-10
Hydrocarbons, aliphatic, unsaturated	lb	6.7E-11	6.7E-11
Hydrocarbons, aromatic	lb	3.0E-09	3.0E-09
Hydrocarbons, unspecified	lb	2.9E-09	2.9E-09
Hydrogen-3, Tritium	Bq	1.02	1.02
Hydrogen chloride	lb	1.3E-12	1.3E-12
Hydrogen fluoride	lb	3.1E-15	3.1E-15
Hydrogen peroxide	lb	7.5E-13	7.5E-13
Hydrogen sulfide	lb	2.8E-09	2.8E-09
Hydroxide	lb	3.7E-11	3.7E-11
Hypochlorite	lb	2.8E-11	2.8E-11
Iodide	lb	5.6E-10	5.6E-10
Iodine-129	Bq	9.0E-06	9.0E-06
Iodine-131	Bq	2.4E-07	2.4E-07
Iodine-133	Bq	3.7E-08	3.7E-08
Iron	lb	0.11	0.11
Iron-59	Bq	1.0E-08	1.0E-08
Iron, ion	lb	3.7E-06	3.7E-06
Isopropylamine	lb	7.4E-17	7.4E-17
Lactic acid	lb	1.4E-16	1.4E-16
Lanthanum-140	Bq	6.3E-08	6.3E-08
Lead	lb	3.7E-04	3.7E-04
Lead-210	Bq	1.2E-05	1.2E-05
Lead-210/kg	lb	8.2E-14	8.3E-14
Lead 210	lb	8.9E-22	8.9E-22
Lithium, ion	lb	0.50	0.54
m-Xylene	lb	2.3E-05	2.4E-05
Magnesium	lb	0.41	0.42
Manganese	lb	0.0059	0.0057
Manganese-54	Bq	3.3E-06	3.3E-06
Mercury	lb	8.0E-07	7.8E-07
Metallic ions, unspecified	lb	2.6E-07	2.6E-07
Methane, dibromo-	lb	1.0E-18	1.0E-18
Methane, dichloro-, HCC-30	lb	5.9E-11	5.9E-11
Methane, monochloro-, R-40	lb	2.5E-08	2.6E-08
Methane, trichlorofluoro-, CFC-11	lb	4.6E-13	4.6E-13
Methanol	lb	5.3E-11	5.3E-11
Methyl acetate	lb	2.0E-17	2.0E-17
Methyl acrylate	lb	5.7E-13	5.7E-13
Methyl amine	lb	3.4E-16	3.4E-16
Methyl ethyl ketone	lb	5.0E-08	5.2E-08
Methyl formate	lb	5.0E-17	5.0E-17
Metolachlor	lb	5.2E-14	5.2E-14
Metribuzin	lb	1.3E-14	1.3E-14
Molybdenum	lb	1.8E-05	1.8E-05
Molybdenum-99	Bq	2.2E-08	2.2E-08
n-Hexacosane	lb	4.1E-07	4.3E-07
n-Hexadecane	lb	5.7E-15	5.7E-15

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 13. Cradle-to-Gate Waterborne Emissions for Injection Molded Plastic Parts (Per 1,000 pounds of fabricated plastic parts) (Page 3 of 4)

		PP Part	LLDPE Part
Naphthalene	lb	1.4E-05	1.4E-05
Naphthalene, 2-methyl-	lb	1.2E-05	1.2E-05
Naphthalenes, alkylated, unspecified	lb	1.3E-06	1.3E-06
Nickel	lb	1.7E-04	1.7E-04
Nickel, ion	lb	1.2E-07	1.2E-07
Niobium-95	Bq	9.9E-08	9.9E-08
Nitrate	lb	6.9E-08	6.9E-08
Nitrate compounds	lb	6.2E-13	6.2E-13
Nitric acid	lb	9.8E-16	9.8E-16
Nitrite	lb	1.5E-10	1.5E-10
Nitrobenzene	lb	1.6E-15	1.6E-15
Nitrogen	lb	0.0015	0.0015
Nitrogen, organic bound	lb	5.4E-09	5.4E-09
Nitrogen, total	lb	4.5E-04	4.3E-04
o-Cresol	lb	2.3E-05	2.3E-05
o-Xylene	lb	4.0E-06	4.1E-06
Octadecane	lb	1.2E-05	1.2E-05
Oils, unspecified	lb	0.022	0.023
Organic substances, unspecified	lb	4.3E-14	4.3E-14
p-Cresol	lb	2.4E-05	2.5E-05
p-Xylene	lb	4.0E-06	4.1E-06
PAH, polycyclic aromatic hydrocarbons	lb	8.1E-11	8.1E-11
Particulates, < 10 um	lb	1.6E-14	1.6E-14
Particulates, > 10 um	lb	2.7E-07	2.7E-07
Pendimethalin	lb	2.9E-13	2.9E-13
Phenanthrene	lb	3.7E-07	3.7E-07
Phenanthrenes, alkylated, unspecified	lb	5.3E-07	5.4E-07
Phenol	lb	0.0012	0.0012
Phenol, 2,4-dimethyl-	lb	2.2E-05	2.2E-05
Phenols, unspecified	lb	2.2E-04	2.4E-04
Phosphate	lb	3.5E-04	3.5E-04
Phosphorus	lb	1.6E-10	1.0E-04
Phosphorus compounds, unspecified	lb	8.7E-12	8.7E-12
Plutonium-alpha	Bq	2.5E-07	2.5E-07
Polonium-210	Bq	1.7E-05	1.7E-05
Potassium	lb	6.8E-12	6.8E-12
Potassium-40	Bq	4.6E-06	4.6E-06
Potassium, ion	lb	7.9E-07	7.9E-07
Process solvents, unspecified	lb	1.4E-14	1.0E-04
Propanal	lb	8.4E-17	8.4E-17
Propane, 1,2-dichloro-	lb	5.6E-21	5.6E-21
Propanol	lb	3.2E-16	3.2E-16
Propene	lb	5.4E-09	5.4E-09
Propionic acid	lb	2.4E-16	2.4E-16
Propylamine	lb	3.4E-17	3.4E-17
Propylene oxide	lb	6.6E-12	6.6E-12
Protactinium-234	Bq	6.6E-06	6.6E-06
Radioactive species, alpha emitters	Bq	2.9E-08	2.9E-08
Radioactive species, Nuclides, unspecified	Bq	26,043	25,099
Radium-224	Bq	2.8E-04	2.8E-04
Radium-226	Bq	0.0056	0.0056
Radium-226/kg	lb	2.9E-11	2.9E-11
Radium-228	Bq	5.6E-04	5.6E-04
Radium-228/kg	lb	1.5E-13	1.5E-13
Rubidium	lb	5.6E-11	5.6E-11
Ruthenium-103	Bq	4.6E-09	4.6E-09
Ruthenium-106	Bq	6.2E-08	6.2E-08
Scandium	lb	4.1E-10	4.1E-10
Selenium	lb	6.9E-05	6.7E-05
Silicon	lb	1.5E-05	1.5E-05
Silver	lb	0.0013	0.0013
Silver-110	Bq	1.7E-05	1.7E-05
Silver, ion	lb	5.2E-11	5.2E-11
Sodium-24	Bq	1.6E-07	1.6E-07
Sodium dichromate	lb	1.5E-07	1.5E-07
Sodium formate	lb	6.5E-14	6.5E-14
Sodium hydroxide	lb	2.5E-17	2.5E-17
Sodium, ion	lb	6.44	6.43
Solids, inorganic	lb	1.8E-07	1.8E-07
Solved solids	lb	18.4	18.4
Strontium	lb	0.043	0.043
Strontium-89	Bq	3.8E-07	3.8E-07
Strontium-90	Bq	0.0015	0.0015
Styrene	lb	1.0E-06	1.0E-06
Sulfate	lb	0.41	0.40
Sulfide	lb	1.0E-04	5.6E-05
Sulfite	lb	8.1E-11	8.1E-11
Sulfur	lb	0.0020	0.0021
Surfactants	lb	6.3E-05	3.3E-05
Surfactants, unspecified	lb	1.3E-04	1.6E-04
Suspended solids, unspecified	lb	4.68	4.75
t-Butyl methyl ether	lb	3.3E-11	3.3E-11
t-Butylamine	lb	3.8E-16	3.8E-16
Tar	lb	2.5E-20	2.5E-20
Technetium-99m	Bq	5.0E-07	5.0E-07
Tellurium-123m	Bq	6.9E-08	6.9E-08
Tellurium-132	Bq	1.3E-09	1.3E-09
Tetradecane	lb	1.9E-05	1.9E-05
Thallium	lb	6.4E-06	6.5E-06
Thorium-228	Bq	0.0011	0.0011
Thorium-230	Bq	9.0E-04	9.0E-04
Thorium-232	Bq	6.5E-07	6.5E-07
Thorium-234	Bq	6.6E-06	6.6E-06
Tin	lb	1.4E-04	1.4E-04
Tin, ion	lb	6.0E-09	6.0E-09
Titanium	lb	2.8E-12	2.8E-12
Titanium, ion	lb	4.7E-04	4.7E-04
TOC, Total Organic Carbon	lb	0.0010	0.0010
Toluene	lb	0.0011	0.0011
Toluene, 2-chloro-	lb	3.0E-16	3.0E-16

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 13. Cradle-to-Gate Waterborne Emissions for Injection Molded Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 4 of 4)

		PP Part	LLDPE Part
Tributyltin compounds	lb	6.4E-12	6.4E-12
Triethylene glycol	lb	9.8E-12	9.8E-12
Trifluralin	lb	1.7E-13	1.7E-13
Trimethylamine	lb	3.5E-17	3.5E-17
Tungsten	lb	1.1E-09	1.1E-09
Uranium-234	Bq	7.9E-06	7.9E-06
Uranium-235	Bq	1.3E-05	1.3E-05
Uranium-238	Bq	4.5E-05	4.5E-05
Uranium alpha	Bq	3.8E-04	3.8E-04
Urea	lb	1.1E-16	1.1E-16
Vanadium	lb	4.9E-05	3.6E-05
Vanadium, ion	lb	1.2E-08	1.2E-08
VOC, volatile organic compounds, unspecified origin	lb	2.0E-09	2.0E-09
Xylene	lb	5.2E-04	5.2E-04
Yttrium	lb	5.3E-06	5.4E-06
Zinc	lb	0.0014	0.0014
Zinc-65	Bq	2.2E-06	2.2E-06
Zinc, ion	lb	9.2E-08	9.2E-08
Zirconium-95	Bq	2.6E-08	2.6E-08

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

CHAPTER 3. THERMOFORMING

INTRODUCTION

This chapter describes the thermoforming plastic fabrication process and presents LCI results for 1,000 pounds of fabricated plastic in terms of energy requirements, solid wastes, and atmospheric and waterborne emissions. The production and combustion of fuels used for process and transportation energy and generation of U.S. grid electricity were modeled using data sets developed by Franklin for the U.S. LCI Database. The data for virgin PP are the ACC resin data revised in 2011.

THERMOFORMING UNIT PROCESS

Like injection molding, thermoforming is a principal fabrication technique for rapidly creating large quantities of plastic articles. This technique is relatively simple and well established. A sheet of extruded plastic is fed, usually on a roll or from an extruder, into a heated chamber where the plastic is softened. The sheet is then clamped over a negative mold while in a softened state and then cooled. A punch loosens the plastic forms and eliminates sheet webbing that may be recycled back into the process. Thin-gauge sheet or film is used in thermoforming to produce disposable/recyclable food, medical and general retail products such as containers, cups, lids, and trays. Thick-gauge sheet is used to produce larger, usually more permanent, items such as plastic pallet, truck beds, and spas.

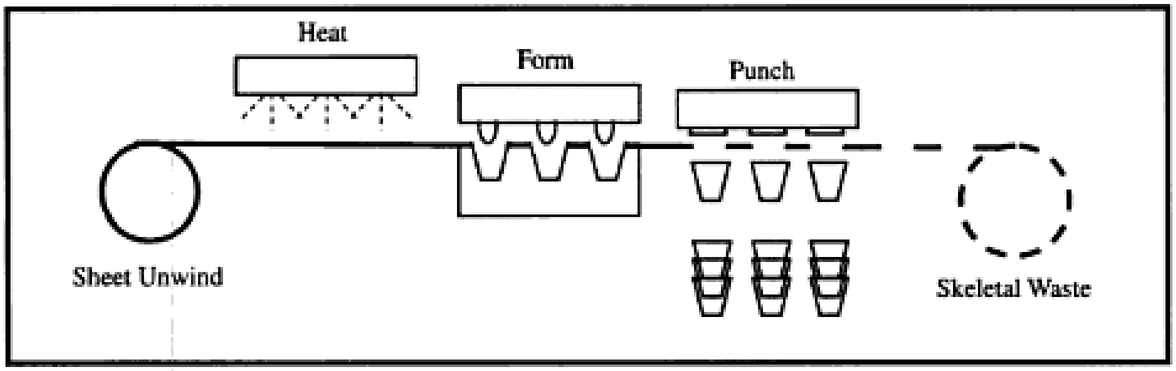

Figure 14. Main Stages of the Thermoforming Process per Hannay 2002 [12]

Though the mold limits the range of shapes available, this technique is particularly advantageous for thin-walled packaging, and/or large formings. Vacuum/pressure is utilized to prevent air traps, and plug-assisted devices are used to ensure uniform wall thickness and material distribution. The process may also be varied to make multilayer barriers and add heat resistance to the end product.

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[12] Hannay F. 2002. Rigid Plastics Packaging-Materials, Processes, and Applications. Smithers Rapra Publishing

Parameters having an influence on the specific energy consumption (SEC) for the thermoforming process are temperature-related, material-related, pressure/vacuum-related, and assisting plug-related. Temperature-related aspects are the heating temperature and heating time at the thermoforming machinery. Many thermoforming operations are continuous, meaning that sheet is extruded at the thermoforming step rather than purchased and inserted into the thermoforming machine on a roll. Continuous thermoforming can reduce overall SEC given that resin is heated once to form sheet and then formed while it is still in a softened state, rather than being heated twice (i.e., once to produce sheet and again to soften the purchased sheet at the thermoforming step).

The part's physical characteristics influencing overall energy requirements are the resin type, the weight of the part, and the shape of the part which determines the percentage of material input that becomes prompt scrap. The part's resin type determines the processing temperatures required for heating and cooling and these aspects can determine the optimal cycle time for producing one part. Given a specific thermoforming machine and mold size, the resin type and the dimensions of the resin sheet have significant influence on the heat requirements of the thermoforming process. Assisted plug-related aspects are variations in the plug material, moving speed, and moving distance or displacement. The wall thickness and uniformity of the thermoformed part can be influenced by these plug assistance-related parameters. Of course, plant management and operational characteristics, which determine machine downtimes and frequency of start-ups, vary among facilities and can also significantly influence SEC.

Thermoformed products generated by facilities providing data for this analysis were produced using sheet manufacturing equipment in combination with either vacuum form (VF) or pressure form (PF) equipment. All participating facilities use continuous thermoforming techniques. Nearly all of the weight, of thermoformed products represented by the LCI data, was formed from a PP-type resin. Product sizes produced by participating facilities varied but were largely produced from thin-gauge PP sheet.

The average participating facility produces several varieties of parts and annually produces about 281 pounds of parts per square foot of manufacturing floor space. In terms of process energy consumption, the average participating facility consumes electricity at molding equipment and/or for printing and decorating. Natural gas is largely consumed at the finishing steps, and other process fuels are consumed at this step and for molding equipment. The amount of incoming corrugated box material is equivalent to that coming out of the process as it is purchased to be used as shipping packaging for finished thermoformed items. An average of 149 pounds of rigid plastic part scrap is produced for every 1,000 pounds of thermoformed parts produced; this scrap is sold for recycling. The remaining solid waste generated from the facilities surveyed in this analysis is landfilled. For every 1,000 pounds of thermoformed plastic, 2.10 pounds of solid waste is sent to landfill. Of this solid waste, an average of 96 percent by mass is process waste such as contaminated resin scrap, hydraulic oil, and/or inks; while, five percent is packaging waste from incoming materials. Table 14 displays the weighted industry average LCI data compiled from the data collected in this study for the thermoforming unit process.

Table 14. LCI Unit Process Data for Thermoforming

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)			
Outputs to Technosphere								
Rigid Plastic Part	1,000	lb			1,000	kg		
Corrugate for Shipping	101	lb			101	kg		
Rigid Plastic Scrap	149	lb			149	kg		
Inputs from Technosphere (to Product)								
Virgin Resin	1,158	lb			1,158	kg		
Colorant	10.0	lb	*		10.0	kg		
Inputs from Technosphere (to Process)								
Corrugate for Shipping	101	lb			101	kg		
Process Water Consumption	100	gal	*		834	liter		
Energy Usage				**Total Energy Thousand Btu**				**Total Energy GigaJoules**
Process Energy								
Electricity (grid)	1,058	kwh		10,889	2,333	kwh		25.4
Natural gas	143	cu ft		160	8.93	cu meters		0.37
LPG	1.00	gal		108	8.34	liter		0.25
Gasoline	0.010	gal		1.42	0.083	liter		0.0033
Diesel	0.10	gal		15.9	0.83	liter		0.037
Total Process				11,050				25.7
Incoming Materials Transportation Energy								
Combination truck	76.1	ton-miles			245	tonne-km		
Diesel	0.80	gal		127	6.67	liter		0.30
Rail	669	ton-miles			2,154	tonne-km		
Diesel	1.66	gal		264	13.9	liter		0.61
Total Transportation				391				0.91
Environmental Emissions								
Atmospheric Emissions								
Particulates	0.0010	lb	*		0.0010	kg	*	
Solid Wastes								
Landfilled	2.10	lb			2.10	kg		

* This parameter was reported by fewer than three companies. To indicate known values while protecting the confidentiality of individual company responses, the parameter is reported only by order of magnitude.

Source: Franklin Associates, A Division of ERG

CRADLE-TO-GATE LCI RESULTS FOR THERMOFORMED PLASTIC PARTS

For thermoforming, the cradle-to-gate results tables and figures break out results by four main process steps: (1) production of the virgin resin inputs, (2) production of other material inputs, (3) transportation energy required for incoming materials, and (4) required processing energy input. The virgin resin data results are for ACC virgin resin data updated in 2011. Because nearly all products fabricated by facilities surveyed for this analysis are made of PP, only results for thermoforming of this resins are shown in this report. In the previous section, Table 14 shows the industrial average for mass of colorant material input to 1,000 pounds of plastic parts produced by thermoforming. However, not all thermoformed products are pigmented, and the material composition of colorant for polymers can vary widely in the industry. Colorants may be organic or inorganic, natural or synthetic, and have different toxicity properties depending on their composition. Because of this wide variability and the fact that no representative LCI data for colorants used in this application are available, the production of colorant is not included in the cradle-to-gate LCI results.

The other material input to the thermoforming process is corrugated fiber boxes used for shipping finished product. Corrugated fiber boxes are modeled using data adapted from the LCI of converted corrugated boxes published by the Corrugated Packaging Alliance (CPA) in 2009.[13] Though reported data indicated some lubricating oil used to maintain processing equipment, the amount is a fraction of one percent of the material inputs to this process and is not included.

Throughout the cradle-to-gate LCI results shown in the remainder of this chapter, the results for corrugated packaging (included in the results for “Other Materials”) correspond to the *average* amount of corrugated packaging reported in Table 14. The amount of corrugated packaging used for *specific* thermoformed products is expected to vary, depending on part size, configuration, number of parts per box, etc. When using the generic thermoforming data set to model specific product systems, actual packaging requirements should be used whenever possible.

Process energy is the energy used to extract, refine, and deliver electricity and/or fuels for combustion required at the thermoforming step. Transportation energy is the energy for the production and consumption of fuels used to deliver incoming materials to the thermoforming facility. The production and combustion of fuels used for process and transportation energy and generation of U.S. grid electricity were modeled using LCI data sets developed by Franklin for the U.S. LCI Database.

Energy Results

Cumulative energy consumption for production of rigid plastic parts produced by thermoforming is shown by energy category and process step for PP parts in Table 15 and Figure 15.

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[13] CPA (2010). Life Cycle Assessment of U.S. Industry-Average Corrugated Product, Final Report, Prepared for the Corrugated Packaging Alliance, A Joint Initiative of the American Forest & Paper Association, the Fibre Box Association, and the Association of Independent Corrugated Converters. Prepared by PE Americas and Five Winds International, December 30, 2009.

Table 15. Cradle-to-Gate Cumulative Energy Demand for Thermoformed PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	**TOTAL (1)**	**% TOTAL (1)**
Nuclear	0.42	0.069	0.0040	2.30	**2.79**	**6%**
Coal	1.10	0.19	0.010	08.1	**09.4**	**19%**
Natural Gas	22.2	0.14	0.020	2.24	**24.6**	**50%**
Petroleum	9.59	0.23	0.41	0.74	**11.0**	**22%**
Hydro	0.048	0.0073	4.6E-04	0.27	**0.32**	**1%**
Biomass	0.0010	0.77	9.9E-06	0.0058	**0.78**	**2%**
TOTAL (1)	**33.4**	**1.40**	**0.45**	**13.7**	**48.9**	
% TOTAL (1)	**68%**	**3%**	**<1%**	**28%**		

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

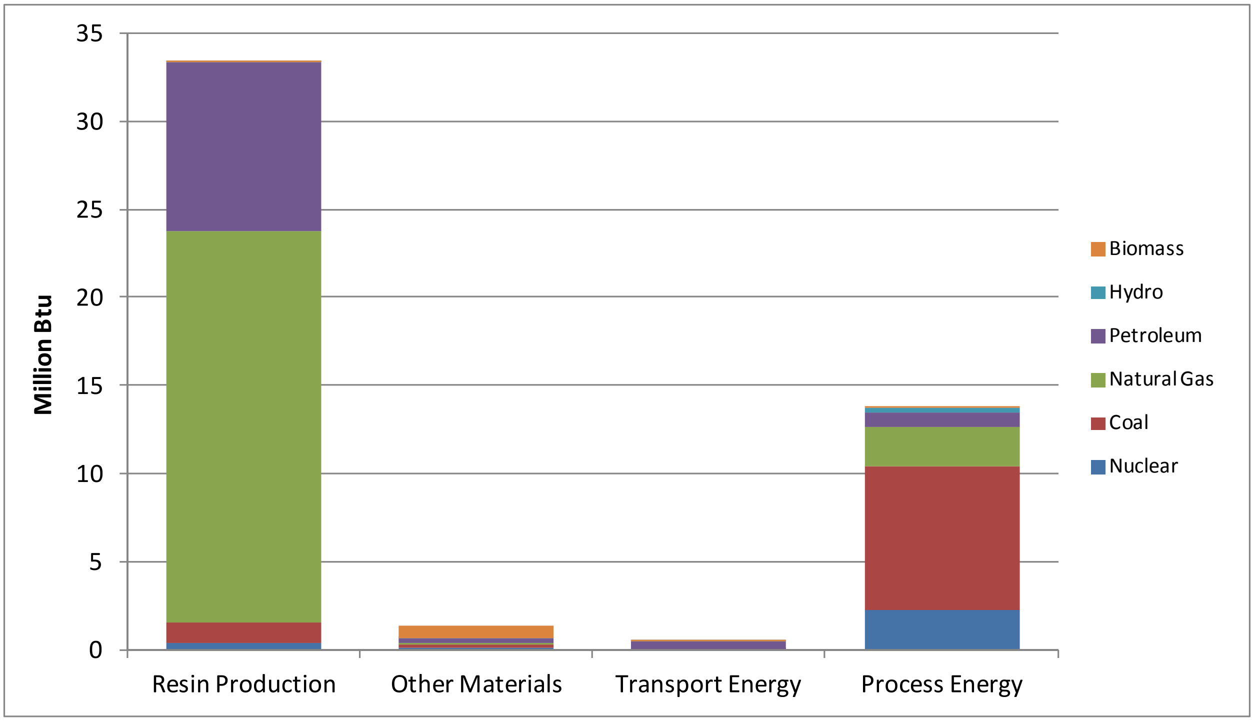

Figure 15. Cradle-to-Gate Cumulative Energy Demand for Thermoformed PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

The cradle-to-gate results show that total energy requirements for the fabrication step of producing rigid plastic parts by thermoforming are less than half of the energy requirements for producing the virgin resin input material. As shown in Table 16 and in Figure 16, 96 percent of energy requirements for the fabrication unit process (i.e., gate-to-gate process) are in providing electricity for thermoforming machinery, two percent of energy requirements are for delivery of materials to the facility by rail, and one percent of energy requirements are for natural gas supplied to finishing operations. The largest share of rail transport is required for delivery of incoming virgin resin materials.

Table 16. Unit Process Energy Demand for Thermoforming Plastic Parts
(Million Btu of energy per 1,000 pounds of fabricated plastic)

	Electricity Inputs	Natural Gas Inputs	Diesel Inputs	LPG Inputs	Gasoline Inputs	Rail Transport	Truck Transport	**TOTAL (1)**	**% TOTAL (1)**
Nuclear	2.30	4.2E-04	1.5E-04	9.3E-04	1.3E-05	0.0027	0.0013	**2.31**	**16%**
Coal	8.13	0.0011	3.9E-04	0.0025	3.4E-05	0.0070	0.0035	**8.14**	**58%**
Natural Gas	2.08	0.16	7.4E-04	0.0046	6.3E-05	0.013	0.0065	**2.26**	**16%**
Petroleum	0.63	5.7E-04	0.015	0.095	0.0013	0.28	0.13	**1.15**	**8%**
Hydro	0.27	4.9E-05	1.7E-05	1.1E-04	1.5E-06	3.1E-04	1.5E-04	**0.27**	**2%**
TOTAL (1)	**13.4**	**0.16**	**0.016**	**0.10**	**0.0014**	**0.30**	**0.15**	**14.1**	
% TOTAL (1)	**95%**	**1%**	**<1%**	**<1%**	**<1%**	**2%**	**<1%**		

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

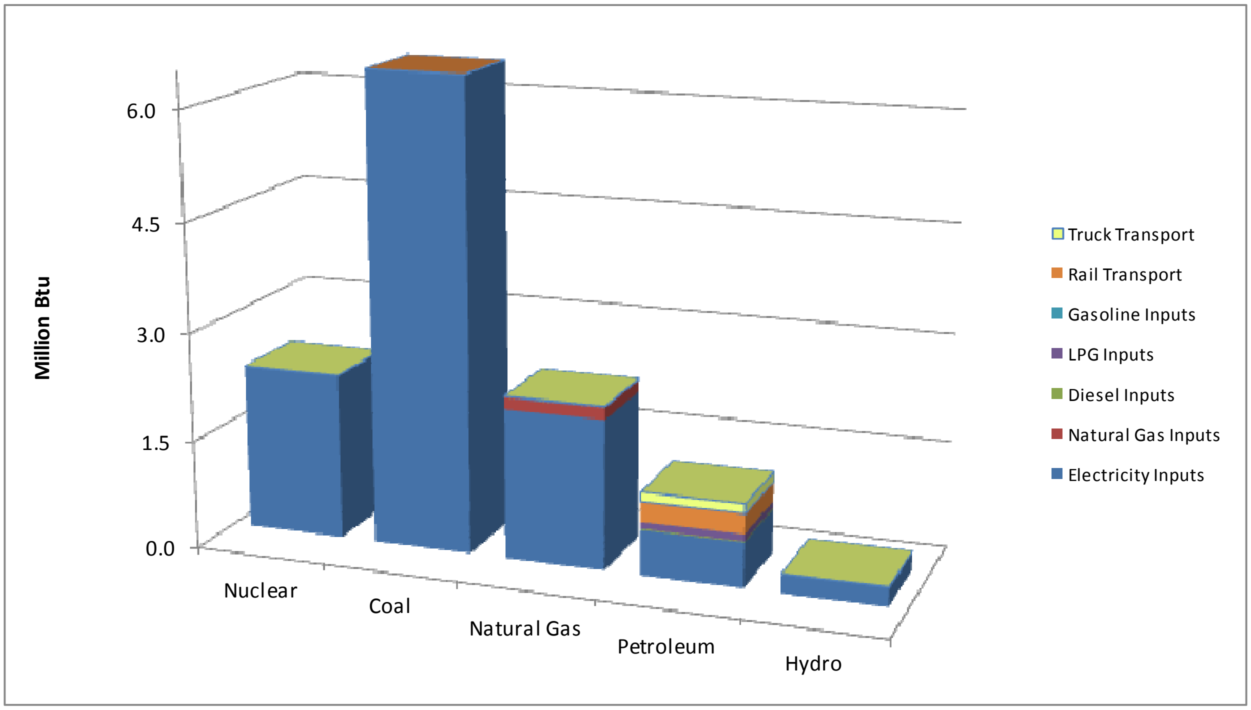

Figure 16. Unit Process Energy Demand for Thermoforming Plastic Parts
(Million Btu of energy per 1,000 pounds of fabricated plastic)

Much of the energy demand for production of virgin resin and other materials is energy of material resources (EMR). EMR is not an expended energy but 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 or corrugated fiber. Use of these material resources as a material input removes them as fuel resources from the energy pool; however, some of this energy remains embodied in the material produced. A detailed description of EMR methodology can be found in Chapter 1: LCI PRACTITIONER METHODOLOGY VARIATION. Table 17 and Figure 17 show the relative amounts of cradle-to-gate EMR versus non-EMR energy demand for thermoforming PP parts.

Table 17. EMR vs. Non-EMR Cradle-to-Gate Energy Demand for Thermoformed PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	TOTAL (1)	% TOTAL (1)
Expended Energy	11.5	0.68	0.45	13.7	**26.3**	**54%**
Natural Gas EMR	14.5	0.016	0	0	**14.5**	**30%**
Petroleum EMR	7.46	2.6E-04	0	0	**7.46**	**15%**
Biomass EMR	0	0.70	0	0	**0.70**	**1%**
TOTAL (1)	**33.4**	**1.40**	**0.45**	**13.7**	**48.9**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

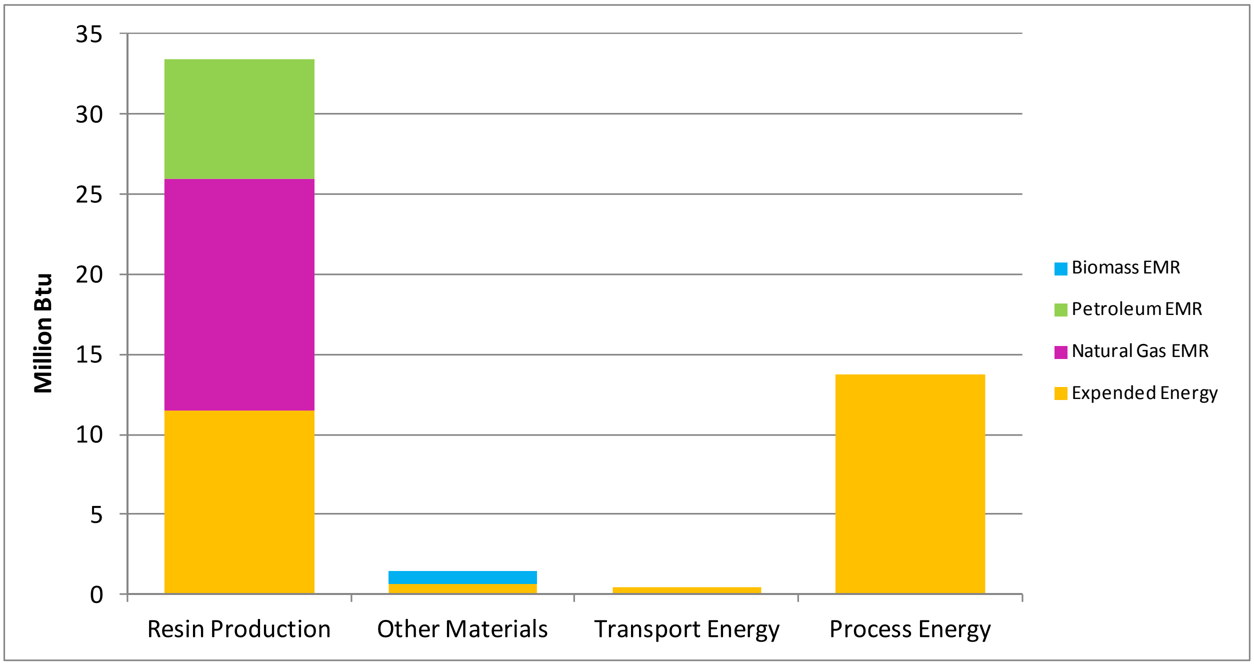

Figure 17. EMR vs. Non-EMR Cradle-to-Gate Energy Demand for Thermoformed PP Plastic Parts (Million Btu of energy per 1,000 pounds of fabricated plastic)

Water Use Results

Consumptive water use for cradle-to-gate production of rigid plastic parts produced by the thermoforming fabrication method is shown by process step in Table 18 and Figure 18.

Table 18. Cradle-to-Gate Water Use for Thermoformed PP Plastic Parts
(Gallons of water per 1,000 pounds of fabricated plastic)

	Resin Inputs	Other Materials	Transport Energy	Process Energy	**TOTAL (1)**
Per 1,000 lb PP Part	1,093	216	16.2	6.51	**1,332**
% TOTAL (1)	**82%**	**16%**	**1%**	**0%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

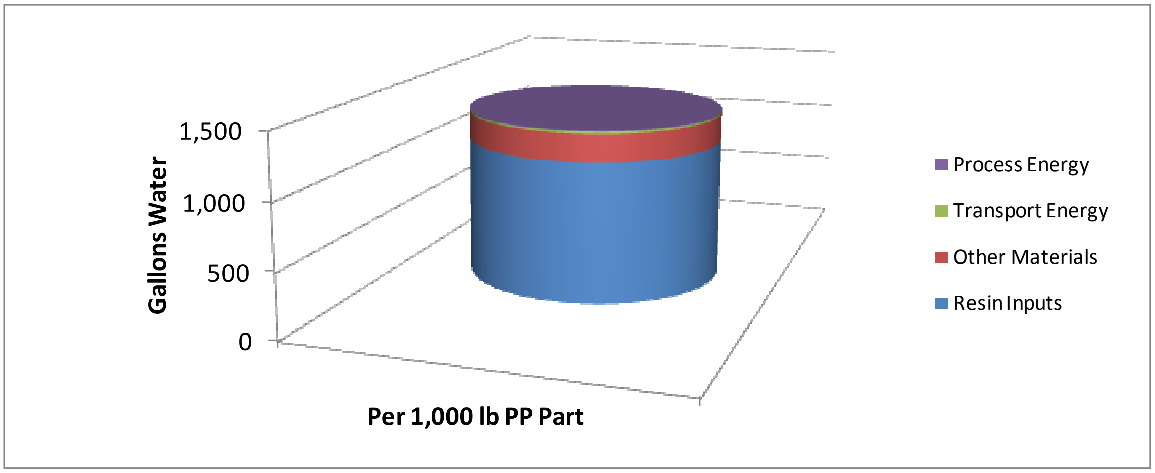

Figure 18. Cradle-to-Gate Water Use for Thermoformed PP Plastic Parts
(Gallons of water per 1,000 pounds of fabricated plastic)

The cradle-to-gate results show that the bulk of water is consumed in production of the virgin resin inputs. At the fabrication step, water consumed during production of other materials and incoming process water are the next largest contributing aspects to total water consumption. Water consumed at the thermoforming facility, 100 gallons per 1,000 pounds of fabricated plastic, is included in the 'other materials' assessment. The remaining 116 gallons in the 'other materials' step is consumed during the production of the corrugated fiber box material required for outgoing shipment of the thermoformed parts. The 'process energy' and 'transport energy' columns show water consumption associated with the steps to extract, process, and deliver the fuels used for process and transportation steps, including water consumption associated with electricity generation.

Solid Waste Results

Solid waste generation for cradle-to-gate production of rigid plastic parts produced by the thermoforming fabrication method is shown by process step in Table 19 and Figure 19.

Table 19. Cradle-to-Gate Solid Waste Generation for Thermoformed PP Plastic Parts
(Pounds of solid waste per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	Process Wastes	**TOTAL (1)**
Per 1,000 lb PP Part	130	19.2	1.68	238	2.10	**391**
% TOTAL (1)	**33%**	**5%**	**<1%**	**61%**	**<1%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

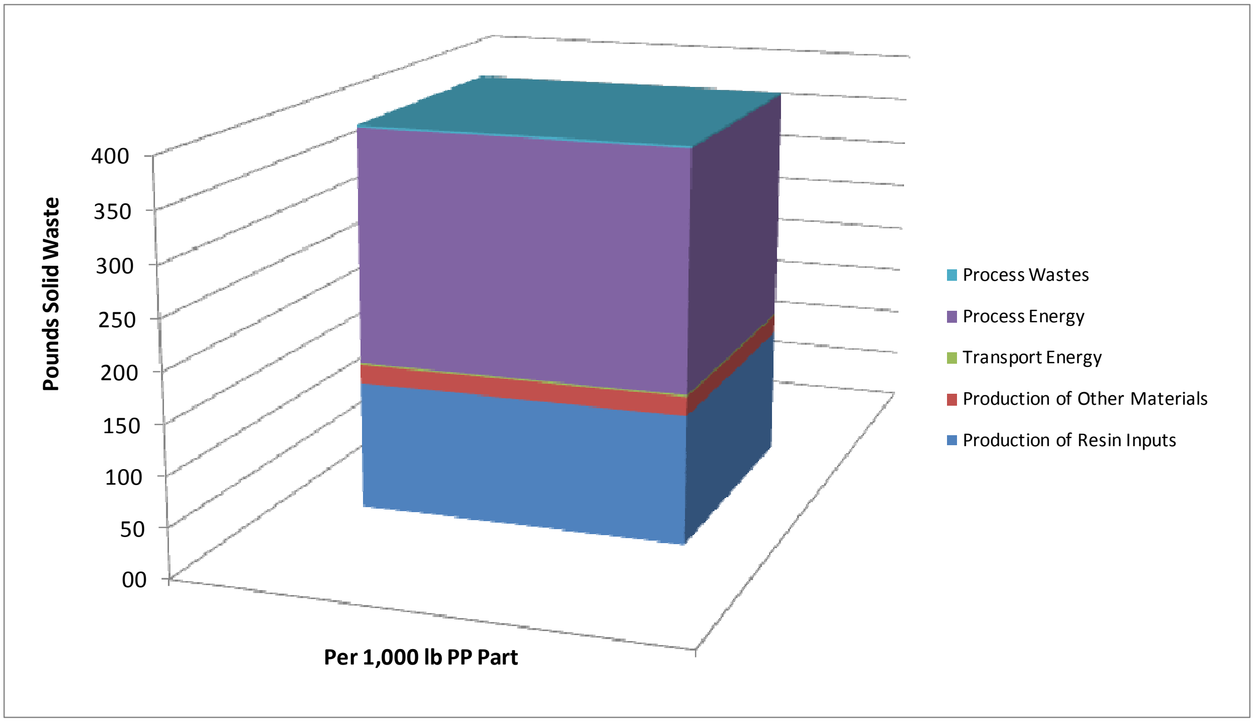

Figure 19. Cradle-to-Gate Solid Waste Generation for Thermoformed PP Plastic Parts
(Pounds of solid waste per 1,000 pounds of fabricated plastic)

The cradle-to-gate results for solid waste generation indicate that over half of total generation occurs during the production and combustion of the fuels required directly for operations and to produce electricity for operations at the thermoforming facility. The next largest portion of solid waste is that generated during the production of the virgin resin material inputs. Scrap that is put to some use on-site or by an off-site user is not included in the total solid waste generation inventory. Also, because this is a cradle-to-gate LCI analysis, (i.e., extends only through production of the fabricated plastic part) no postconsumer wastes are modeled. The disposition of a fabricated plastic product depends on the product application (packaging, durable product, etc.), its composition, access to recycling programs, and other product-specific factors that are outside the scope of a generic cradle-to-gate LCI.

Atmospheric and Waterborne Emissions

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels required for thermoforming rigid PP parts. The emissions tables in this section present emission quantities based upon the best data available. However, in the many unit processes included in the system models, some emissions data have been collected as reported from the industrial sources, some are estimated from EPA emission factors, and some have been calculated based on reaction chemistry or other information.

Atmospheric and waterborne emissions for each production of thermoformed PP plastic parts include emissions from (1) production of the virgin resin inputs, (2) production of other material inputs such as corrugated shipping packaging, (3) production and combustion of fuels during transportation of incoming materials, (4) production and combustion of required processing fuels and production of the required electricity at the thermoforming facility, and from (5) the thermoforming facility itself during plastics fabrication processes. Non-fuel related emissions at the thermoforming facility are particulate matter from the thermoforming process. The majority of atmospheric emissions are often related to the combustion of fuels during any of these steps, particularly in the case of greenhouse gas emissions, which are the focus of this discussion.

Greenhouse Gas (GHG) Emissions. The atmospheric emissions that typically contribute the majority of the total greenhouse gas impacts for product systems are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Greenhouse gas impacts are reported as carbon dioxide equivalents (CO_2 eq). Global warming potential (GWP) factors are used to convert emissions of individual greenhouse gases to the basis of CO_2 eq. The GWP of each greenhouse gas represents the relative global warming contribution of a pound of that substance compared to a pound of carbon dioxide. For each emission at each step of the cradle-to-gate thermoformed PP part, the weight of each greenhouse gas emitted is multiplied by its GWP, then the CO_2 eq for all the individual GHGs are added to arrive at the total CO_2 eq. GHG results for production of thermoformed plastic parts are shown in Table 20 and Figure 20.

The GWP factors that are most widely used are those from the International Panel on Climate Change (IPCC) Second Assessment Report (SAR), published in 1996. The IPCC SAR 100-year global warming potentials (GWP) are 21 for methane and 310 for nitrous oxide. Two subsequent updates of the IPCC report with slightly different GWPs have been published since the SAR; however, some reporting standards that were developed at the time of the SAR continue to use the SAR GWP factors.[14] In addition to GHG results based on IPCC SAR GWP factors, the tables in this report also show GHG results using IPCC 2007 GWP factors, which are 25 for methane and 298 for nitrous oxide. The total CO_2 eq using the 2007 factors is slightly higher than the CO_2 eq calculated using 1996 SAR factors.

Table 20. Cradle-to-Gate GHGs for Thermoformed PP Plastic Parts
(Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

	Production of Resin Inputs	Production of Other Materials	Transport Energy	Process Energy	TOTAL (1)	% TOTAL (1)
Fossil CO2	1,500	138	68.2	1,768	**3,475**	**87%**
Methane	400	5.71	3.33	98.5	**508**	**13%**
Nitrous Oxide	6.88	0.62	0.53	11.7	**19.8**	**<1%**
Others	0.16	0.41	0.0066	0.0028	**0.57**	**<1%**
TOTAL (1)	**1,908**	**145**	**72.1**	**1,878**	**4,003**	**100%**
% TOTAL (1)	**48%**	**4%**	**2%**	**47%**	**100%**	

(1) Totals may not sum due to rounding

Source: Franklin Associates, A Division of ERG

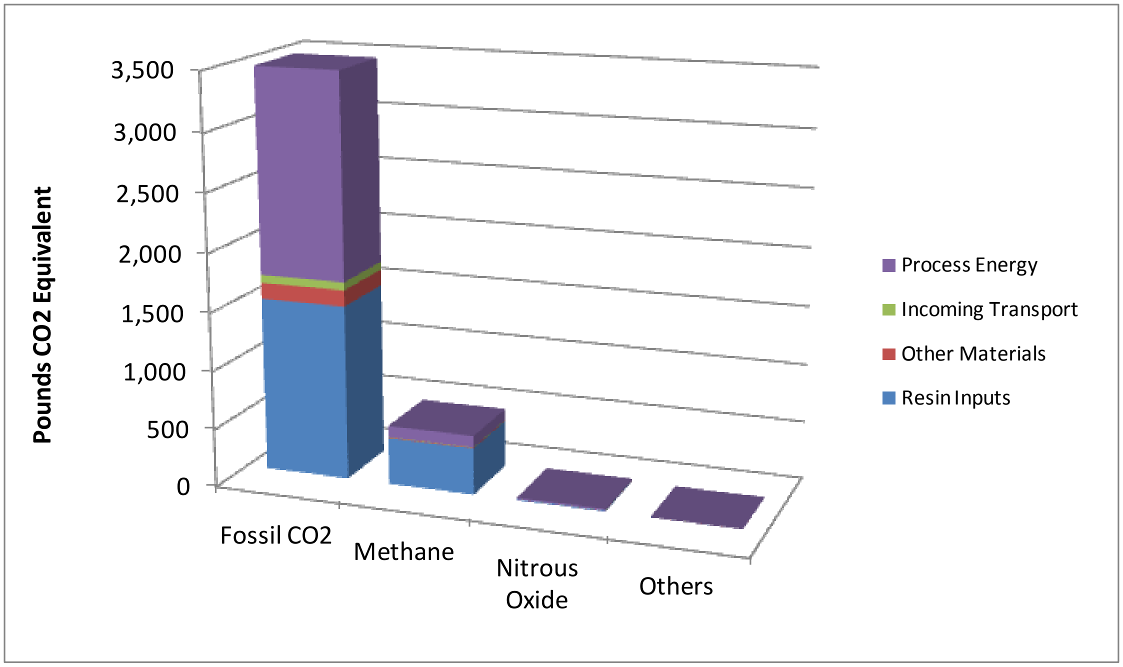

Figure 20. Cradle-to-Gate GHGs for Thermoformed PP Plastic Parts
(Pounds CO2 equivalents per 1,000 pounds of fabricated plastic)

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[14] The United Nations Framework Convention on Climate Change reporting guidelines for national inventories continue to use GWPs from the IPPC Second Assessment Report (SAR). For this reason, the U.S. EPA also uses GWPs from the IPCC SAR, as described on page ES-1 of EPA 430-R-08-005 **Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006** (April 15, 2008).

The results show that over half of the GHG emissions are associated with production of electricity and production and combustion of fuels used at the thermoforming facility. The production of virgin resin, which requires a substantial amount of fuels production and combustion, as well as some fugitive emissions of carbon dioxide and methane released during the extraction, transport, and processing of natural gas and crude oil feedstocks for resin production, produces the bulk of remaining GHG emissions. No GHG emissions were reported for the process at the injection molding facility; the only GHG emissions from these operations are associated with incoming transport or process energy inputs. The breakout by GHG shows, again, that carbon dioxide emissions are the largest contributors to the global warming potential (GWP) of the GHGs; methane emissions have the second largest contribution and nitrous oxide emissions the third largest contribution. Several other emissions from the cradle-to-gate plastic fabrication systems are GHGs (e.g., sulfur hexafluoride, CFCs, and HCFCs) but their cumulative amounts and associated contribution to the overall GWP is less than one percent.

Other Atmospheric and Waterborne Emissions. Tables showing the full list of atmospheric and waterborne emissions for cradle-to-gate thermoformed PP product are shown in Table 21 and Table 22, respectively.

Table 21. Cradle-to-Gate Atmospheric Emissions for Thermoformed PP Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 1 of 4)

		PP Part
1-Butanol	lb	3.0E-17
1-Pentanol	lb	2.4E-17
1-Pentene	lb	1.8E-17
1-Propanol	lb	3.3E-15
1,4-Butanediol	lb	6.4E-16
2-Aminopropanol	lb	2.0E-17
2-Butene, 2-methyl-	lb	4.0E-21
2-Chloroacetophenone	lb	3.8E-09
2-Methyl-1-propanol	lb	6.6E-17
2-Nitrobenzoic acid	lb	3.5E-17
2-Propanol	lb	9.9E-12
2,4-D	lb	8.6E-13
4-Methyl-2-pentanone	lb	8.4E-05
5-methyl Chrysene	lb	8.3E-09
Acenaphthene	lb	1.9E-07
Acenaphthylene	lb	9.4E-08
Acetaldehyde	lb	6.6E-04
Acetic acid	lb	2.6E-10
Acetic acid, methyl ester	lb	4.5E-15
Acetone	lb	6.0E-04
Acetonitrile	lb	1.8E-13
Acetophenone	lb	8.1E-09
Acid gases	lb	7.8E-19
Acidity, unspecified	lb	3.3E-12
Acids, unspecified	lb	1.4E-11
Acrolein	lb	0.0011
Acrylic acid	lb	2.6E-14
Actinides, radioactive, unspecified	Bq	1.7E-08
Aerosols, radioactive, unspecified	Bq	1.9E-07
Alachlor	lb	6.2E-13
Aldehydes, unspecified	lb	0.0017
alpha-Pinene	lb	0.0019
Aluminium	lb	2.1E-08
Aluminum	lb	4.6E-17
Ammonia	lb	0.012
Ammonium carbonate	lb	1.2E-13
Ammonium chloride	lb	0.0010
Ammonium, ion	lb	1.2E-16
Aniline	lb	2.8E-16
Anthracene	lb	7.9E-08
Anthranilic acid	lb	2.6E-17
Antimony	lb	8.2E-06
Antimony-124	Bq	2.5E-11
Antimony-125	Bq	1.6E-10
Argon-41	Bq	1.3E-04
Arsenic	lb	1.7E-04
Arsenic trioxide	lb	3.7E-19
Arsine	lb	3.1E-17
Barium	lb	6.6E-06
Barium-140	Bq	1.0E-08
Bentazone	lb	5.2E-13
Benzal chloride	lb	3.1E-20
Benzaldehyde	lb	8.6E-14
Benzene	lb	0.11
Benzene, 1-methyl-2-nitro-	lb	3.1E-17
Benzene, 1,2-dichloro-	lb	6.6E-16
Benzene, 1,2,4-trichloro-	lb	5.2E-05
Benzene, 1,3,5-trimethyl-	lb	7.7E-19
Benzene, chloro-	lb	1.2E-08
Benzene, ethyl-	lb	0.013
Benzene, hexachloro-	lb	2.5E-12
Benzene, pentachloro-	lb	4.7E-14
Benzo(a)anthracene	lb	3.0E-08
Benzo(a)pyrene	lb	5.1E-08
Benzo(b)fluoranthene	lb	4.5E-17
Benzo(b,j,k)fluoranthene	lb	4.1E-08
Benzo(ghi)perylene	lb	1.0E-08
Benzyl chloride	lb	3.8E-07
Beryllium	lb	8.7E-06
Bicyclo[3.1.1]heptane, 6,6-dimethyl-2-	lb	0.0011
Biphenyl	lb	6.4E-07
Boron	lb	4.4E-10
Boron trifluoride	lb	4.1E-21
Bromine	lb	5.0E-11
Bromoform	lb	2.1E-08
Bromoxynil	lb	7.0E-13
BTEX (Benzene, Toluene, Ethylbenzene,	lb	1.1E-11
Butadiene	lb	2.5E-06
Butane	lb	6.5E-09
Butene	lb	1.3E-10
Butyrolactone	lb	1.5E-16
Cadmium	lb	3.0E-05
Calcium	lb	7.8E-10
Carbon-14	Bq	0.0013
Carbon dioxide	lb	0.14
Carbon dioxide, biogenic	lb	154
Carbon dioxide, fossil	lb	3,475
Carbon dioxide, land transformation	lb	0.0020
Carbon disulfide	lb	7.7E-08
Carbon monoxide	lb	7.92
Carbon monoxide, biogenic	lb	2.9E-09
Carbon monoxide, fossil	lb	1.12
Carbonyl sulfide	lb	3.4E-11
Cerium-141	Bq	2.5E-09
Cesium-134	Bq	7.9E-09
Cesium-137	Bq	1.8E-08
Chloramine	lb	1.3E-16
Chloride	lb	1.9E-12
Chlorinated fluorocarbons and hydrochl	lb	3.7E-12
Chlorine	lb	1.6E-04

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 21. Cradle-to-Gate Atmospheric Emissions for Thermoformed PP Plastic Parts (Per 1,000 pounds of fabricated plastic parts) (Page 2 of 4)

		PP Part
Chloroacetic acid	lb	1.3E-04
Chloroform	lb	3.6E-11
Chlorosilane, trimethyl-	lb	2.5E-16
Chlorosulfonic acid	lb	2.3E-13
Chlorpyrifos	lb	1.1E-04
Chromium	lb	1.6E-10
Chromium-51	Bq	3.0E-05
Chromium VI	lb	1.3E-12
Chromium, ion	lb	3.8E-08
Chrysene	lb	1.2E-13
Clomazone	lb	7.7E-05
Cobalt	lb	2.7E-10
Cobalt-58	Bq	3.2E-09
Cobalt-60	Bq	9.7E-07
Copper	lb	9.0E-09
Cumene	lb	1.3E-06
Cyanide	lb	2.0E-16
Cyanoacetic acid	lb	4.5E-15
Cyclohexane	lb	8.6E-05
D-limonene	lb	1.4E-17
Dibenz(a,h)anthracene	lb	3.0E-21
Diethanolamine	lb	1.3E-16
Diethylamine	lb	2.5E-16
Dimethyl malonate	lb	0.0018
Dimethyl sulfide	lb	0.066
Dinitrogen monoxide	lb	8.9E-08
Dioxins, measured as 2,3,7,8-tetra-chlorodibenzo-p-dioxin	lb	7.4E-17
Dipropylamine	lb	7.4E-17
Ethane	lb	1.1E-08
Ethane, 1,1-difluoro-, HFC-152a	lb	5.8E-14
Ethane, 1,1,1-trichloro-, HCFC-140	lb	1.1E-08
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	lb	1.5E-11
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	lb	1.2E-15
Ethane, 1,2-dibromo-	lb	6.4E-10
Ethane, 1,2-dichloro-	lb	2.2E-08
Ethane, 1,2-dichloro-1,1,2-trifluoro-, HCFC-123	lb	8.8E-14
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	lb	1.7E-12
Ethane, chloro-	lb	2.3E-08
Ethane, hexafluoro-, HFC-116	lb	9.6E-10
Ethanol	lb	3.0E-11
Ethene	lb	7.1E-10
Ethene, chloro-	lb	3.6E-11
Ethene, tetrachloro-	lb	1.7E-05
Ethyl acetate	lb	4.6E-11
Ethyl cellulose	lb	9.3E-14
Ethylamine	lb	8.0E-17
Ethylene diamine	lb	3.5E-16
Ethylene dibromide	lb	2.2E-06
Ethylene oxide	lb	4.5E-12
Ethyne	lb	3.9E-11
Fluoranthene	lb	2.7E-07
Fluorene	lb	3.4E-07
Fluoride	lb	4.7E-05
Fluorine	lb	3.7E-08
Fluosilicic acid	lb	1.8E-09
Formaldehyde	lb	0.0014
Formamide	lb	4.4E-17
Formic acid	lb	1.3E-12
Furan	lb	1.7E-09
Glyphosate	lb	4.1E-11
Glyphosate-trimesium	lb	3.4E-12
Heat, waste	Btu	6,387
Helium	lb	5.1E-10
Heptane	lb	1.3E-09
Hexamethylene diamine	lb	7.0E-18
Hexane	lb	7.0E-06
Hydrazine, methyl-	lb	9.1E-08
Hydrocarbons, aliphatic, alkanes, cyclic	lb	7.5E-13
Hydrocarbons, aliphatic, alkanes, unspecified	lb	1.6E-08
Hydrocarbons, aliphatic, unsaturated	lb	2.6E-09
Hydrocarbons, aromatic	lb	1.2E-08
Hydrocarbons, chlorinated	lb	9.3E-12
Hydrocarbons, unspecified	lb	0.072
Hydrogen	lb	0.0054
Hydrogen-3, Tritium	Bq	0.0053
Hydrogen bromide	lb	2.3E-14
Hydrogen chloride	lb	0.46
Hydrogen cyanide	lb	1.1E-12
Hydrogen fluoride	lb	0.056
Hydrogen iodide	lb	2.5E-17
Hydrogen peroxide	lb	6.9E-14
Hydrogen sulfide	lb	7.2E-08
Indeno(1,2,3-cd)pyrene	lb	2.3E-08
Iodine	lb	2.4E-11
Iodine-129	Bq	1.0E-06
Iodine-131	Bq	2.5E-05
Iodine-133	Bq	1.4E-08
Iodine-135	Bq	3.7E-09
Iron	lb	6.6E-06
Isocyanic acid	lb	9.2E-13
Isophorone	lb	3.1E-07
Isoprene	lb	5.0E-11
Isopropylamine	lb	3.1E-17
Kerosene	lb	5.0E-04
Krypton-85	Bq	2.2E-04
Krypton-85m	Bq	1.05
Krypton-87	Bq	3.5E-05
Krypton-88	Bq	4.6E-05
Krypton-89	Bq	1.9E-05

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 21. Cradle-to-Gate Atmospheric Emissions for Thermoformed PP Plastic Parts (Per 1,000 pounds of fabricated plastic parts) (Page 3 of 4)

		PP Part
Lactic acid	lb	5.8E-17
Lanthanum-140	Bq	8.8E-10
Lead	lb	1.8E-04
Lead-210	Bq	4.8E-06
Lead compounds	lb	9.1E-19
m-Xylene	lb	1.6E-12
Magnesium	lb	0.0041
Manganese	lb	3.0E-04
Manganese-54	Bq	8.2E-11
Mercaptans, unspecified	lb	1.1E-04
Mercury	lb	3.5E-05
Metals, unspecified	lb	0.0023
Methacrylic acid, methyl ester	lb	1.1E-08
Methane	lb	2.75
Methane, biogenic	lb	3.4E-09
Methane, bromo-, Halon 1001	lb	8.6E-08
Methane, bromochlorodifluoro-, Halon 1211	lb	8.9E-13
Methane, bromotrifluoro-, Halon 1301	lb	4.1E-12
Methane, chlorodifluoro-, HCFC-22	lb	1.0E-06
Methane, chlorotrifluoro-, CFC-13	lb	1.2E-05
Methane, dichloro-, HCC-30	lb	1.6E-04
Methane, dichlorodifluoro-, CFC-12	lb	3.7E-09
Methane, dichlorofluoro-, HCFC-21	lb	8.9E-18
Methane, fossil	lb	17.6
Methane, monochloro-, R-40	lb	2.8E-07
Methane, tetrachloro-, CFC-10	lb	2.4E-06
Methane, tetrafluoro-, CFC-14	lb	9.6E-09
Methane, trichlorofluoro-, CFC-11	lb	3.9E-13
Methane, trifluoro-, HFC-23	lb	2.8E-15
Methanesulfonic acid	lb	2.0E-16
Methanol	lb	0.012
Methyl acetate	lb	8.2E-18
Methyl acrylate	lb	2.9E-14
Methyl amine	lb	1.4E-16
Methyl borate	lb	1.0E-17
Methyl ethyl ketone	lb	1.1E-04
Methyl formate	lb	1.2E-16
Methyl lactate	lb	6.4E-17
Methyl mercaptan	lb	2.2E-04
Methyl methacrylate	lb	1.8E-16
Metolachlor	lb	1.2E-12
Metribuzin	lb	3.0E-13
Molybdenum	lb	2.9E-11
Monoethanolamine	lb	1.6E-09
Naphthalene	lb	2.5E-05
Nickel	lb	6.6E-04
Niobium-95	Bq	9.8E-12
Nitrate	lb	1.5E-11
Nitric oxide	lb	1.6E-13
Nitrobenzene	lb	4.0E-16
Nitrogen	lb	2.2E-09
Nitrogen dioxide	lb	2.0E-05
Nitrogen oxides	lb	9.05
Nitrogen, total	lb	2.7E-13
Nitrous oxide	lb	5.5E-04
NMVOC, non-methane volatile organic comp	lb	1.38
Noble gases, radioactive, unspecified	Bq	9.35
Octane	lb	2.0E-12
Odorous sulfur	lb	4.2E-14
Organic acids	lb	3.8E-06
Organic substances, unspecified	lb	0.014
Oxygen	lb	1.2E-08
Ozone	lb	9.1E-10
PAH, polycyclic aromatic hydrocarbons	lb	1.1E-05
Palladium	lb	2.0E-23
Particulates, < 10 um	lb	1.41
Particulates, < 2.5 um	lb	0.25
Particulates, > 10 um	lb	9.1E-07
Particulates, > 2.5 um, and < 10um	lb	0.23
Particulates, unspecified	lb	1.48
Pendimethalin	lb	6.7E-12
Pentane	lb	8.2E-09
Phenanthrene	lb	1.0E-06
Phenol	lb	1.0E-04
Phenol, 2,4-dichloro-	lb	5.3E-17
Phenol, pentachloro-	lb	6.6E-11
Phenols, unspecified	lb	3.5E-05
Phosphate	lb	4.8E-15
Phosphine	lb	2.3E-17
Phosphorus	lb	3.4E-10
Phthalate, dioctyl-	lb	3.9E-08
Platinum	lb	3.4E-17
Plutonium-238	Bq	1.3E-13
Plutonium-alpha	Bq	3.1E-12
Polonium-210	Bq	8.4E-06
Polychlorinated biphenyls	lb	3.0E-12
Polycyclic organic matter, unspecified	lb	2.9E-05
Potassium	lb	0.0012
Potassium-40	Bq	1.0E-06
Propanal	lb	2.0E-07
Propane	lb	7.6E-09
Propene	lb	1.6E-04
Propionic acid	lb	1.0E-11
Propylamine	lb	1.4E-17
Propylene oxide	lb	4.2E-06
Protactinium-234	Bq	1.6E-07
Pyrene	lb	1.2E-07
Radioactive species, other beta emitters	Bq	6.4E-06
Radioactive species, unspecified	Bq	9.6E+06
Radionuclides (Including Radon)	lb	0.028

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 21. Cradle-to-Gate Atmospheric Emissions for Thermoformed PP Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 4 of 4)

		PP Part			PP Part
Radium-226	Bq	6.5E-06	Thorium-234	Bq	1.6E-07
Radium-228	Bq	2.1E-06	Tin	lb	1.2E-10
Radon-220	Bq	2.9E-05	Tin oxide	lb	7.9E-20
Radon-222	Bq	21.6	Titanium	lb	2.2E-10
Rhodium	lb	1.9E-23	TOC, Total Organic Carbon	lb	2.2E-04
Ruthenium-103	Bq	2.1E-12	Toluene	lb	0.17
Scandium	lb	4.4E-12	Toluene, 2-chloro-	lb	1.6E-16
Selenium	lb	4.9E-04	Toluene, 2,4-dinitro-	lb	1.5E-10
Silicon	lb	2.3E-09	Trichloroethane	lb	3.2E-09
Silicon tetrafluoride	lb	2.4E-14	Trifluralin	lb	6.7E-12
Silver	lb	2.0E-13	Trimethylamine	lb	1.5E-17
Silver-110	Bq	2.1E-11	Tungsten	lb	4.9E-13
Sodium	lb	2.7E-05	Uranium	lb	1.7E-13
Sodium chlorate	lb	2.8E-13	Uranium-234	Bq	2.0E-06
Sodium dichromate	lb	3.1E-13	Uranium-235	Bq	3.5E-07
Sodium formate	lb	2.7E-14	Uranium-238	Bq	3.0E-06
Sodium hydroxide	lb	2.6E-13	Uranium alpha	Bq	8.9E-06
Strontium	lb	2.3E-11	Used air	lb	2.7E-05
Styrene	lb	4.5E-05	Vanadium	lb	2.0E-10
Sulfate	lb	6.7E-09	Vinyl acetate	lb	4.1E-09
Sulfur dioxide	lb	15.5	VOC, volatile organic compounds	lb	1.09
Sulfur hexafluoride	lb	7.6E-12	Water	lb	1.5E-05
Sulfur oxides	lb	2.50	Xenon-131m	Bq	1.8E-04
Sulfur trioxide	lb	3.4E-15	Xenon-133	Bq	0.0068
Sulfur, total reduced	lb	0.0092	Xenon-133m	Bq	8.1E-06
Sulfuric acid	lb	1.2E-13	Xenon-135	Bq	0.0027
Sulfuric acid, dimethyl ester	lb	2.6E-08	Xenon-135m	Bq	0.0017
t-Butyl methyl ether	lb	2.0E-08	Xenon-137	Bq	5.1E-05
t-Butylamine	lb	1.6E-16	Xenon-138	Bq	3.9E-04
Tar	lb	1.7E-18	Xylene	lb	0.097
Tellurium	lb	1.7E-13	Zinc	lb	8.3E-06
Terpenes	lb	0.0066	Zinc-65	Bq	4.1E-10
Thallium	lb	1.6E-12	Zinc oxide	lb	1.6E-19
Thorium	lb	1.4E-13	Zirconium	lb	2.0E-13
Thorium-228	Bq	2.9E-07	Zirconium-95	Bq	4.0E-10
Thorium-230	Bq	6.2E-07			
Thorium-232	Bq	3.0E-07			

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 22. Cradle-to-Gate Waterborne Emissions for Thermoformed PP Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 1 of 4)

		PP Part			PP Part
1-Butanol	lb	1.7E-13	Benzene, pentamethyl-	lb	5.6E-08
1-Pentanol	lb	5.8E-17	Benzenes, alkylated, unspecified	lb	8.1E-05
1-Pentene	lb	4.4E-17	Benzo(a)anthracene	lb	3.3E-15
1,4-Butanediol	lb	2.5E-16	Benzo(b)fluoranthene	lb	3.7E-15
2-Aminopropanol	lb	5.0E-17	Benzoic acid	lb	9.3E-04
2-Hexanone	lb	6.0E-06	Beryllium	lb	1.1E-05
2-Methyl-1-propanol	lb	1.6E-16	Biphenyl	lb	5.3E-06
2-Methyl-2-butene	lb	9.7E-21	BOD5, Biological Oxygen Demand	lb	0.44
2-Propanol	lb	4.6E-13	Borate	lb	6.4E-15
2,4-D	lb	3.7E-14	Boron	lb	0.0029
4-Methyl-2-pentanone	lb	3.1E-06	Bromate	lb	3.0E-10
Acenaphthene	lb	4.9E-14	Bromide	lb	0.16
Acenaphthylene	lb	7.8E-15	Bromine	lb	4.6E-09
Acetaldehyde	lb	9.5E-13	Butene	lb	4.8E-14
Acetic acid	lb	1.4E-11	Butyl acetate	lb	2.2E-13
Acetone	lb	7.5E-06	Butyrolactone	lb	3.7E-16
Acetonitrile	lb	1.7E-16	Cadmium	lb	1.8E-11
Acetyl chloride	lb	4.6E-17	Cadmium, ion	lb	3.3E-05
Acidity, unspecified	lb	5.5E-05	Calcium, ion	lb	2.52
Acids, unspecified	lb	1.2E-10	Carbon-14	Bq	1.4E-06
Acrylate, ion	lb	6.1E-14	Carbon disulfide	lb	1.6E-15
Acrylonitrile	lb	4.1E-16	Carbonate	lb	8.9E-10
Actinides, radioactive, unspecified	Bq	1.6E-06	Carboxylic acids, unspecified	lb	2.3E-08
Alachlor	lb	2.7E-14	Cerium-141	Bq	1.1E-08
Aldehydes (unspecified)	lb	2.3E-19	Cerium-144	Bq	3.3E-09
Aluminium	lb	1.2E-06	Cesium	lb	5.6E-12
Aluminum	lb	0.061	Cesium-134	Bq	1.7E-06
Americium-241	Bq	2.8E-08	Cesium-136	Bq	1.9E-09
Ammonia	lb	0.019	Cesium-137	Bq	2.0E-04
Ammonia, as N	lb	5.0E-04	Chloramine	lb	1.1E-15
Ammonium, ion	lb	2.2E-04	Chlorate	lb	2.3E-09
Aniline	lb	6.8E-16	Chloride	lb	29.2
Anthracene	lb	3.9E-15	Chlorinated solvents, unspecified	lb	1.3E-12
Antimony	lb	3.3E-05	Chlorine	lb	7.7E-11
Antimony-122	Bq	6.1E-09	Chloroacetic acid	lb	3.6E-12
Antimony-124	Bq	4.7E-07	Chloroacetyl chloride	lb	6.6E-17
Antimony-125	Bq	4.5E-07	Chloroform	lb	3.5E-15
Antimony compounds	lb	1.1E-19	Chlorosulfonic acid	lb	6.1E-16
AOX, Adsorbable Organic Halogen as Cl	lb	4.1E-04	Chlorpyrifos	lb	9.8E-15
Arsenic	lb	2.3E-12	Chromium	lb	0.0012
Arsenic, ion	lb	2.1E-04	Chromium-51	Bq	2.0E-06
Barite	lb	1.8E-08	Chromium VI	lb	1.3E-06
Barium	lb	0.74	Chromium, ion	lb	2.1E-04
Barium-140	Bq	2.7E-08	Chrysene	lb	1.9E-14
Bentazone	lb	2.2E-14	Clomazone	lb	5.1E-15
Benzene	lb	0.0013	Cobalt	lb	2.0E-05
Benzene, 1-methyl-4-(1-methylethyl)-	lb	7.4E-08	Cobalt-57	Bq	6.1E-08
Benzene, 1,2-dichloro-	lb	7.5E-14	Cobalt-58	Bq	9.2E-06
Benzene, chloro-	lb	1.5E-12	Cobalt-60	Bq	1.4E-05
Benzene, ethyl-	lb	8.4E-05	COD, Chemical Oxygen Demand	lb	0.50

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 22. Cradle-to-Gate Waterborne Emissions for Thermoformed PP Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
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		PP Part
Copper	lb	6.9E-05
Copper, ion	lb	3.3E-04
Cresol	lb	2.1E-17
Cumene	lb	1.5E-08
Curium alpha	Bq	3.7E-08
Cyanide	lb	5.5E-08
Cyclohexane	lb	4.6E-17
Decane	lb	2.7E-05
Detergent, oil	lb	5.2E-04
Detergents, unspecified	lb	1.9E-14
Dibenzofuran	lb	1.4E-07
Dibenzothiophene	lb	1.3E-07
Dichromate	lb	1.1E-12
Diethylamine	lb	3.2E-16
Dimethylamine	lb	1.7E-15
Dioxins, measured as 2,3,7,8-tetrachlorodiben	lb	1.2E-19
Dipropylamine	lb	1.8E-16
Dissolved organics	lb	2.7E-17
Dissolved solids	lb	9.87
DOC, Dissolved Organic Carbon	lb	4.4E-06
Docosane	lb	8.0E-07
Dodecane	lb	5.1E-05
Eicosane	lb	1.4E-05
Ethane, 1,2-dichloro-	lb	3.6E-13
Ethanol	lb	4.3E-13
Ethene	lb	4.1E-11
Ethene, chloro-	lb	6.9E-13
Ethyl acetate	lb	3.7E-16
Ethylamine	lb	1.9E-16
Ethylene diamine	lb	8.4E-16
Ethylene oxide	lb	2.4E-12
Fluoranthene	lb	3.9E-15
Fluorene	lb	1.9E-06
Fluorene, 1-methyl-	lb	8.5E-08
Fluorenes, alkylated, unspecified	lb	4.7E-06
Fluoride	lb	0.0036
Fluorine	lb	3.1E-07
Fluosilicic acid	lb	3.2E-09
Formaldehyde	lb	6.4E-11
Formamide	lb	1.1E-16
Formate	lb	4.9E-14
Formic acid	lb	3.1E-17
Furan	lb	1.4E-16
Glutaraldehyde	lb	2.2E-12
Glyphosate	lb	1.8E-12
Glyphosate-trimesium	lb	1.4E-13
Haloalkanes	lb	1.2E-13
Heat, waste	Btu	1.41
Hexadecane	lb	5.5E-05
Hexane	lb	2.4E-18
		PP Part
Hexanoic acid	lb	1.9E-04
Hydrocarbons, aliphatic, alkanes, unspecified	lb	7.2E-10
Hydrocarbons, aliphatic, unsaturated	lb	6.7E-11
Hydrocarbons, aromatic	lb	3.0E-09
Hydrocarbons, unspecified	lb	2.9E-09
Hydrogen-3, Tritium	Bq	0.46
Hydrogen chloride	lb	1.3E-12
Hydrogen fluoride	lb	3.1E-15
Hydrogen peroxide	lb	7.5E-13
Hydrogen sulfide	lb	2.8E-09
Hydroxide	lb	3.7E-11
Hypochlorite	lb	2.8E-11
Iodide	lb	5.6E-10
Iodine-129	Bq	4.1E-06
Iodine-131	Bq	1.1E-07
Iodine-133	Bq	1.7E-08
Iron	lb	0.13
Iron-59	Bq	4.6E-09
Iron, ion	lb	3.7E-06
Isopropylamine	lb	7.4E-17
Lactic acid	lb	1.4E-16
Lanthanum-140	Bq	2.9E-08
Lead	lb	4.3E-04
Lead-210	Bq	5.5E-06
Lead-210/kg	lb	9.5E-14
Lead 210	lb	8.9E-22
Lithium, ion	lb	0.61
m-Xylene	lb	2.7E-05
Magnesium	lb	0.50
Manganese	lb	0.0072
Manganese-54	Bq	1.5E-06
Mercury	lb	9.0E-07
Metallic ions, unspecified	lb	2.6E-07
Methane, dibromo-	lb	1.0E-18
Methane, dichloro-, HCC-30	lb	5.9E-11
Methane, monochloro-, R-40	lb	3.0E-08
Methane, trichlorofluoro-, CFC-11	lb	4.6E-13
Methanol	lb	5.3E-11
Methyl acetate	lb	2.0E-17
Methyl acrylate	lb	5.7E-13
Methyl amine	lb	3.4E-16
Methyl ethyl ketone	lb	6.0E-08
Methyl formate	lb	5.0E-17
Metolachlor	lb	5.2E-14
Metribuzin	lb	1.3E-14
Molybdenum	lb	2.1E-05
Molybdenum-99	Bq	9.9E-09
n-Hexacosane	lb	5.0E-07
n-Hexadecane	lb	5.7E-15
Naphthalene	lb	1.7E-05

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 22. Cradle-to-Gate Waterborne Emissions for Thermoformed PP Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
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		PP Part			PP Part
Naphthalene, 2-methyl-	lb	1.4E-05	Radium-226/kg	lb	3.3E-11
Naphthalenes, alkylated, unspecified	lb	1.3E-06	Radium-228	Bq	2.5E-04
Nickel	lb	1.9E-04	Radium-228/kg	lb	1.7E-13
Nickel, ion	lb	1.2E-07	Rubidium	lb	5.6E-11
Niobium-95	Bq	4.5E-08	Ruthenium-103	Bq	2.1E-09
Nitrate	lb	6.9E-08	Ruthenium-106	Bq	2.8E-08
Nitrate compounds	lb	6.2E-13	Scandium	lb	4.1E-10
Nitric acid	lb	9.8E-16	Selenium	lb	8.5E-05
Nitrite	lb	1.5E-10	Silicon	lb	1.5E-05
Nitrobenzene	lb	1.6E-15	Silver	lb	0.0016
Nitrogen	lb	0.0015	Silver-110	Bq	7.9E-06
Nitrogen, organic bound	lb	5.4E-09	Silver, ion	lb	5.2E-11
Nitrogen, total	lb	5.5E-04	Sodium-24	Bq	7.5E-08
o-Cresol	lb	2.6E-05	Sodium dichromate	lb	1.5E-07
o-Xylene	lb	4.1E-06	Sodium formate	lb	6.5E-14
Octadecane	lb	1.4E-05	Sodium hydroxide	lb	2.5E-17
Oils, unspecified	lb	0.025	Sodium, ion	lb	7.74
Organic substances, unspecified	lb	4.3E-14	Solids, inorganic	lb	1.8E-07
p-Cresol	lb	2.9E-05	Solved solids	lb	24.0
p-Xylene	lb	4.1E-06	Strontium	lb	0.050
PAH, polycyclic aromatic hydrocarbons	lb	8.1E-11	Strontium-89	Bq	1.7E-07
Particulates, < 10 um	lb	1.6E-14	Strontium-90	Bq	7.0E-04
Particulates, > 10 um	lb	2.7E-07	Styrene	lb	1.0E-06
Pendimethalin	lb	2.9E-13	Sulfate	lb	0.51
Phenanthrene	lb	3.9E-07	Sulfide	lb	1.1E-04
Phenanthrenes, alkylated, unspecified	lb	5.5E-07	Sulfite	lb	8.1E-11
Phenol	lb	0.0013	Sulfur	lb	0.0024
Phenol, 2,4-dimethyl-	lb	2.6E-05	Surfactants	lb	6.4E-05
Phenols, unspecified	lb	2.6E-04	Surfactants, unspecified	lb	1.3E-04
Phosphate	lb	3.5E-04	Suspended solids, unspecified	lb	4.89
Phosphorus	lb	1.6E-10	t-Butyl methyl ether	lb	3.3E-11
Phosphorus compounds, unspecified	lb	8.7E-12	t-Butylamine	lb	3.8E-16
Plutonium-alpha	Bq	1.1E-07	Tar	lb	2.5E-20
Polonium-210	Bq	7.7E-06	Technetium-99m	Bq	2.3E-07
Potassium	lb	6.8E-12	Tellurium-123m	Bq	3.2E-08
Potassium-40	Bq	2.1E-06	Tellurium-132	Bq	5.7E-10
Potassium, ion	lb	7.9E-07	Tetradecane	lb	2.2E-05
Process solvents, unspecified	lb	1.4E-14	Thallium	lb	7.0E-06
Propanal	lb	8.4E-17	Thorium-228	Bq	5.0E-04
Propane, 1,2-dichloro-	lb	5.6E-21	Thorium-230	Bq	4.1E-04
Propanol	lb	3.2E-16	Thorium-232	Bq	3.0E-07
Propene	lb	5.4E-09	Thorium-234	Bq	3.0E-06
Propionic acid	lb	2.4E-16	Tin	lb	1.6E-04
Propylamine	lb	3.4E-17	Tin, ion	lb	6.0E-09
Propylene oxide	lb	6.6E-12	Titanium	lb	2.8E-12
Protactinium-234	Bq	3.0E-06	Titanium, ion	lb	5.1E-04
Radioactive species, alpha emitters	Bq	1.3E-08	TOC, Total Organic Carbon	lb	0.0010
Radioactive species, Nuclides, unspecified	Bq	14,635	Toluene	lb	0.0013
Radium-224	Bq	1.3E-04	Toluene, 2-chloro-	lb	3.0E-16
Radium-226	Bq	0.0025	Tributyltin compounds	lb	6.4E-12

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG

Table 22. Cradle-to-Gate Waterborne Emissions for Thermoformed PP Plastic Parts
(Per 1,000 pounds of fabricated plastic parts)
(Page 4 of 4)

		PP Part
Triethylene glycol	lb	9.8E-12
Trifluralin	lb	1.7E-13
Trimethylamine	lb	3.5E-17
Tungsten	lb	1.1E-09
Uranium-234	Bq	3.6E-06
Uranium-235	Bq	5.9E-06
Uranium-238	Bq	2.0E-05
Uranium alpha	Bq	1.7E-04
Urea	lb	1.1E-16
Vanadium	lb	5.3E-05
Vanadium, ion	lb	1.2E-08
VOC, volatile organic compounds, unspecified origin	lb	2.0E-09
Xylene	lb	6.2E-04
Yttrium	lb	6.2E-06
Zinc	lb	0.0016
Zinc-65	Bq	1.0E-06
Zinc, ion	lb	9.2E-08
Zirconium-95	Bq	1.2E-08

Note: Radionuclides are in units of becquerel (Bq) per 1,000 lbs of fabricated plastic part.

Source: Franklin Associates, A Division of ERG