REVIEW OF LIFE CYCLE INVENTORY STUDY FOR 100% POSTCONSUMER RECYCLED HDPE AND PET RESINS

I. OVERVIEW

For many years, recycling advocates have asserted that it makes both economic and ecologic sense to recycle high volume consumer plastic packaging used both at home and in out-of-home applications. Until now, there has been little data to support this contention. Given the increasing demand for recycled plastic resins and a growing interest in sustainable packaging, a scientific analysis of the environmental impact of recycled plastics is a valuable tool for all involved stakeholders.

In an effort to determine the environmental merits of plastic bottle recycling, four associations collaborated on the fielding of a Life Cycle Inventory (LCI) Study that examines the relative environmental impacts of virgin vs. recycled High Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) resins. The groups are The Plastics Division of the American Chemistry Council, the Association of Postconsumer Plastic Recyclers (APR), the National Association for PET Container Resources (NAPCOR), and the PET Resin Association (PETRA.)

For reference, HDPE is widely used in containers such as milk jugs and detergent bottles, while PET is the primary resin used to produce soft drink and water bottles. Thanks to both curbside recycling programs and bottle deposit laws, these two plastics are easy for consumers to recycle. For reference, the *EPA's Municipal Solid Waste in the United States: 2008 Facts and Figures* indicates the following recycling rates:

Plastic Resin/Applications	2008 Recycling Rate
PET, Bottles & Jars	27%
HDPE Natural (white translucent) Bottles	29%

The study was performed by Franklin Associates, an independent provider of life cycle services. (The full study is attached to this review.) All data were drawn from published sources. Besides its own data, which are published in the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) U.S. Life Cycle Database (www.nrel.gov/lci), virgin HDPE and PET data were taken from the American Chemistry Council's database, revised in early 2010.

II. METHODOLOGY

The steps for production of postconsumer recycled resins were divided into three main stages: recovery (collection), sorting and separation, and reclaimer operations (conversion into new resins). Then, the energy requirements, solid wastes, and atmospheric and waterborne emissions were developed for 100% postconsumer recycled HDPE and PET resins, and the data were compared to its virgin counterparts.

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The results were developed using two common approaches, both of which are acceptable under ISO standards:

In the “cut-off” method, all virgin material production results (known as “burdens”) are assigned to the first use of the material. The burdens assigned to the recycled system begin with recovery of the postconsumer material. Then, all of the burdens for material recovery, transport, separation & sorting, and reprocessing are assigned to the recycled material. This method helps maximize the benefits of recycled resin use.

In the open-loop allocation method, the burdens for virgin and recycled material are shared among all the sequential useful lives of the material. For purposes of presenting results for recycled resin, the analysis assumes two useful lives (virgin and then one recycled product) prior to disposal. The use of "open loop" values is helpful in deriving conservative comparisons to virgin resins.

Also, collection of materials for recycling is performed two ways: by weight and by volume. Each produces a different profile relating to fuel consumption, primarily during transport. To account for these differences, the two allocations methods described above, cut-off and open-loop, were analyzed using both weight and compacted volume data.

III. STUDY SCOPE AND LIMITATIONS

1. This analysis is focused on the production of recycled resin as a manufacturing input. Thus, no burdens are included for manufacturing, use, or end-of-life management of products made from the recycled resins. The environmental burdens of those lifecycle stages will depend upon the specific application in which the resin is being used.
2. Based on the uncertainty of data used for energy, solid waste, and emissions modeling, differences between systems are not considered meaningful unless they are greater than 10% for energy and postconsumer solid waste, and 25% for industrial solid waste and emissions data.
3. The three categories studied – energy, solid waste, and emissions are independent of each other and no agreed upon weighting system has been developed that allows for their being combined to produce “an answer”.
4. The data collected does not compare recycling to other alternative end-of-life scenarios such as energy recovery or chemical transformation. Each alternative could have different advantages and disadvantages.

IV. FINDINGS

A. Energy Consumption

Recycled HDPE and PET resin production consumes significantly less energy than does the production of virgin HDPE and PET resins. Depending upon the resin and allocation methodology, the recycled resins consume between 38-88% less energy during production than do comparable virgin resins. (See table, top of next page.)

Energy Consumption:
Million Btu Consumed Per 1000 Lbs. of Resin Produced

Resin	Virgin	Cut-Off Weight-Based	Cut-Off Volume-Based (50% Compaction)	Open-loop Weight-Based	Open-loop Volume-Based (50% Compaction)
PET	31.9	4.9	5.1	18.4	18.5
HDPE	35.8	3.7	4.0	19.7	19.9

B. Greenhouse Gas Emissions (CO_2 Equivalents)

<u>Recycled HDPE and PET resin production generates significantly fewer greenhouse gases than does the production of virgin HDPE and PET resins</u>. Depending upon the resin and allocation methodology, the recycled resins generate between 35-78% less greenhouse gases during production than do comparable virgin resins. (As shown below and as expected, the relative results versus virgin resins are similar to the energy consumption figures stated above.)

Greenhouse Gas Emissions:
Lbs. of CO_2 Equivalents Generated Per 1000 Lbs. of Resin Produced

Resin	Virgin	Cut-Off Weight-Based	Cut-Off Volume-Based (50% Compaction)	Open-loop Weight-Based	Open-loop Volume-Based (50% Compaction)
PET	2,746	764	802	1,755	1,774
HDPE	1,822	609	667	1,216	1,244

C. Solid Waste

<u>While the topline solid waste figures for recycled resins are higher than for virgin PET and HDPE, a closer analysis indicates that solid waste from recycled resin processing may actually be viewed as significantly less than waste from virgin resin processing</u>. The difference relates to the fact that the topline waste numbers for recycled resins include co-mingled contaminants, which are not technically part of the recycled virgin production process. (See the table at the top of the next page.)

To quote from the original study:

The process wastes shown for recycled resin production are largely contaminants that were co-collected with the recovered plastic and are separated from the recovered material during sorting and separation processes. Although the contaminant wastes are removed and disposed at facilities where recycling processes occur, these wastes are not caused by recycling processes. The data provided by material recovery facilities and reclaimers for this study show that all usable materials are recovered from the incoming material received wherever possible, including materials other than the desired resin. Therefore, the majority of the solid waste disposed from the sorting and processing operations is material that would have been disposed as waste regardless of whether postconsumer plastic recycling takes place.

Solid Waste:
Lbs. Generated Per 1000 Lbs. of Resin Produced

Resin	Virgin	Cut-Off Weight-Based	Cut-Off Volume-Based (50% Compaction)	Open-loop Weight-Based	Open-loop Volume-Based (50% Compaction)
PET					
Process & Fuel Waste	142	342	343	242	242
Recycled Waste Without Sorting & Reclaimer Process Waste	N/A	49.4	49.9	95.7	95.9
HDPE					
Process & Fuel Waste	74.6	212	213	143	144
Recycled Waste Without Sorting & Reclaimer Process Waste	N/A	48.3	49.1	61.5	61.9

V. CONCLUSION

Postconsumer recycling of PET and HDPE resins has a positive impact on the overall environmental footprint associated with the production, use and disposal of these materials. Recycled HDPE and PET resin production consumes significantly less energy, generates significantly fewer greenhouse gases, and produces less solid waste than does the production of virgin HDPE and PET resins. Thus, consumer recycling of packaging made primarily from PET and HDPE should be encouraged among consumers, municipalities, businesses, and government.

VI. INDICATED ACTIONS

Businesses that manufacture products from recycled resins should actively promote the fact that they are doing so. The best way to reinforce the value of plastics recycling is for consumers to experience and use products made from recycled resins.

Robert Lilienfeld

Robert Lilienfeld, Editor

FINAL REPORT

LIFE CYCLE INVENTORY OF
100% POSTCONSUMER HDPE AND PET RECYCLED RESIN
FROM POSTCONSUMER CONTAINERS AND PACKAGING

PREPARED FOR

THE PLASTICS DIVISION OF THE AMERICAN CHEMISTRY COUNCIL, INC.,
THE ASSOCIATION OF POSTCONSUMER PLASTIC RECYCLERS (APR),
THE NATIONAL ASSOCIATION FOR PET CONTAINER RESOURCES
(NAPCOR), AND THE PET RESIN ASSOCIATION (PETRA)

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APRIL 7, 2010

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CHAPTER 1

LIFE CYCLE METHODOLOGY

OVERVIEW

The life cycle inventory (LCI) presented in this study quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of recycled PET and HDPE resin from postconsumer plastic.

This analysis does not include 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. (An exception is made in the case of global warming potential impacts, which are calculated based on internationally accepted factors for various greenhouse gases' global warming potentials relative to carbon dioxide.)

A life cycle inventory quantifies the energy consumption and environmental emissions (i.e., atmospheric emissions, waterborne emissions, and solid wastes) for a given product based upon the study boundaries established. Figure 1-1 illustrates the general approach used in a full LCI analysis.

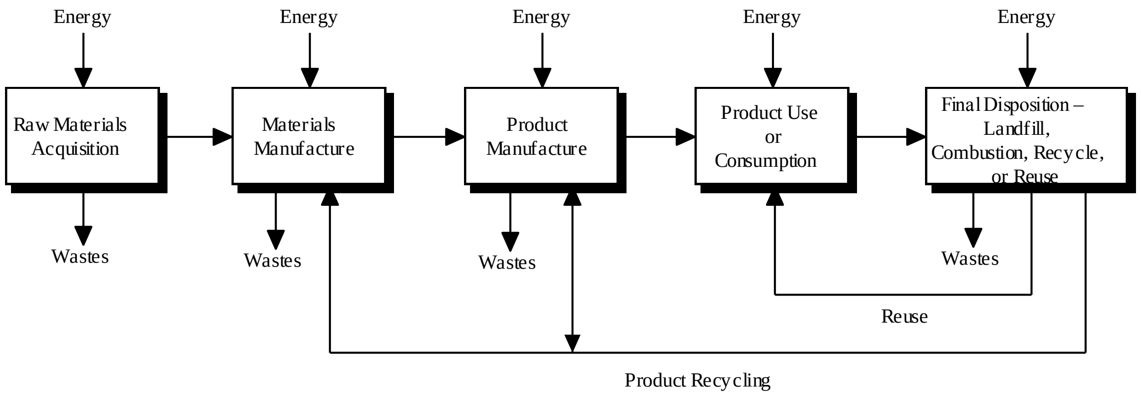

Figure 1-1. General materials flow for "cradle-to-grave" analysis of a product system.

LIFE CYCLE INVENTORY METHODOLOGY

Key elements of the LCI methodology include the study boundaries, resource inventory (raw materials and energy), emissions inventory (atmospheric, waterborne, and solid waste), and disposal practices.

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

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

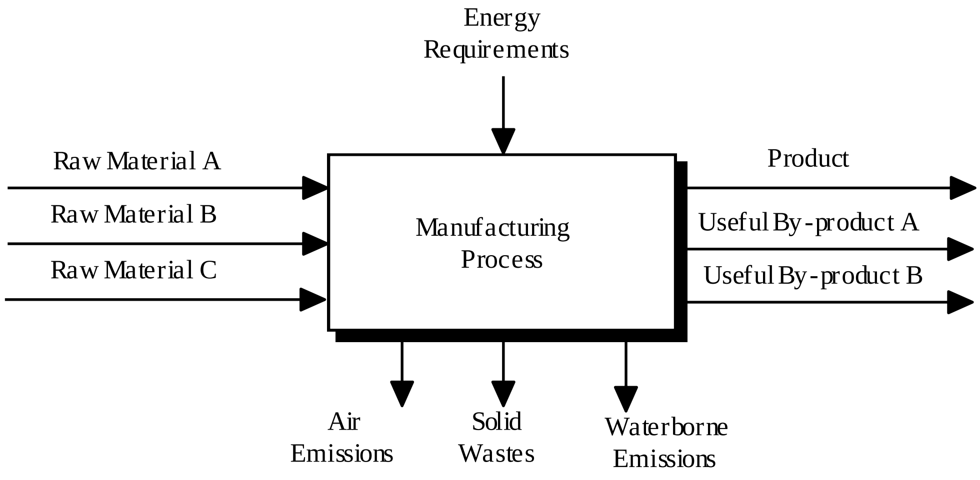

Figure 1-2. "Black box" concept for developing LCI data.

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

Material Requirements

Once the LCI study boundaries have been defined and the individual processes identified, a material balance is performed for each individual process. This analysis identifies and quantifies the input raw materials required per standard unit of output, such as 1,000 pounds, 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.

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

Energy Requirements

The average energy requirements for each process identified in the LCI are first quantified in terms of fuel or electricity units, such as cubic feet of natural gas, 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 for each step in the life cycle are developed in the conventional units of ton-miles by each transport mode (e.g. truck, rail, barge, etc.). Government statistical data for the average efficiency of each transportation mode are used to convert from ton-miles to fuel consumption.

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

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

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

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

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

The “other” category includes sources such as solar, biomass and geothermal energy. Also included in the LCI energy profile are the Btu values for all transportation steps and all fossil fuel-derived raw materials. Energy results for the packaging systems studied in this analysis are provided in Chapter 2.

Environmental Emissions

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

The different categories of atmospheric and waterborne emissions are not totaled in this LCI because it is widely recognized that various substances emitted to the air and water differ greatly in their effect on the environment.

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 LCI. 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 results discussion in Chapter 3 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 packaging components that are disposed when a container of product is emptied. 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.

LCI PRACTITIONER METHODOLOGY VARIATION

There is general consensus among life cycle practitioners on the fundamental methodology for performing LCIs.[1] However, for some specific aspects of life cycle inventory, there is some minor variation in methodology used by experienced practitioners. These areas include the method used to allocate energy requirements and environmental releases among more than one useful product produced by a process, 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.

Co-product Credit

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

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[1] 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.

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

Co-product credit is done out of necessity when raw materials and emissions cannot be directly attributed to one of several product outputs from a system. It has long been recognized that the practice of giving co-product credit is less desirable than being able to identify which inputs lead to particular outputs. In this study, co-product allocations are necessary because of multiple useful outputs from some of the "upstream" chemical processes involved in producing the resins used to manufacture plastic packaging components.

Franklin Associates follows the guidelines for allocating co-product credit shown in the ISO 14044:2006 standard on life cycle assessment requirements and guidelines. In this standard, the preferred hierarchy for handling allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. How product allocation is made will vary from one system to another but the choice of parameter is not arbitrary. ISO 14044 section 4.3.4.2 states "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 various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. Simple mass and enthalpy allocation have been chosen as the common forms of allocation in this analysis. However, these allocation methods were not chosen as a default choice, but made on a case by case basis after due consideration of the chemistry and basis for production.

In the sequence of processes used to produce plastic resins from natural gas and petroleum feedstocks, some processes produce material or energy co-products. 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.)

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

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

Energy of Material Resource

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

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.

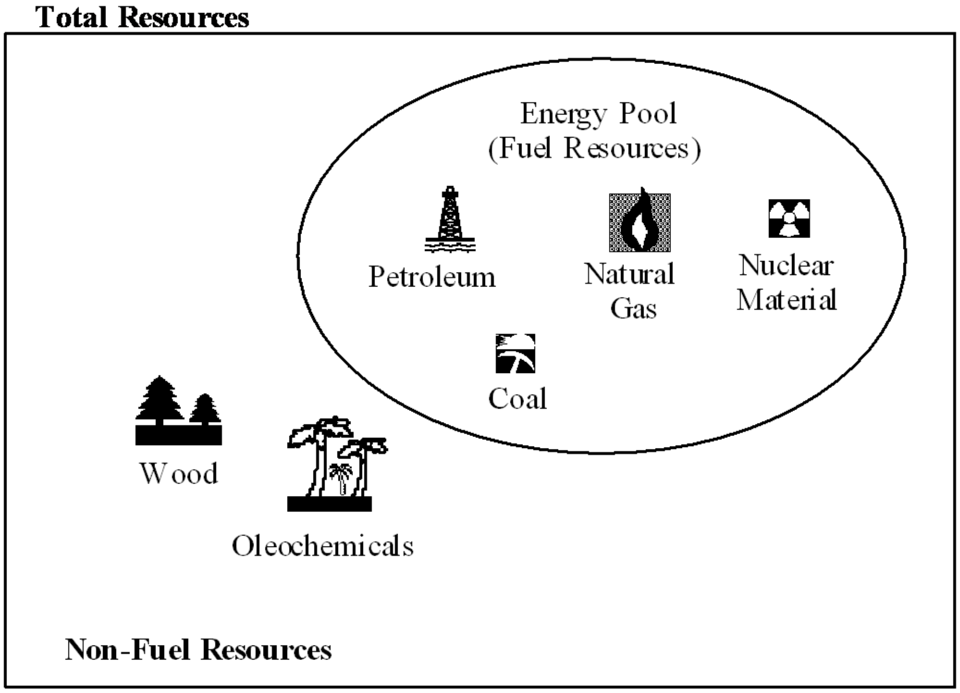

Figure 1-3. Illustration of the Energy of Material Resource Concept.

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.

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

Postconsumer Recycling Methodology

When material is used in one system and subsequently recovered, reprocessed, and used in another application, there are different methods that can be used to allocate environmental burdens among different useful lives of the material. Material production, recycling, and disposal burdens can be allocated over all the useful lives of the material, or boundaries can be drawn between each successive useful life of the material. In this analysis, separate sets of results are developed using each of these approaches.

The method in which virgin material burdens and recycling burdens are allocated among a limited number of useful lives of the material is referred to as the open-loop allocation method. In this method, the burdens for virgin material production, recovery and recycling, and ultimate disposal of recycled material are shared among all the sequential useful lives of the material.

The other method is referred to here as the “cut-off” method. Under this approach, a boundary is drawn between the initial use of the material and subsequent recovery and recycling of the material. All virgin material production burdens are assigned to the first use of the material, and the burdens assigned to the recycled resin system begin with recovery of the postconsumer material. All of the burdens for material recovery, transport, separation and sorting, and reprocessing are assigned to the recycled material.

DATA

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 quality and uncertainty are discussed in more detail at the end of this section.

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

Process Data

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

Each process identified during the construction of the flow diagram is then researched to identify potential industry sources for data. In this study, data on sorting and separation of postconsumer materials were collected from material recovery facilities (MRFs) and a plastic recycling facility (PRF). Data on processing of postconsumer plastic into clean recycled resin were gathered from PET and HDPE reclaimers.

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 MRFs and reclaimers, only weighted average data sets can be shown for each type of facility. Because only one PRF data set was received, PRF data cannot be shown.

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.

Data Sources. In addition to the MRF, PRF, and reclaimer data sets gathered for this project, data from a number of published sources were utilized for this report. The data sources used to characterize each stage of recycled resin production are listed under the relevant sections in Chapter 2. The data for virgin HDPE and PET used in the open-loop scenarios are the ACC data updated in 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 energy requirements and environmental emissions for the production and combustion of process fuels are calculated.

Energy data are developed in the form of units of each primary fuel required per unit of each fuel type. For electricity production, federal government statistical records provided data for the amount of fuel required to produce electricity from each fuel source, and the total amount of electricity generated from petroleum, natural gas, coal, nuclear, hydropower, and other (solar, geothermal, etc.). Literature sources and federal government statistical records provided data for the emissions resulting from the combustion of fuels in utility boilers, industrial boilers, stationary equipment such as pumps and compressors, and transportation equipment. Because electricity 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. This fuels and energy database, which is published in the U.S LCI Database, is used in this analysis.

Data Quality Goals for This Study

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

The data quality goal for this study was to use data that most accurately represents current U.S. production of postconsumer recycled resin. 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.

Data Accuracy

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

A key question is whether the LCI profiles are accurate and study conclusions are correct. The accuracy of an environmental profile depends on the accuracy of the numbers that are combined to arrive at that conclusion. Because of the many processes required to produce each foodservice product, 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.

METHODOLOGY ISSUES

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

Precombustion Energy and Emissions

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

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

Electricity Grid Fuel Profile

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

METHODOLOGICAL DECISIONS

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

Geographic Scope

Data 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

There is currently a lack of detailed 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."[4] 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.

The water use data in this report include only the water use reported by the MRFs, PRF, and reclaimers for processing of postconsumer resin. No water use for production of virgin resin is included.

System Components Not Included

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

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

Space Conditioning. The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the datasets for most industrial processes, such as the chemical processes used to produce virgin resins. However, the MRFs, PRF, and reclaimers who provided data for this analysis did not separate process energy from space conditioning energy.

For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. Energy consumed for space conditioning is usually less than one percent of the total energy consumption for the manufacturing process. This assumption has been checked in the past by Franklin Associates staff using confidential data from manufacturing plants.

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

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 production of surfactants, defoamers, and wetting agents used by reclaimers in washing processes were not included if they were less than one percent of the weight of the material washed.

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.

CHAPTER 2

RECOVERY AND RECYCLING PROCESSES

INTRODUCTION

In this analysis, the steps for production of postconsumer recycled resin are divided into three main stages:

(1) Recovery: Collection of postconsumer plastic,
(2) Sorting and Separation: Sorting of plastics from other co-collected recovered materials (such as paper, steel, and aluminum), and separating mixed plastics into individual resins,
(3) Reclaimer Operations: Processing of the resin by a reclaimer to convert the received material into clean resin ready to be converted into a product.

This chapter describes the methodology and data sources used to quantify each stage of the process.

RECOVERY

Postconsumer PET and HDPE products that are recovered for recycling are primarily packaging products, including soft drink and milk bottles, other bottles and containers, and other PET and HDPE packaging. Collection of these materials occurs through residential curbside or drop-off programs, deposit redemption systems, and commercial collection programs. The percentage of containers recovered through the California deposit system is shown as “CRV” (California refund value) in Table 2-1.

The percent of PET and HDPE recovery through the various collection programs was determined from an analysis of the following data sources:

PET Collection:

- NAPCOR RPET 2007 Market Update. Received from NAPCOR November 26, 2008.

HDPE Collection:

- California Department of Conservation. Biannual Report of Beverage Container Sales, Returns, Redemption, and Recycling Rates. Notice. November 7, 2008

Curbside/Drop-off Mix:

- Businesses and Environmentalists Allied for Recycling (BEAR), a Project of Global Green USA. *Understanding Beverage Container Recovery: A Value Chain Assessment Prepared for the Multi-Stakeholder Recovery Project (MSRP), Stage 1*. January 16, 2002.

National PET and HDPE Recovery for 2007:

- U.S. EPA. *Municipal Solid Waste in the United States: 2007 Facts and Figures*. http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm

Residential/Commercial Mix:

- U.S. Recovery – Franklin Associates. *Solid Waste Management at the Crossroads*. December 1997.

The results of this analysis are shown below.

Table 2-1. Collection Systems for the Recovery of PET And HDPE

	Curbside	Drop-off	Deposit	CRV*	Commercial
PET	47.8%	11.0%	13.0%	22.3%	5.9%
HDPE**	73.0%	16.8%		4.3%	5.9%

*California refund value
**Excluding HDPE film packaging.

The following sections describe how fuel use for each type of collection was estimated for this analysis. Curbside collection accounts for the largest percentage of material collected; however, description of curbside collection fuel use is presented last, since several scenarios are evaluated. In each case, fuel use is estimated for collection of 1000 pounds of postconsumer plastic material. Some of the estimates utilize default data from the U.S. EPA Municipal Solid Waste (MSW) Decision Support Tool (DST):

U.S. EPA. Office of Research and Development, APPCD. *Default Data and Data Input Requirement for the Municipal Solid Waste Management Decision Support Tool Final*. December 2000. https://webdstmsw.rti.org/docs/Inputs_Document_OCR.pdf

Fuel Use for Consumer Dropoff at a Recycling Center

As shown in Table 2-1, dropoff recycling centers account for approximately 17 percent of postconsumer HDPE and 11 percent of postconsumer PET. Fuel use by consumers delivering household recyclables to a dropoff center was estimated based on following assumptions:

- 16.9 pounds of household recyclables generated per week (EPA MSW report)
- Recyclables dropped off every other week (ERG assumption)
- Distance driven: 10 miles (EPA MSW Decision Support Tool default value)
- Fuel economy of personal vehicle used for trip: 20 mpg (MSW DST default)
- Percent of trips that are dedicated trips: 50% (MSW DST default; remainder of trips are assumed to have a different primary purpose so that dropoff of recyclables is incidental)

Using these factors, the gallons of gasoline used per thousand pounds of material delivered to a recycling center is calculated as 1000 lb/(16.9 lb/wk * 2 wks/trip) x 10 miles/trip, divided by 20 mpg x 50% dedicated trips = 7.4 gallons per thousand pounds.

Fuel Use for Deposit Dropoff

It is assumed that a consumer would not make a trip for the sole purpose of returning deposit containers. Consumers would drop off bottles as an incidental stop on a trip with some other primary purpose (e.g., deposit bottles purchased at a grocery store would be returned on the next trip to the store to buy groceries), so fuel use for returning deposit containers is treated as incidental, with no consumer transport burdens assigned to returning deposit containers. Accumulated quantities of deposit containers are modeled as being transported from the collection point to an intermediate processing center (IPC). Based on information provided by a confidential source, transport of deposit containers to the IPC is modeled as a volume-limited load of loose bottles transported by a single-unit truck. The distance is estimated as 20 miles, and a fuel economy of 8.2 mpg is used for the truck[5]. At the IPC, the containers are baled for shipment to the next processing location.

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[5] From http://www.bts.gov/publications/national_transportation_statistics/excel/table_04_13.xls

Fuel Use for CRV and Commercial Collection

Similar to the deposit system, no consumer transport burdens are assigned to postconsumer plastic recovered through the CRV program or from commercial sources. For this scenario, transport of bottles from the site to an IPC or to a material recovery facility (MRF) is also based on a volume-limited shipment of loose bottles; however, it is assumed that the accumulated quantities transported per pickup are larger so that a tractor-trailer truck is used, with a fuel economy of 6.5 mpg. Based on information provided by a confidential source, the distance hauled is longer and is estimated as 150 miles. At the IPC or MRF some additional sorting may be done before the resin is baled for shipment to the next processing location.

Fuel Use for Residential Curbside Collection

Residential curbside collection accounts for the majority of postconsumer plastic recovery (almost half of PET and nearly three-quarters of HDPE). To develop fuel requirements for curbside collection of PET and HDPE, recovery data were gathered from various sources to determine the percentage of material collected curbside for three levels of separation: single stream, dual stream, and curbside sort. Single stream and dual stream were further divided into manual and automated collection. Curbside sort is manual.

The percentages of recyclables collected by each collection system were developed from the following data sources:

Collection System – Percentages of Single Stream, Dual Stream, Curbside Sort:

- Governmental Advisory Associates, Inc. *Materials Recycling and Processing in the United States. 2007-2008 Yearbook & Directory*. Eileen Brettler Berenyi. 2007

Collection System – Percentages Automated/Manual:

- Skumatz, Lisa and Juri Freeman. "On Common Ground" *Resource Recycling*. November 2008.

The characteristics of the collection vehicles used for each system and the number of households served per vehicle route trip were developed from the following data sources:

Collection System – Truck Profile:

- Keep America Beautiful, Inc. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*. Appendix H. Franklin Associates September 1994.
- Discussions with two recyclable material haulers representing both single stream and dual stream collection systems. February 2009.
- Heil Environmental. Automated Refuse Collection White Paper. 2004. http://www.heil.com/library/getfile.asp?id=901A4E00-2840

The total quantity of recyclables per truckload was based on the number of households served per collection vehicle route, the average pounds of recyclables set out per household per week, and the composition of the recyclables generated. The truck fuel requirements were then allocated to the materials collected. The following data sources were used:

Composition by Weight of Materials Collected per Vehicle Load:

- U.S. EPA. *Municipal Solid Waste in the United States: 2007 Facts and Figures*. http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm
- Businesses and Environmentalists Allied for Recycling (BEAR), a Project of Global Green USA. *Understanding Beverage Container Recovery: A Value Chain Assessment Prepared for the Multi-Stakeholder Recovery Project (MSRP), Stage 1*. January 16, 2002.
- Percentages developed for PET and HDPE collection systems shown in previous section.

The results of this analysis are shown in Table 2-2.

Table 2-2. Curbside Collection Profile by Weight

	Single stream collection		Dual stream collection		Curbside sort collection
Percent of Material Collected	26.3%		52.5%		21.3%
	20.8%	5.5%	41.4%	11.0%	21.3%
Truck type	Manual	Fully Automated	Manual	Fully/semi-automated	Manual
Truck cubic yards	34	42	30	42	23
Truck mpg	3.5	3.5	3.5	3.5	3.5
Route distance round trip	50	50	50	50	50
Households per route	710	1,200	800	1,000	560
Set-out rate	57%	57%	57%	57%	57%
Average set-outs per route	405	684	456	570	319
Pounds material per set-out	16.9	16.9	13.5	13.5	10.1
Pounds material per load	6,845	11,560	6,156	7,695	3,222
Truck Load Composition (by weight)					
PET	**1.9%**	**1.9%**	**1.9%**	**1.9%**	**3.1%**
HDPE	**2.1%**	**2.1%**	**2.1%**	**2.1%**	**3.5%**
Other plastic	0.2%	0.2%	0.2%	0.2%	
ONP (old newspaper)	37.6%	37.6%	38.4%	38.4%	62.9%
OMG (old magazines)	3.8%	3.8%	3.9%	3.9%	6.3%
Corrugated containers	3.4%	3.4%	3.5%	3.5%	
Other paper	33.6%	33.6%	34.3%	34.3%	
Aluminum	1.8%	1.8%	1.8%	1.8%	2.9%
Steel	6.4%	6.4%	6.6%	6.6%	10.8%
Glass	6.2%	6.2%	6.4%	6.4%	10.4%
Nonrecyclables	3.0%	3.0%	1.0%	1.0%	0.0%
Total	100%	100%	100%	100%	100%

The weight of collected material influences the fuel economy of the collection vehicle; however, collection route planning is typically based on the *volume* of material that will be collected from the households on the route. Consumer compaction of recyclables prior to set-out can vary widely depending on household practices. Additional compaction of the material is done by the compaction mechanism on the collection vehicle.

In order to allocate fuel use to collected recyclables on a volume basis, the first step was to calculate the uncompacted volume for the weight of recyclables collected per vehicle route. This was done using density factors from a report based on waste sampling studies[6]. The composition by volume for the weight of uncompacted household recyclables per collection route is shown in Table 2-3.

For the weight of recyclables collected on the vehicle route, the uncompacted volume of the materials is greater than the volume capacity of the vehicle, so the next step was to calculate the compacted volume of the collected material using compacted densities from the same waste sampling studies. The compacted densities and volume percentages are shown in Table 2-4.

In order for the volume of household recyclables picked up on the route to fit in the collection vehicle, an overall compaction rate of approximately 50 percent is required. Therefore, the volume-based fuel allocation shown in Table 2-5 is based on a compaction rate of 50 percent.

Table 2-3. Truck Load Composition, Uncompacted Volume (for the pounds of recyclables collected on a route)

		Single-stream collection		Dual-stream collection		Separated collection
	Uncompacted density (lb/cu yd)	Manual	Fully Automated	Manual	Fully/semi automated	Manual compart-ment
PET	**53**	**3.0%**	**3.0%**	**3.0%**	**3.0%**	**9.0%**
HDPE	**53**	**3.3%**	**3.3%**	**3.3%**	**3.3%**	**10.1%**
Other Plastic	53	0.3%	0.3%	0.3%	0.3%	0.0%
ONP	170	18.6%	18.6%	18.8%	18.8%	56.9%
OMG	170	1.9%	1.9%	1.9%	1.9%	5.7%
Corrugated	43	6.7%	6.7%	6.8%	6.8%	0.0%
Other paper	48	59.0%	59.0%	59.5%	59.5%	0.0%
Aluminum	60	2.5%	2.5%	2.5%	2.5%	7.5%
Steel	200	2.7%	2.7%	2.7%	2.7%	8.3%
Glass	650	0.8%	0.8%	0.8%	0.8%	2.5%
Nonrecyclables (contaminants)	203	1.2%	1.2%	0.4%	0.4%	0.0%
		100.0%	100.0%	100.0%	100.0%	100.0%

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[6] **Estimates of the Volume of MSW and Selected Components in Trash Cans and Landfills**. Conducted for the Council for Solid Waste Solutions by Franklin Associates, Ltd., Prairie Village, KS and The Garbage Project, Tucson, AZ. 1990.

Table 2-4. Truck Load Composition, Compacted Volume (for the pounds of recyclables collected on a route)

		Single-stream collection		Dual-stream collection		Separated collection
	Compacted density (lb/cu yd)	Manual	Fully Automated	Manual	Fully/semi automated	Manual compart-ment
PET	**295**	**3.8%**	**3.8%**	**3.9%**	**3.9%**	**6.4%**
HDPE	**295**	**4.3%**	**4.3%**	**4.4%**	**4.4%**	**7.1%**
Other Plastic	295	0.4%	0.4%	0.4%	0.4%	0.0%
ONP	672	34.0%	34.0%	34.5%	34.5%	56.5%
OMG	672	3.4%	3.4%	3.5%	3.5%	5.7%
Corrugated	609	3.4%	3.4%	3.5%	3.5%	0.0%
Other paper	602	33.9%	33.9%	34.4%	34.4%	0.0%
Aluminum	212	5.0%	5.0%	5.1%	5.1%	8.3%
Steel	486	8.0%	8.0%	8.2%	8.2%	13.4%
Glass	2,370	1.6%	1.6%	1.6%	1.6%	2.7%
Nonrecyclables (contaminants)	852	2.1%	2.1%	0.7%	0.7%	0.0%
		100.0%	100.0%	100.0%	100.0%	100.0%

Table 2-2 shows that the fuel economy for collection vehicles is approximately 3.5 mpg. This include fuel use while idling at stops, as well as fuel used while the vehicle is traveling. For a round trip route of 50 miles, 14.3 gallons of fuel would be required. Table 2-5 shows the amount of fuel allocated to curbside collection of 1,000 pounds of postconsumer plastic for each collection system using weight-based allocation and volume allocation (based on 50 percent compaction).

Table 2-5. Fuel Use for Curbside Collection Options

	Single-stream collection		Dual-stream collection		Separated collection
	Manual	Fully Automated	Manual	Fully/semi-automated	Manual compart-ment
Weight Basis					
Pounds of material per full load	6,845	11,560	6,156	7,695	3,222
Gal fuel per load	14.3	14.3	14.3	14.3	14.3
Gal fuel per thou lb of material collected	**2.09**	**1.24**	**2.32**	**1.86**	**4.43**
Volume Basis					
Cubic yards per load at 50% compaction of materials on truck	23	38	20	26	11
Gal fuel per cu yd of material on truck	0.63	0.37	0.70	0.56	1.34
Gallons per thou lb plastic at 50% compaction density	**4.29**	**2.54**	**4.74**	**3.80**	**9.06**

The fuel requirements for collection of postconsumer plastics are summarized in Tables 2-6 and 2-7. Table 2-6 shows the total fuel use for curbside collection of postconsumer plastic using the two different methods of allocating collection fuel among the co-collected materials. Table 2-7 shows the total fuel use for collection of each resin, based on the percentages that are collected by each method and the fuel used for each method.

Table 2-6

FUEL USE FOR CURBSIDE COLLECTION OF 1,000 POUNDS OF POSTCONSUMER PLASTICS, USING TWO METHODS FOR ALLOCATING COLLECTION FUEL USE TO COLLECTED MATERIALS*

		Gal Diesel Fuel per 1,000 Pounds Plastic for Different Allocation Methods	
Curbside Collection System	**% of Plastic Collected**	**Weight-based**	**Volume-based (50% compaction)**
Single-stream Manual	20.8%	2.09	4.29
Single-stream Automated	5.5%	1.24	2.54
Dual Manual	41.4%	2.32	4.74
Dual Automated	11.0%	1.86	3.80
Curb Sort Manual	21.3%	4.43	9.06
Weighted Average	**100.0%**	**2.61**	**5.35**

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* Co-collected materials include plastics, paper, steel, aluminum, glass, and other household recyclables.
Percent of plastic collected by each curbside collection system from Table 2-2.
Fuel use for collecting 1,000 pounds by each curbside collection system from Table 2-5.

Source: Franklin Associates, A Division of ERG

Table 2-7

TOTAL FUEL USE FOR COLLECTION OF 1,000 POUNDS OF POSTCONSUMER PLASTICS, INCLUDING TWO METHODS FOR ALLOCATING POSTCONSUMER COLLECTION FUEL USE

				Gal Diesel Fuel for Curbside Collection				**Gal Diesel for Transport to Intermediate Processing Center**	
PET	**% of total PET collection**	**Gal Gasoline for Consumer Drop-off**		**Wt-based**		**Vol-based (50% comp)**		Comb. (semi) Truck	Single-unit Truck
Curbside collection	47.8%			2.61	or	5.35			
Drop-off recycling centers	11.0%	7.40							
Deposit programs	13.0%								1.05
California redemption program	22.3%							3.78	
Commercial collection	5.9%							3.78	
	100%								
								gal diesel	
Weighted average fuel use		gal gasoline		gal single-unit diesel*				comb truck	single-unit truck
for PET collection		**0.81**	+	**1.25**	**or**	**2.55**	+	**1.06**	**0.14**

				Gal Diesel Fuel for Curbside Collection				**Gal Diesel for Transport to Intermediate Processing Center**	
HDPE	**% of total HDPE collection**	**Gal Gasoline for Consumer Drop-off**		**Wt-based**		**Vol-based (50% comp)**		Comb. (semi) Truck	Single-unit Truck
Curbside collection	73.0%			2.61	or	5.35			
Drop-off recycling centers	16.8%	7.40							
California redemption program	4.3%							3.78	
Commercial collection	5.9%							3.78	
	100%								
Weighted average fuel use		gal gasoline		gal single-unit diesel*				comb truck	
for HDPE collection		**1.24**	+	**1.91**	**or**	**3.90**	+	**0.39**	

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* Only one of these values should be used, depending on collection fuel allocation method selected

Percentage of each resin from each collection system from Table 2-1.
Curbside collection fuel use from Table 2-6.
Fuel use for transportation of collected material to a MRF is included in Table 2-8.

SORTING AND SEPARATION

Once the postconsumer PET and HDPE have been collected, they must be separated from other co-collected materials and plastics. Although some recovered plastic is separated by curbside sorting and the use of separate bins at drop-off recycling centers, sorting and separation of plastics most commonly takes place at material recovery facilities (MRFs). Sorting operations at MRFs range from manual sorting of items on a conveyor to highly automated systems using magnets, air classifiers, optical sorters, and other technologies to sort and separate mixed incoming materials. Postconsumer plastics may be separated and baled as mixed plastics, or the facility may have the capability to further sort down to individual resin bales.

The following data source was used to classify MRF operations into four general categories and estimate the percentage of postconsumer plastic handled by each type of MRF:

> Governmental Advisory Associates, Inc. *Materials Recycling and Processing in the United States. 2007-2008 Yearbook & Directory*. Eileen Brettler Berenyi. 2007

Based on statistics in the Governmental Advisory Associates (GAA) database, more than 80 percent of recyclables collected are processed in single-stream or dual-stream facilities. Single-stream MRFs include those which have a single incoming feed line as well as MRFs that process only one type of material, either fiber (paper and paperboard) or non-fiber. Dual-stream MRFs sort fiber on one line and glass, plastic, and metal on the other. In some cases, dual-stream MRFs may mechanically sort the commingled stream and floor sort the fiber.

MRF technology levels for non-fiber lines were separated into 4 categories:

- Level 1 – manual separation only, with conveyor or balers;
- Level 2 – use of conveyor, baler, and magnetic separator;
- Level 3 – in addition to level 2 equipment, the use of other separator technology such as eddy current, air classifier, trommels, and screens, or an integrated sort system;
- Level 4 – the addition of computer-assisted technology, i.e., scanners.

Overall, four MRF categories were developed, based on information in the GAA database about MRF throughput, materials handled, number of sorting streams, and technology. The four categories and the estimated percentage of plastic estimated to be handled under each category were as follows:

- Single-sort high technology: 26.3 percent
- Dual-sort high technology: 25.7 percent
- Dual-sort low technology: 26.7
- Multi-sort low technology: 21.3

Energy requirements for each type of MRF were estimated based on equipment listings in the GAA database and energy requirements for different types of equipment from the EPA MSW Decision Support Tool.

Based on the total quantities of postconsumer PET and HDPE that were recovered in 2007 (from the EPA MSW Characterization report) and the tons per day throughput for the plastic recovery facility (PRF) reported in the GAA database, approximately 4 to 5 percent of recovered postconsumer PET and HDPE is routed through a PRF. The majority of plastic material received at the PRF comes from MRFs, but there is also a significant amount received from deposit programs. At the PRF, mixed plastic bales are broken and the material is ground and separated by resin type. The resulting “dirty flake” material is sent to reclaimers.

Data were also collected from MRFs and a PRF using data collection forms developed specifically for this project by ERG. Four completed MRF surveys and one completed PRF survey were received. For the MRFs, one data set was for a large facility that processed both single-stream and dual-stream collected material, two were for medium dual-stream facilities, and one was for a small dual-stream facility. The data provided on the forms included information on the sources of material received at the MRF; the transportation mode and distance for incoming material from each source; the types and quantities of useful materials recovered from the incoming material; the types of equipment used at the facility; energy and water use at the facility; and the solid wastes, atmospheric and waterborne emissions from the facility. For each facility, the operating data were allocated over the total weight of recovered materials.

A weighted average data set was developed based on the amount of material processed at each facility. Individual facility data cannot be shown because of data confidentiality; however, the weighted average data set is shown in Table 2-8. To protect confidential data, the PRF data set cannot be shown.

For sorting at MRFs, total solid wastes were allocated over the total pounds of useful output, so that the pounds of MRF sorting waste is the same for 1,000 pounds of output, whether it is HDPE or PET. The same approach was used to calculate the sorting waste per 1,000 pounds of output material for the PRF. However, in the results tables in Chapter 3, different amounts of sorting waste are shown for HDPE and PET in Tables 3-3 and 3-4 because different percentages of the two resins are routed through MRFs and PRF, based on information from the GAA database.

Table 2-8

DATA FOR THE PROCESSING OF 1,000 POUNDS OF POSTCONSUMER MATERIAL AT A MATERIAL RECOVERY FACILITY (MRF)

Energy Usage			**Total Energy MBtu**
Incoming material transportation			
Combination truck	8.06	ton-miles	
Diesel	0.08	gal	13.4
Single unit truck	7.47	ton-miles	
Diesel	0.17	gal	26.7
Total Transportation			40.1
Process Energy			
Electricity (grid)	7.42	kwh	76.3
Natural gas	0.036	cu ft	0.04
Diesel	0.22	gal	34.8
Propane	0.30	gal	32.6
Total Process			144
Environmental Emissions			
Solid Wastes to landfill	87.1	lb	

References: Confidential data sets provided by 4 MRFs.

Source: Franklin Associates, A Division of ERG

Overall facility energy use reported on the MRF surveys was compared to MRF energy requirements estimated for each facility using MSW DST default factors for the types of equipment reported by the surveyed facilities. Electricity use reported by the facilities correlated well with calculated electricity requirements.

RECLAIMER OPERATIONS

Data collection forms for HDPE and PET reclaimers were developed for this project by ERG. Completed forms were received from 4 PET facilities and 6 HDPE facilities. The data sets were used to compile a weighted average for each resin based on each facility’s recycled resin output as a percentage of the total output of that recycled resin for all reporting facilities. As with the MRF data sets, only the weighted average data sets can be shown in order to protect the confidentiality of individual facility data sets.

PET Reclamation

For the facilities that provided data for this analysis, incoming material travels an average of 497 miles by truck and 120 miles by rail in 39,000 pound loads. The percentages of incoming material received by PET reclaimers from MRFs, PRF, and deposit programs varied widely by reclaimer facility.

Most of the reporting facilities receive postconsumer PET as individual resin bales. The bales must be broken down and the material sorted to remove foreign material. The sorted materials may or may not go through a pre-washing stage before they are granulated to flake. Some amount of reclaimed resin is received at the facility already in flake form. This flake may be clean or dirty, but all reclaimed flake is washed to market specifications as part of the reclaimer processing operations. This is most often achieved with a caustic wash, but different reclaimers reported using a variety of washing chemicals including surfactants, defoamers, and wetting agents.

Even though the incoming material has undergone some presorting before it is received, other materials are mixed in with the PET. Other materials recovered from the incoming material include polyolefin cap material (HDPE, PP), PVC, and aluminum. Other (non-PET) useful materials recovered comprise, on average, just over 1 percent of the weight of incoming material received. About 80 percent of the weight of incoming material ends up as recycled PET resin. When considering the useful output from the reclamation facility, recycled PET resin accounted for 98 percent on average of the recovered material output for the responding facilities; therefore, 98 percent of the facility operating burdens are allocated to PET. Unusable contaminants represent an average of 18.3 percent of the weight of incoming material, or over 200 pounds of solid wastes per thousand pounds of useful output (resin plus other saleable coproducts recovered).

It is important to note that the amount of material landfilled per pound of recovered material is subject to annual change due to market interest in saleable coproducts. For example, the waste per pound of recovered material calculated from the reclaimer survey forms is very similar to NAPCOR statistics for 2007, but NAPCOR data for 2006 and 2008 show considerably lower quantities of waste per pound of saleable material recovered. Market prices for the other materials that are mixed in with the incoming PET influence reclaimers' decision whether to expend the effort to recover the other materials or dispose of them.

Clean postconsumer PET is commonly sold in flake form, or it can be pelletized. Some reclaimers extrude the postconsumer PET directly into a staple fiber product. Depending on the level of processing, the postconsumer PET resin may be used for food-grade or non-food applications. The material and energy requirements per 1000 pounds of postconsumer PET flake output are listed in Table 2-9.

Table 2-9

DATA FOR THE PROCESSING OF 1,000 POUNDS OF POSTCONSUMER RECYCLED PET FLAKE

Raw Materials			
Sorted postconsumer PET	1,250	lb	
100% sodium hydroxide	23.8	lb	
Surfactant	0.76	lb	
Defoamer	2.23	lb	
Wetting agent	0.87	lb	
Energy Usage			**Total Energy MBtu**
Process Energy			
Electricity (grid)	208	kwh	2,140
Natural gas	1,207	cu ft	1,351
LPG	0.031	gal	3
Propane	0.0053	gal	0.58
Total Process			3,495
Transportation Energy			
Combination truck	248	ton-miles	
Diesel	2.61	gal	414
Rail	60.1	ton-miles	
Diesel	0.15	gal	23.7
Total Transportation			438
Water consumption	47.3	gal	
Environmental Emissions			
Atmospheric Emissions			
Particulates	0.039	lb	
Volatiles	0.037	lb	
Solid Wastes to landfill	220	lb	
Waterborne emissions			
BOD	7.26	lb	
COD	20.2	lb	
Suspended Solids	2.98	lb	

References: Confidential data sets provided by 4 PET reclaimer facilities.

Source: Franklin Associates, A Division of ERG

Some recycled PET is sold in the form of resin pellets. The additional energy required to convert 1,000 pounds of recycled PET flake to resin pellets is 218 kWh, based on primary data from the reclaimer surveys. No further details can be provided about the data in order to comply with confidentiality agreements with data providers.

The PET recycling data do not include solid stating to convert the resin to a bottle-ready state. If the recycled resin data are being used in a life cycle inventory for the production of bottles, the practitioner constructing the model may need to add energy for solid stating of the recycled PET resin.

HDPE Reclamation

For the HDPE reclaimer facilities that provided operating data, incoming material travels an average of 525 miles by truck in 38,990 pound loads. The percentages of incoming material received by HDPE reclaimers were predominantly from MRFs (on average 92%) with a smaller portion from PRFs (on average 8%), and a negligible amount from deposit programs.

Most of the reporting facilities receive postconsumer HDPE as individual resin bales (on average 94%). The bales must be broken down and the material sorted to remove foreign material. A typical processing sequence includes debaling, grinding, washing, drying, extruding and pelletizing. As with postconsumer PET material, all reclaimed flake is washed as part of the reclaimer processing operations. Material may be washed before grinding, after grinding, or both. Some amount of reclaimed resin is received at the facility already in flake form (on average 8%). Most reclaimers reported using small amounts of various chemicals in the washing process, although types and quantities varied. In all cases, the amount of washing chemicals was equivalent to less than 1 percent of the weight of the material washed.

Even though the incoming HDPE material has undergone sorting and separation prior to shipment to the reclaimer, recovery of small amounts of non-HDPE materials was reported by several recyclers, include aluminum, PET, and cardboard. On average, other recovered materials account for less than 1 percent of the weight of incoming material received; therefore, over 99 percent of the facility operating burdens are allocated to HDPE. Unusable contaminants result in nearly 80 pounds of solid waste per thousand pounds of material received. The majority of this solid waste is landfilled.

Clean postconsumer HDPE is most commonly sold in pellet form, with the reclaimers reporting only a very small percentage of output sold as flake. The weighted average material and energy requirements for producing 1,000 pounds of postconsumer recycled HDPE pellets are listed in Table 2-10.

Table 2-10

DATA FOR THE PROCESSING OF 1,000 POUNDS OF POSTCONSUMER RECYCLED HDPE PELLET

			Total Energy MBtu
Raw Materials			
Sorted postconsumer HDPE	1,079	lb	
100% sodium hydroxide	0.27	lb	
Defoamant	1.52	lb	
Wetting Agent	0.57	lb	
Surfactant	0.77	lb	
Alkaline Cleaner	0.060	lb	
Energy Usage			
Process Energy			
Electricity (grid)	222	kwh	2,289
Diesel	0.022	gal	3.47
Natural gas	123	cu ft	138
LPG	0.094	gal	10.1
Propane	0.038	gal	4.14
Total Process			2,444
Incoming Transportation Energy			
Combination Truck	262	ton-miles	
Diesel	2.76	gal	437.5
Total Transportation			437.5
Water Consumption	53.3	gal	
Environmental Emissions			
Atmospheric Emissions			
Particulates (PM10)	0.023	lb	
Particulates (PM2.5)	0.015	lb	
Solid Wastes to Landfill	65.7	lb	
Solid Wastes (to Waste-to-Energy)	13.4	lb	
Waterborne Emissions			
BOD	0.30	lb	
COD	0.0015	lb	
Suspended Solids	0.29	lb	
Dissolved Solids	0.0091	lb	

References: Confidential data sets provided by 6 HDPE reclaimer facilities.

Source: Franklin Associates, A Division of ERG

CHAPTER 3

LIFE CYCLE INVENTORY RESULTS FOR PRODUCTION OF POSTCONSUMER PET AND HDPE RESIN

INTRODUCTION

This chapter presents the energy requirements, solid wastes, and atmospheric and waterborne emissions for the sequence of processes used to collect, transport, separate, and process postconsumer HDPE and PET plastic products into clean recycled resin ready for use to manufacture a plastic product. The process data sets for each step were presented in Chapter 2. 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 HDPE and PET used in the open-loop scenarios are the ACC resin data revised in 2010.

RECYCLING ALLOCATION METHODS

As described in the **Postconsumer Recycling** section of Chapter 1, results are presented for two commonly used recycling allocation methodologies. Both of these methodological approaches are acceptable under the ISO standards; however, there are differences in the results obtained by using the two approaches.

In the method referred to here as the “cut-off” method, all virgin material production burdens are assigned to the first use of the material, and the burdens assigned to the recycled resin system begin with recovery of the postconsumer material. All of the burdens for material recovery, transport, separation and sorting, and reprocessing are assigned to the recycled material.

In the open-loop allocation method, the burdens for virgin material production, recovery and recycling, and ultimate disposal of recycled material are shared among all the sequential useful lives of the material. Therefore, the share of virgin material burdens allocated to any individual use of the resin depends upon assumptions about the total number of useful lives of the resin. This analysis does not define the application in which the recycled resin will be used, and no projections are made about future recovery and recycling of the material. For the purposes of presenting cradle-to-gate open-loop results for recycled resin, this analysis uses an assumption of **two** useful lives of the material (resin used in a virgin product, then in a recycled product, then disposed), so the burdens for virgin material production, postconsumer recovery, and reprocessing are divided between the virgin and recycled uses of the material. Because this analysis is focused on production of resin used as an input to product manufacturing, no burdens are included here for manufacturing, use, or end-of-life management of a product made from the recycled resin. Those life cycle stages will depend on the specific product application in which the resin is being used.

When the recycled resin data are used for open-loop modeling of product systems, the number of useful lives of the material should be adjusted as appropriate if there is recycling of the secondary product at the end of its useful life. Further guidance for using the data in this report to model product systems using recycled resin is provided at the end of this chapter.

LIFE CYCLE INVENTORY RESULTS

For each resin, the results tables and figures break out results by the three life cycle stages described in Chapter 2: (1) recovery, (2) sorting and separation, and (3) reclaimer operations. Allocated virgin material production burdens are also included for the open-loop recycling scenarios. Each set of tables and figures shows results for both recycling allocation methods (cut-off and open-loop) as well as for the two methods of allocating curbside collection burdens to plastics (weight-based and volume-based). Weight-based allocation results in slightly lower collection requirements for plastics compared to volume-based allocation.[7] In each table, results for production of virgin resin are shown at the bottom for comparison with the cut-off and open-loop recycling results. In each table, the virgin resin data results are for ACC virgin resin data updated in 2010.

Energy Results

Energy requirements for recycled resin production are shown for PET in Table 3-1 and for HDPE in Table 3-2. Energy results for PET are shown by life cycle stage in Figure 3-1a and by energy category in Figure 3-1b, while HDPE energy results are shown in Figures 3-2a and 3-2b.

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[7] As described in Chapter 2, the volume-based collection scenario is based on 50% compaction, the minimum compaction required for collected recyclables to fit in the collection vehicle.

Table 3-1. Energy and Water Use for Recycled PET Resin
(million Btu of energy and gallons of water per 1,000 pounds of resin)

	Process	Transport	EMR	TOTAL	% of Total	Water Use
PET - Cut-off, weight-based collection						
Collection (weight-based)	0.026	0.51	0	0.53	11%	0
Sorting/Separation	0.10	0.045	0	0.15	3%	0
Reclaimer Processing to Flake	3.77	0.44	0	4.21	86%	47.3
Total for PET Flake	**3.90**	**1.00**	**0**	**4.89**		**47.3**
Percent by Category	80%	20%	0%			
Conversion of Flake to Pellet	2.33	0	0	2.33		0
Total for PET Pellet	**6.22**	**1.00**	**0**	**7.22**		**47.3**
Percent by Category	86%	14%	0%			
PET - Cut-off, volume-based collection (50% compaction)						
Collection (50% compaction)	0.026	0.72	0	0.74	15%	0
Sorting/Separation	0.10	0.045	0	0.15	3%	0
Reclaimer Processing to Flake	3.77	0.44	0	4.21	83%	47.3
Total for PET Flake	**3.90**	**1.21**	**0**	**5.10**		**47.3**
Percent by Category	76%	24%	0%			
Conversion of Flake to Pellet	2.33	0	0	2.33		0
Total for PET Pellet	**6.22**	**1.21**	**0**	**7.43**		**47.3**
Percent by Category	84%	16%	0%			
PET - Open-loop, weight-based collection						
Allocated Virgin Resin Production (2010)	7.45	0.33	8.18	16.0	87%	0
Collection (weight-based)	0.013	0.25	0	0.27	1%	0
Sorting/Separation	0.051	0.022	0	0.073	0.4%	0
Reclaimer Processing to Flake	1.88	0.22	0	2.11	11%	23.7
Total for PET Flake	**9.40**	**0.83**	**8.18**	**18.4**		**23.7**
Percent by Category	51%	4%	44%			
Conversion of Flake to Pellet	1.16	0	0	1.16		0
Total for PET Pellet	**10.56**	**0.83**	**8.18**	**19.6**		**23.7**
Percent by Category	54%	4%	42%			
PET - Open-loop, volume-based collection (50% compaction)						
Allocated Virgin Resin Production (2010)	7.45	0.33	8.18	16.0	86%	0
Collection (50% compaction)	0.013	0.36	0	0.37	2%	0
Sorting/Separation	0.051	0.022	0	0.073	0.4%	0
Reclaimer Processing to Pellet	1.88	0.22	0	2.11	11%	23.7
Total for PET Flake	**9.40**	**0.93**	**8.18**	**18.5**		**23.7**
Percent by Category	51%	5%	44%			
Conversion of Flake to Pellet	1.16	0	0	1.16		0
Total for PET Pellet	**10.56**	**0.93**	**8.18**	**19.7**		**23.7**
Percent by Category	54%	5%	42%			

	Total Energy	% of Virgin
Virgin PET production burdens (2010 resin data)	31.9	
Recycled PET flake		
PET - Cut-off, weight-based collection	4.89	15%
PET - Cut-off, volume-based collection (50% compaction)	5.10	16%
PET - Open-loop, weight-based collection	18.4	58%
PET - Open-loop, volume-based collection (50% compaction)	18.5	58%

Source: Franklin Associates, A Division of ERG

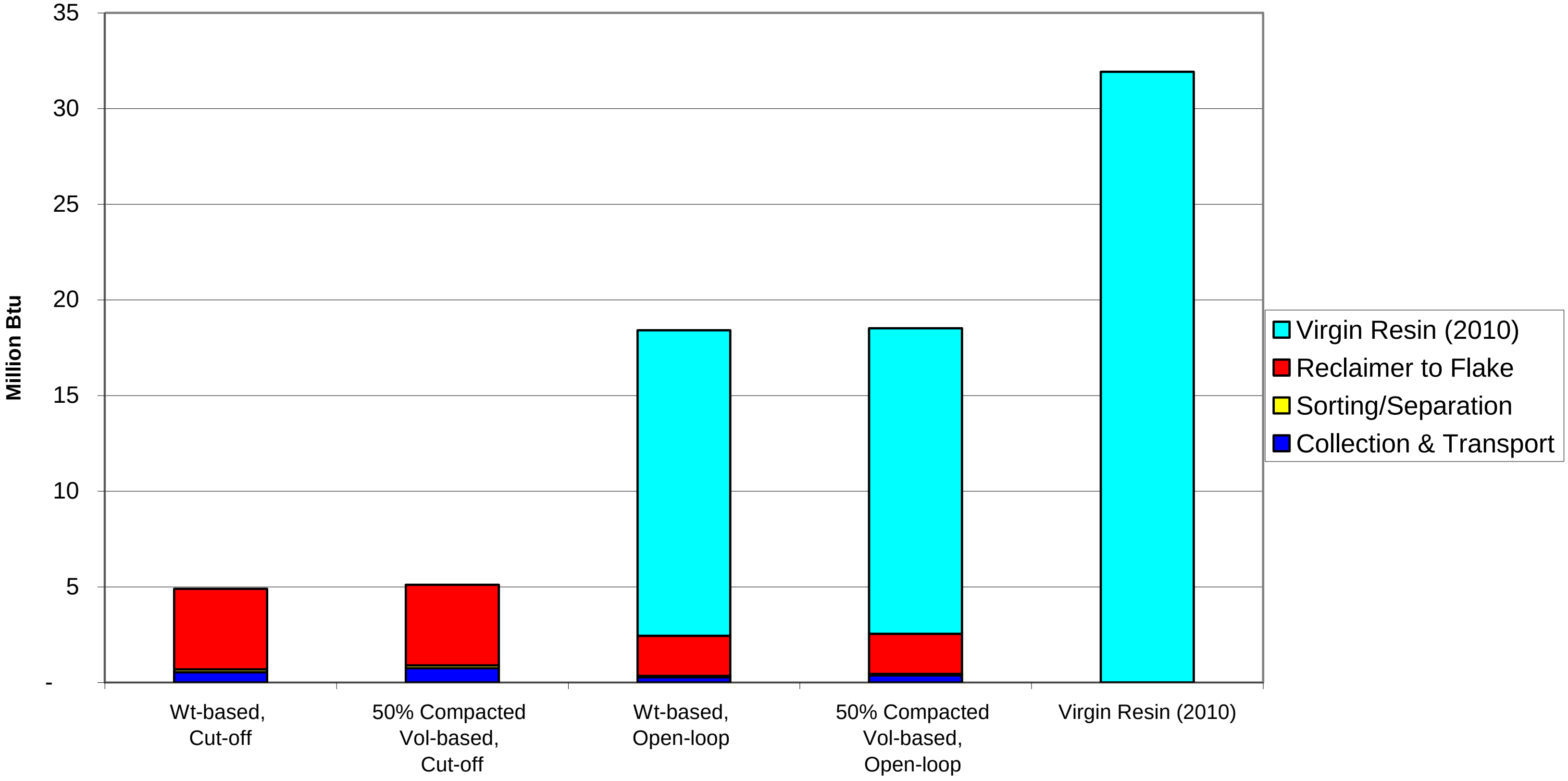
Table 3-2. Energy and Water Use for Recycled HDPE Resin
(million Btu of energy and gallons of water per 1,000 pounds of resin)

	Process	Transport	EMR	TOTAL	% of Total	Water Use
HDPE - Cut-off, weight-based collection						
Collection (weight-based)	0.0065	0.54	0	0.55	15%	0
Sorting/Separation	0.15	0.056	0	0.20	5%	0
Reclaimer Processing to Pellet	2.52	0.44	0	2.97	80%	53.3
Total for HDPE Pellet	**2.68**	**1.04**	**0**	**3.72**		**53.3**
Percent by Category	72%	28%	0%			
HDPE - Cut-off, volume-based collection (50% compaction)						
Collection (50% compaction)	0.0065	0.86	0	0.87	22%	0
Sorting/Separation	0.15	0.056	0	0.20	5%	0
Reclaimer Processing to Pellet	2.52	0.44	0	2.97	73%	53.3
Total for HDPE Pellet	**2.68**	**1.36**	**0**	**4.04**		**53.3**
Percent by Category	66%	34%	0%			
HDPE - Open-loop, weight-based collection						
Allocated Virgin Resin Production (2010)	5.93	0.26	11.7	17.9	91%	0
Collection (weight-based)	0.0033	0.27	0	0.28	1%	0
Sorting/Separation	0.074	0.028	0	0.10	0.5%	0
Reclaimer Processing to Pellet	1.26	0.22	0	1.48	8%	26.7
Total for HDPE Pellet	**7.27**	**0.78**	**11.7**	**19.7**		**26.7**
Percent by Category	37%	4%	59%			
HDPE - Open-loop, volume-based collection (50% compaction)						
Allocated Virgin Resin Production (2010)	5.93	0.26	11.7	17.9	90%	0
Collection (50% compaction)	0.0033	0.43	0	0.44	2%	0
Sorting/Separation	0.074	0.028	0	0.10	0.5%	0
Reclaimer Processing to Pellet	1.26	0.22	0	1.48	7%	26.7
Total for HDPE Pellet	**7.27**	**0.94**	**11.7**	**19.9**		**26.7**
Percent by Category	37%	5%	59%			

	Total Energy	% of Virgin
Virgin HDPE production burdens (2010 resin data)	35.8	
Recycled HDPE Pellet		
HDPE - Cut-off, weight-based collection	3.72	12%
HDPE - Cut-off, volume-based collection (50% compaction)	4.04	13%
HDPE - Open-loop, weight-based collection	19.7	62%
HDPE - Open-loop, volume-based collection (50% compaction)	19.9	62%

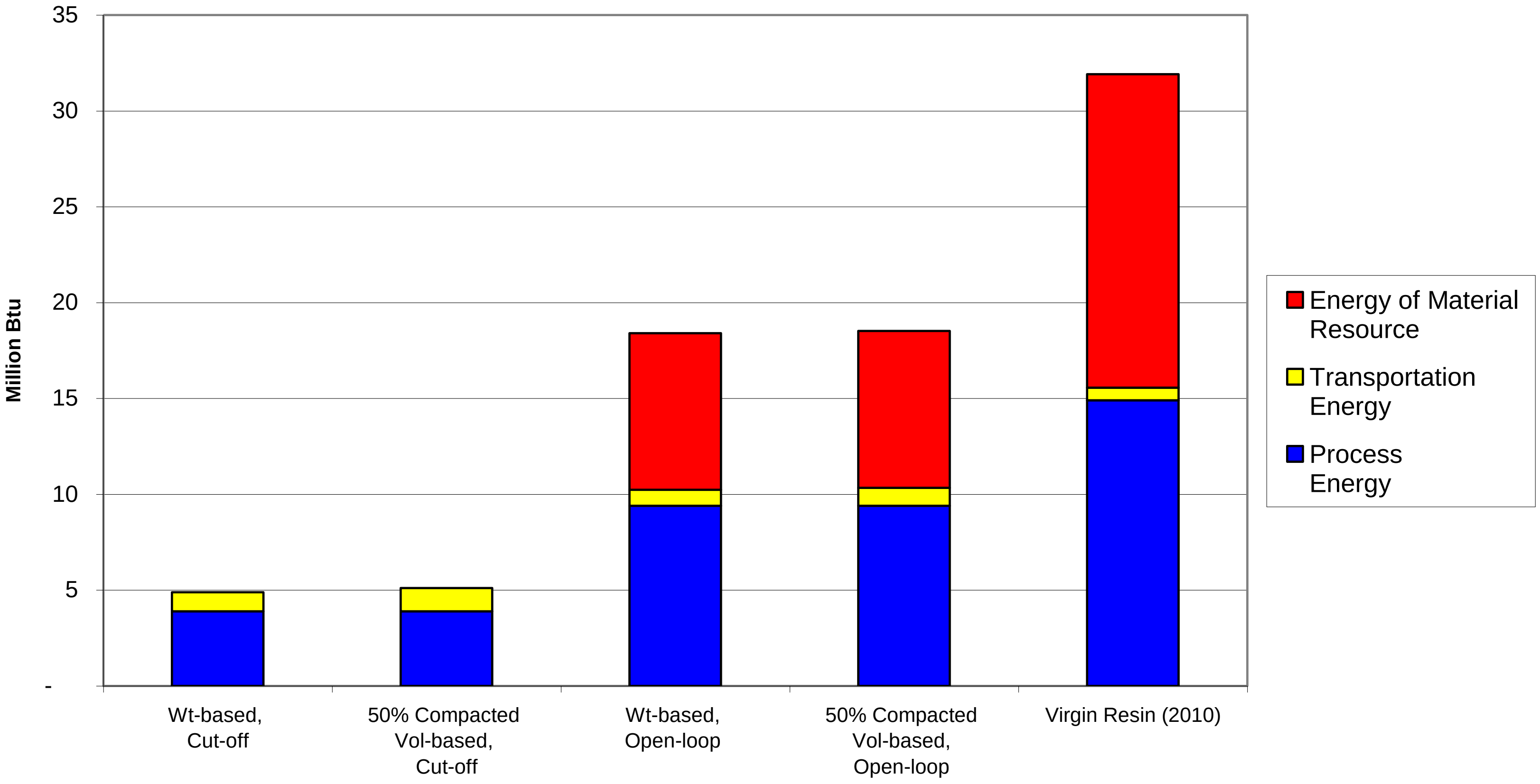
Source: Franklin Associates, A Division of ERG

Figure 3-1a. Energy Results by Life Cycle Stage for Production of Recycled PET Resin Flake (million Btu per 1,000 pounds of resin)



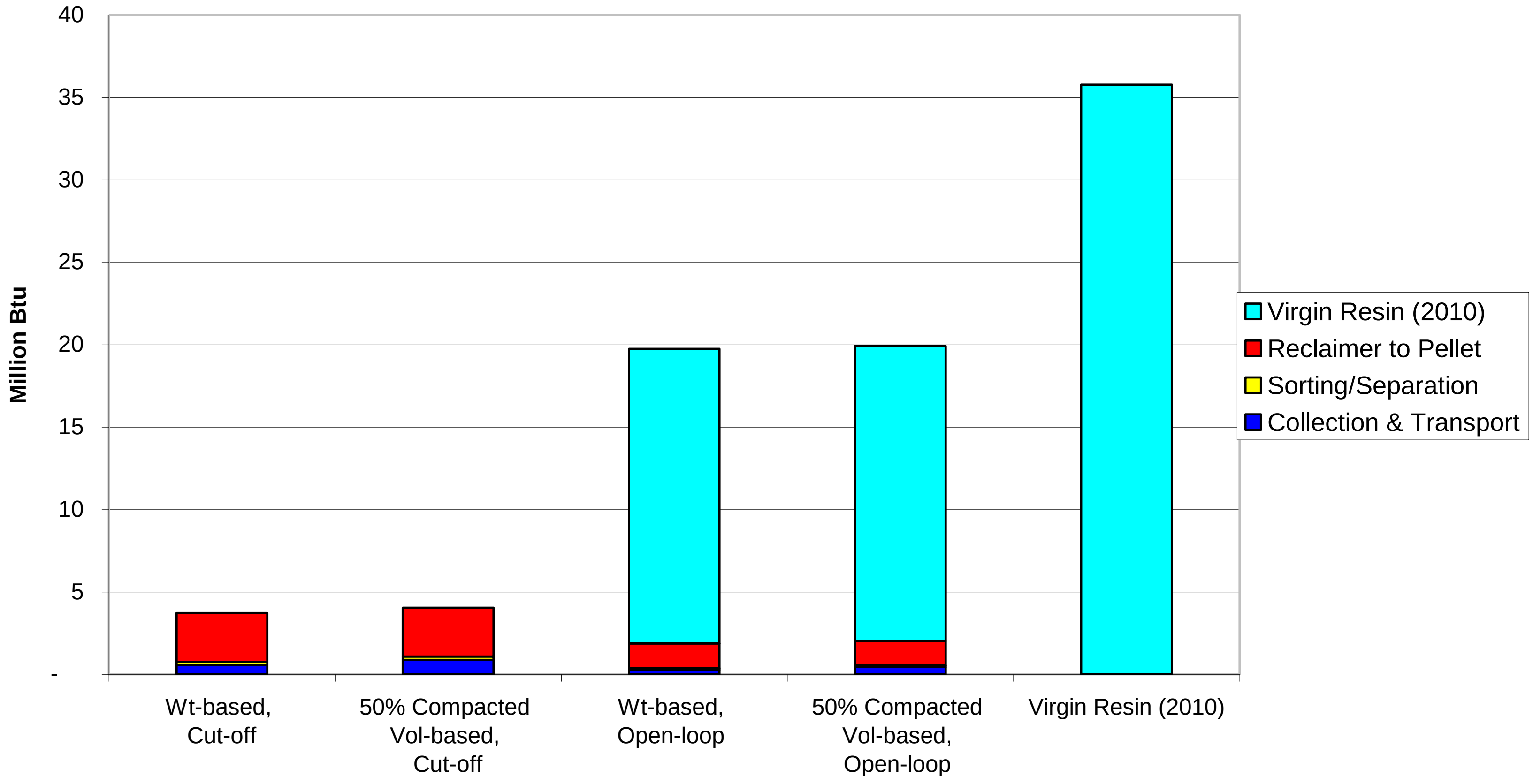
Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-1b. Energy Results by Energy Category for Production of Recycled PET Resin Flake (million Btu per 1,000 pounds of resin)



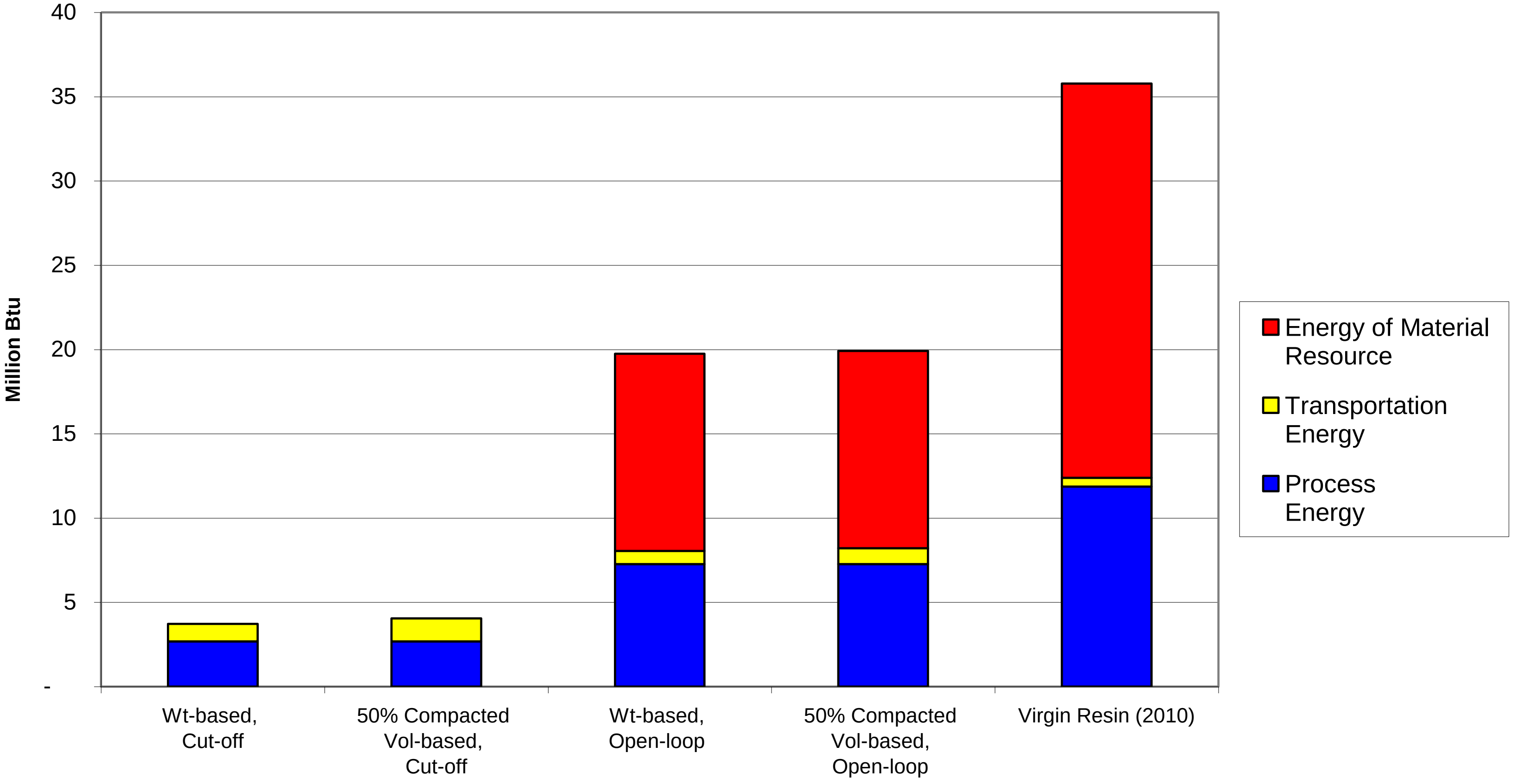
Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-2a. Energy Results by Life Cycle Stage for Production of Recycled HDPE Resin Pellet (million Btu per 1,000 pounds of resin)



Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-2b. Energy Results by Energy Category for Production of Recycled HDPE Resin Pellet (million Btu per 1,000 pounds of resin)



Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

The three energy categories used in the tables and figures are (1) process energy, (2) transportation energy, and (3) energy of material resource. **Process energy** is the energy used to extract and process raw materials and to operate equipment used in the recycling processes. **Transportation energy** is the energy for the production and consumption of fuels used to collect postconsumer material and transport material between process steps.[8] **Energy of material resource (EMR)** is assigned to fuel resources such as crude oil and natural gas used as material feedstocks (e.g., to produce virgin HDPE and PET resin).

The tables show that total energy requirements for recycled PET flake are 15 to 16 percent of virgin PET resin burdens when the cut-off recycling method is used, and 58 percent of virgin resin energy using the open-loop recycling allocation method. Within each method, curbside collection burdens allocated to plastic on a weight basis are lower than volume-based collection allocation. For HDPE, recycled HDPE pellets require 12 to 13 percent as much energy as virgin HDPE resin when the cut-off recycling method is used, and 62 percent as much energy as virgin for the open-loop recycling method. Using the cut-off method, no energy of material resource is assigned to the recycled material, and the largest share of the energy requirements for recycled resin production is for reclaimer operations, as shown in Figures 2-1b and 2-2b.

Water Use Results

Water use for recycled resin production is shown for PET in Table 3-1 and for HDPE in Table 3-2. The water use shown is for postconsumer plastic processing only; no water use for virgin resin production processes are included. The MRFs that provided data for this analysis did not reported any use of water in material sorting and separation operations; therefore, the water use shown in Tables 3-1 and 3-2 is mainly for washing operations at PRF and reclaimer facilities, although some flotation separation was also reported.

Solid Waste Results

Solid wastes for recycled resin production are shown for PET in Table 3-3 and for HDPE in Table 3-4. Solid waste results for PET are shown by life cycle stage in Figure 3-3a and by waste category in Figure 3-3b, while HDPE solid waste results are shown in Figures 3-4a and 3-4b.

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[8] The transportation energy shown in the tables for the Sorting/Separation and Reclaimer Processing steps is the energy required to transport the material **to** the MRF or reclaimer.

Process wastes are wastes or residues from process steps used to extract raw materials and processing them into usable products or to sort, separate, or process postconsumer material. Process scrap that is put to some use on-site or by an off-site user is not included in process wastes. **Fuel-related wastes** are the wastes resulting from the production and consumption of fuels used for process or transportation energy. This includes wastes associated with the combustion of fuels used for operations at the MRF, PRF, or reclaimer facility, as well as wastes associated with the fuel used to collect postconsumer material and transport it to MRFs, PRFs, and reclaimers. Because this analysis extends only through production of recycled resin ready for use and does not include use of the recycled resin in a product system, no postconsumer wastes are modeled.

The solid waste figures show that the solid wastes disposed from recycled resin sorting and processing steps are much higher than process solid wastes from virgin resin production. The process wastes shown for recycled resin production are largely contaminants that were co-collected with the recovered plastic and are separated from the recovered material during sorting and separation processes. Although the contaminant wastes are removed and disposed at facilities where recycling processes occur, these wastes are not *caused* by recycling processes. The data provided by material recovery facilities and reclaimers for this study show that all usable materials are recovered from the incoming material received wherever possible, including materials other than the desired resin. Therefore, the majority of the solid waste disposed from the sorting and processing operations is material that would have been disposed as waste regardless of whether postconsumer plastic recycling takes place. If the co-collected wastes are excluded, the solid wastes for recycled resin production are lower than the solid wastes for virgin resin production, as shown at the bottom of Tables 3-3 and 3-4.

Table 3-3. Solid Waste for Recycled PET Resin
(pounds of waste per 1,000 pounds of resin)

	Process Solid Wastes					
	Landfill	**Incineration**	**Waste-to-Energy**	**Fuel-related Solid Wastes**	**TOTAL**	**% of Total**
PET - Cut-off, weight-based collection						
Collection (weight-based)	0	0	0	1.70	1.70	0.5%
Sorting/Separation	72.7	0	0	1.25	74.0	22%
Reclaimer Processing to Flake	220	0	0	46.4	267	78%
Total for PET Flake	**293**	**0**	**0**	**49.4**	**342**	
Percent by Category	86%	0%	0%	14%		
Conversion of Flake to Pellet	0	0	0	43.0	43.0	
Total for PET Pellet	**293**	**0**	**0**	**92.4**	**385**	
Percent by Category	76%	0%	0%	24%		
PET - Cut-off, volume-based collection (50% compaction)						
Collection (50% compaction)	0	0	0	2.21	2.21	1%
Sorting/Separation	72.7	0	0	1.25	74.0	22%
Reclaimer Processing to Flake	220	0	0	46.4	267	78%
Total for PET Flake	**293**	**0**	**0**	**49.9**	**343**	
Percent by Category	85%	0%	0%	15%		
Conversion of Flake to Pellet	0	0	0	43.0	43.0	
Total for PET Pellet	**293**	**0**	**0**	**92.9**	**386**	
Percent by Category	76%	0%	0%	24%		
PET - Open-loop, weight-based collection						
Allocated Virgin Resin Production (2010)	16.5	1	0	53.7	71.0	29%
Collection (weight-based)	0	0	0	0.85	0.85	0.4%
Sorting/Separation	36.4	0	0	0.63	37.0	15.3%
Reclaimer Processing to Flake	110	0	0	23.2	133	55%
Total for PET Flake	**163**	**1**	**0**	**78.4**	**242**	
Percent by Category	67%	0%	0%	32%		
Conversion of Flake to Pellet	0	0	0	21.5	21.5	
Total for PET Pellet	**163**	**1**	**0**	**99.9**	**264**	
Percent by Category	62%	0%	0%	38%		
PET - Open-loop, volume-based collection (50% compaction)						
Allocated Virgin Resin Production (2010)	16.5	1	0	53.7	71.0	29%
Collection (50% compaction)	0	0	0	1.11	1.11	0%
Sorting/Separation	36.4	0	0	0.63	37.0	15%
Reclaimer Processing to Pellet	110	0	0	23.2	133	55%
Total for PET Flake	**163**	**1**	**0**	**78.7**	**242**	
Percent by Category	67%	0%	0%	32%		
Conversion of Flake to Pellet	0	0	0	21.5	21.5	
Total for PET Pellet	**163**	**1**	**0**	**100**	**264**	
Percent by Category	62%	0%	0%	38%		

	Process + Fuel Waste	**% of Virgin**	**Without Sorting & Reclaimer Process Waste**	**% of Virgin**
Virgin PET production burdens (2010 resin data)	142		142	
Recycled PET flake				
PET - Cut-off, weight-based collection	342	241%	49.4	35%
PET - Cut-off, volume-based collection (50% compaction)	343	242%	49.9	35%
PET - Open-loop, weight-based collection	242	171%	95.7	67%
PET - Open-loop, volume-based collection (50% compaction)	242	171%	95.9	68%

Source: Franklin Associates, A Division of ERG

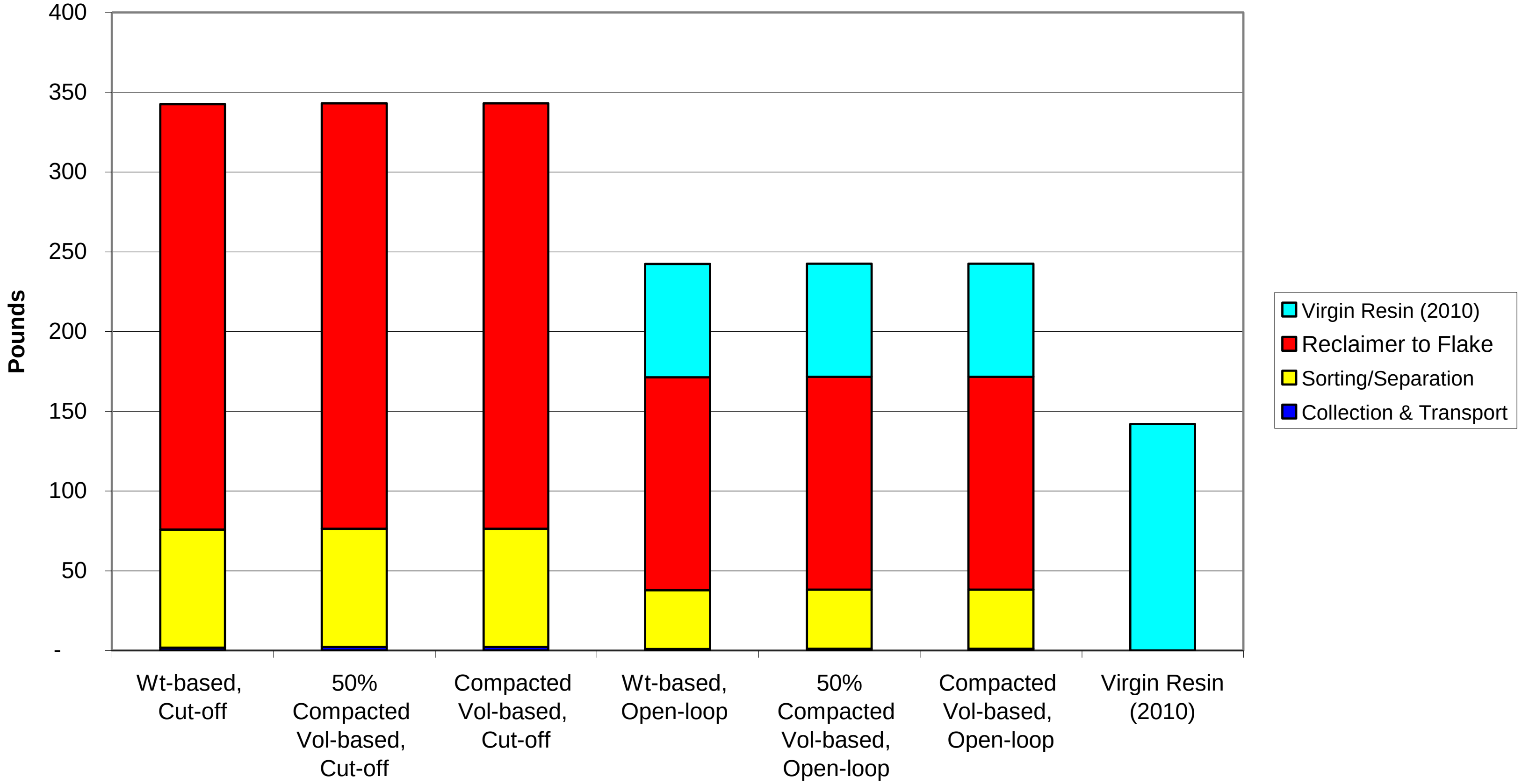
Table 3-4. Solid Waste for Recycled HDPE Resin
(pounds of waste per 1,000 pounds of resin)

	Process Solid Wastes					
	Landfill	**Incineration**	**Waste-to-Energy**	**Fuel-related Solid Wastes**	**TOTAL**	**% of Total**
HDPE - Cut-off, weight-based collection						
Collection (weight-based)	0	0	0	1.42	1.42	0.7%
Sorting/Separation	98.2	0	0	1.79	100	47%
Reclaimer Processing to Pellet	65.7	0	0	45.1	111	52%
Total for HDPE Pellet	**164**	**0**	**0**	**48.3**	**212**	
Percent by Category	77%	0%	0%	23%		
HDPE - Cut-off, volume-based collection (50% compaction)						
Collection (50% compaction)	0	0	0	2.19	2.19	1%
Sorting/Separation	98.2	0	0	1.79	100	47%
Reclaimer Processing to Pellet	65.7	0	0	45.1	111	52%
Total for HDPE Pellet	**164**	**0**	**0**	**49.1**	**213**	
Percent by Category	77%	0%	0%	23%		
HDPE - Open-loop, weight-based collection						
Allocated Virgin Resin Production (2010)	14.8	2	0	20.6	37.3	26%
Collection (weight-based)	0	0	0	0.71	0.71	0.5%
Sorting/Separation	49.1	0	0	0.89	50.0	34.9%
Reclaimer Processing to Pellet	32.8	0	0	22.6	55.4	39%
Total for HDPE Pellet	**96.7**	**2**	**0**	**44.8**	**143**	
Percent by Category	67%	1%	0%	31%		
HDPE - Open-loop, volume-based collection (50% compaction)						
Allocated Virgin Resin Production (2010)	14.8	2	0	20.6	37.3	26%
Collection (50% compaction)	0	0	0	1.10	1.10	1%
Sorting/Separation	49.1	0	0	0.89	50.0	34.8%
Reclaimer Processing to Pellet	32.8	0	0	22.6	55.4	39%
Total for HDPE Pellet	**96.7**	**2**	**0**	**45.2**	**144**	
Percent by Category	67%	1%	0%	31%		

	Process + Fuel Waste	**% of Virgin**	**Without Sorting & Reclaimer Process Waste**	**% of Virgin**
Virgin HDPE production burdens (2010 resin data)	74.6		74.6	
Recycled HDPE Pellet				
HDPE - Cut-off, weight-based collection	212	149%	48.3	34%
HDPE - Cut-off, volume-based collection (50% compaction)	213	150%	49.1	35%
HDPE - Open-loop, weight-based collection	143	101%	61.5	43%
HDPE - Open-loop, volume-based collection (50% compaction)	144	101%	61.9	44%

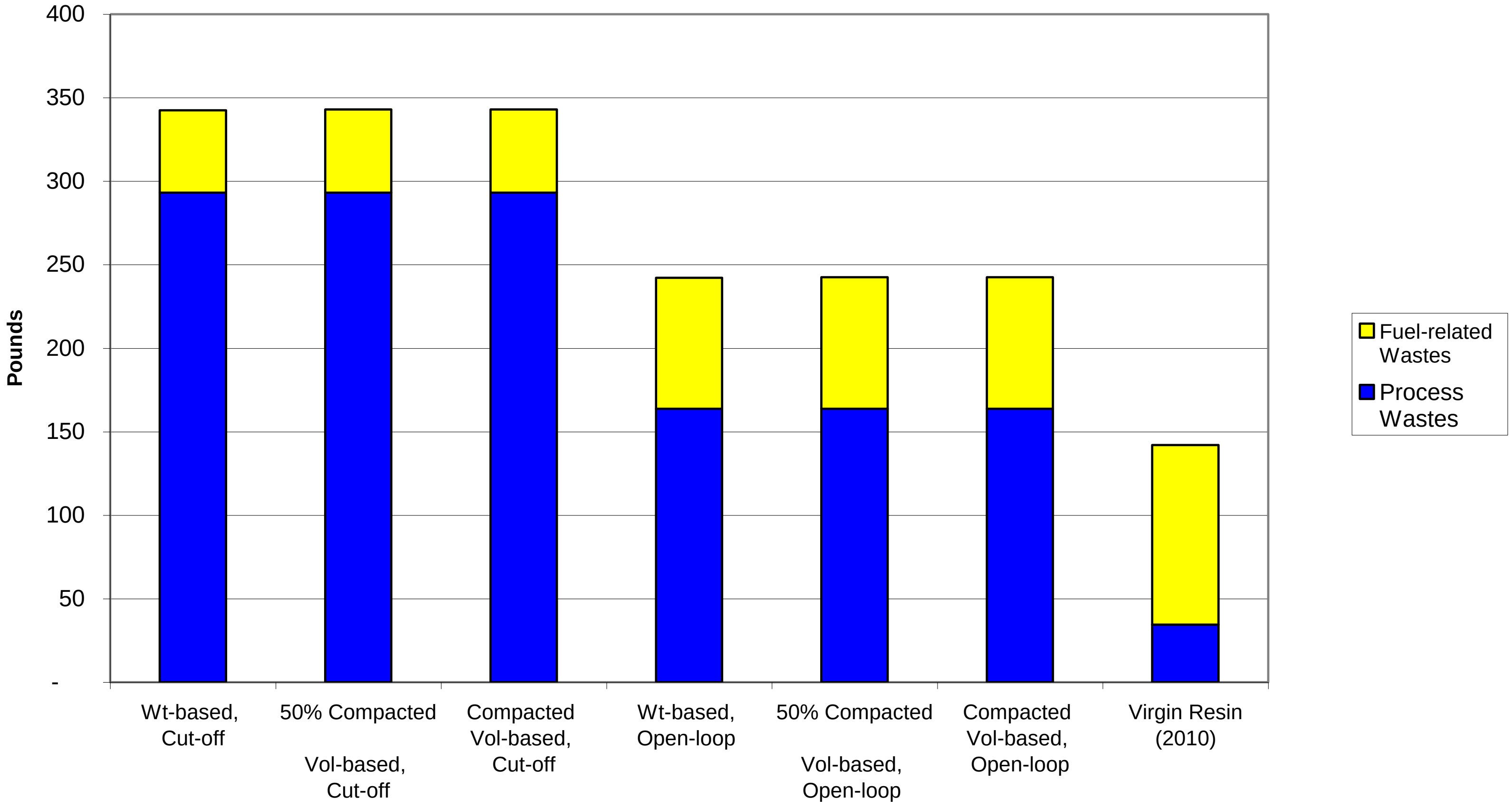
Source: Franklin Associates, A Division of ERG

Figure 3-3a. Solid Waste Results by Life Cycle Stage for Production of Recycled PET Resin Flake (pounds per 1,000 pounds of resin



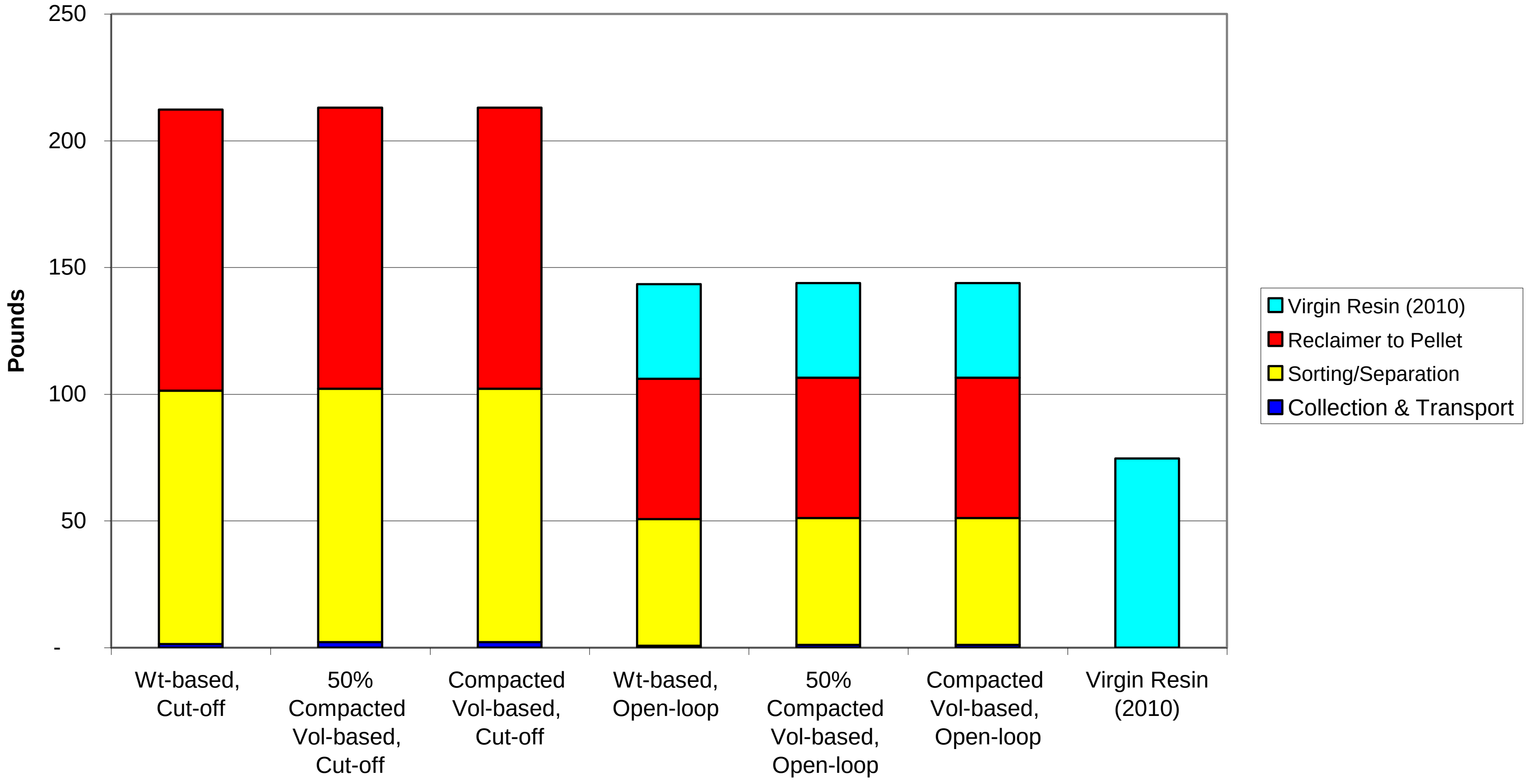
Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-3b. Solid Waste Results by Solid Waste Category for Production of Recycled PET Resin Flake (pounds per 1,000 pounds of resin)



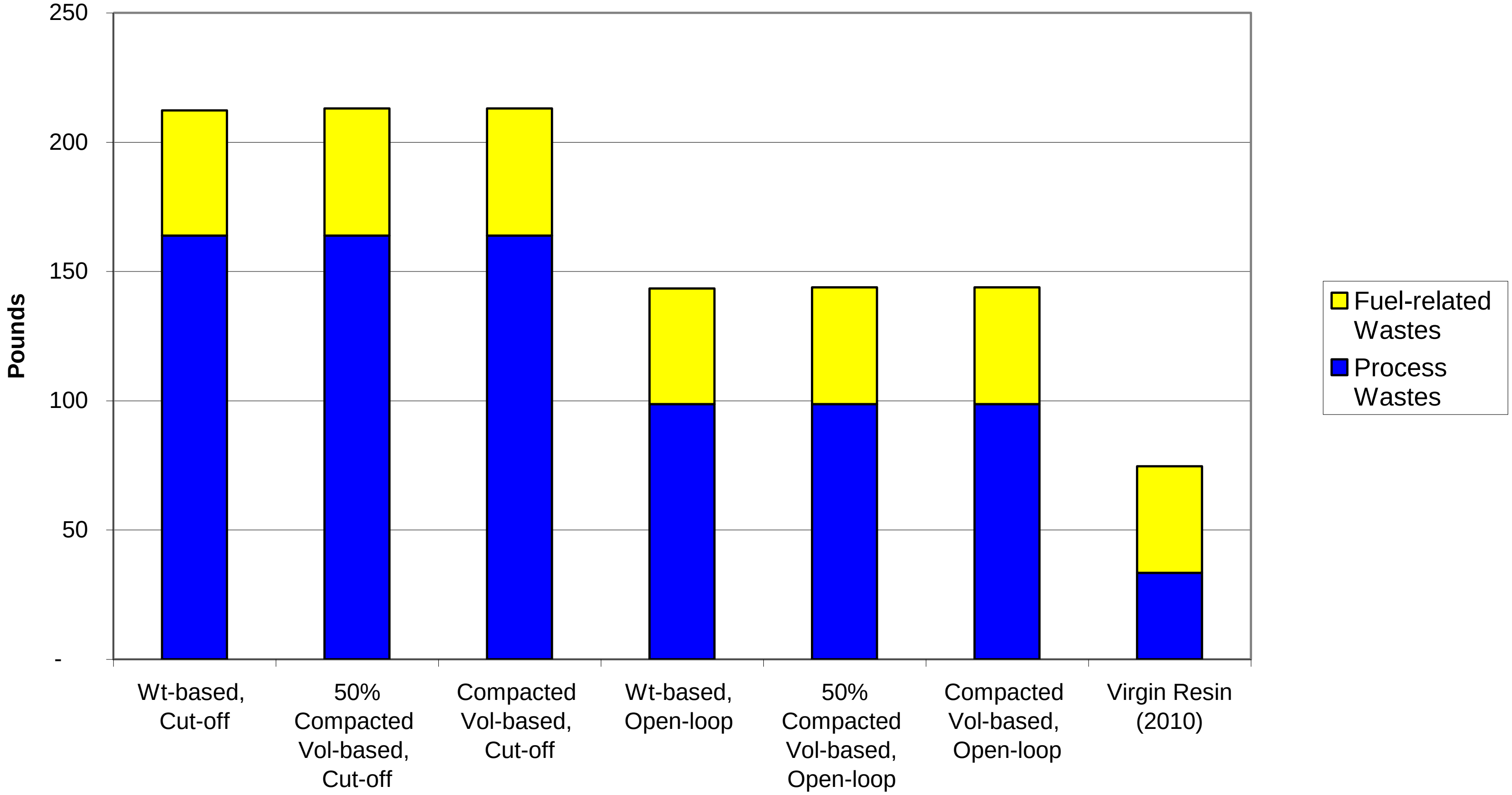
Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-4a. Solid Waste Results by Life Cycle Stage for Production of Recycled HDPE Resin Pellet (pounds per 1,000 pounds of resin)



Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-4b. Solid Waste Results by Solid Waste Category for Production of Recycled HDPE Resin Pellet (pounds per 1,000 pounds of resin)



Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Atmospheric and Waterborne Emissions

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels. The emissions tables in this section present emission quantities based upon the best data available. However, in the hundreds of unit processes included in the system models, some emissions data have been reported from 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 system include emissions from processes and emissions associated with the combustion of fuels. **Process emissions** are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise effect changes on a material or product during its life cycle, while **fuel-related emissions** are those associated with the combustion of fuels used for process energy and transportation energy. 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 resin system, 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 recycled resin production are shown for PET in Table 3-5 and for HDPE in Table 3-6. GHG results for PET are shown by life cycle stage in Figure 3-5a and by emission category in Figure 3-5b, while HDPE GHG results are shown in Figures 3-4a and 3-4b.

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.[9] 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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[9] 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 3-5. Greenhouse Gas Emissions for Recycled PET Resin
(pounds per 1,000 pounds of resin)

	Fuel-Related Emissions (lb)			Process Emissions (lb)			Global Warming Potential (lb CO2 equivalents)		
	Fossil CO2	**Methane**	**Nitrous Oxide**	**Fossil CO2**	**Methane**	**Nitrous Oxide**	**IPCC SAR***	**IPCC 2007****	**% of Total**
PET - Cut-off, weight-based collection									
Collection (weight-based)	90.1	0.12	0.0027	0	0	0	93.4	93.8	12%
Sorting/Separation	23.7	0.038	6.6E-04	0	0	0	24.7	24.9	3%
Reclaimer Processing to Flake	604	1.76	0.014	0	0	0	646	653	85%
Total for PET Flake	**718**	**1.92**	**0.017**	**0**	**0**	**0**	**764**	**771**	
Percent by Category	94%	5%	0.7%	0%	0%	0%			
Conversion of Flake to Pellet	353	0.79	0.0084	0	0	0	372	376	
Total for PET Pellet	**1,072**	**2.70**	**0.026**	**0**	**0**	**0**	**1,136**	**1,147**	
Percent by Category	94%	5%	0.7%	0%	0%	0%			
PET - Cut-off, volume-based collection (50% compaction)									
Collection (50% compaction)	126	0.16	0.0039	0	0	0	131	132	16%
Sorting/Separation	23.7	0.038	6.6E-04	0	0	0	24.7	24.9	3%
Reclaimer Processing to Flake	604	1.76	0.014	0	0	0	646	653	81%
Total for PET Flake	**755**	**1.96**	**0.018**	**0**	**0**	**0**	**802**	**809**	
Percent by Category	94%	5%	0.7%	0%	0%	0%			
Conversion of Flake to Pellet	353	0.79	0.0084	0	0	0	372	376	
Total for PET Pellet	**1,108**	**2.75**	**0.027**	**0**	**0**	**0**	**1,174**	**1,185**	
Percent by Category	94%	5%	0.7%	0%	0%	0%			
PET - Open-loop, weight-based collection									
Allocated Virgin Resin Production (2010)	1,080	3.38	0.025	148	3.18	0	1,373	1,399	78%
Collection (weight-based)	45.0	0.059	0.0013	0	0	0	46.7	46.9	3%
Sorting/Separation	11.9	0.019	3.3E-04	0	0	0	12.4	12.4	0.7%
Reclaimer Processing to Flake	302	0.88	0.0069	0	0	0	323	326	18%
Total for PET Flake	**1,439**	**4.34**	**0.034**	**148**	**3.18**	**0**	**1,755**	**1,785**	
Percent by Category	82%	5%	0.6%	8%	4%	0%			
Conversion of Flake to Pellet	177	0.39	0.0042	0	0	0	186	188	
Total for PET Pellet	**1,615**	**4.73**	**0.038**	**148**	**3.18**	**0**	**1,941**	**1,973**	
Percent by Category	83%	5%	0.6%	8%	3%	0%			
PET - Open-loop, volume-based collection (50% compaction)									
Allocated Virgin Resin Production (2010)	1,080	3.38	0.025	148	3.18	0	1,373	1,399	78%
Collection (50% compaction)	63.2	0.08	0.0019	0	0	0	65.5	65.8	4%
Sorting/Separation	11.9	0.019	3.3E-04	0	0	0	12.4	12.4	0.7%
Reclaimer Processing to Pellet	302	0.88	0.0069	0	0	0	323	326	18%
Total for PET Flake	**1,457**	**4.36**	**0.034**	**148**	**3.18**	**0**	**1,774**	**1,804**	
Percent by Category	82%	5%	0.6%	8%	4%	0%			
Conversion of Flake to Pellet	177	0.39	0.0042	0	0	0	186	188	
Total for PET Pellet	**1,634**	**4.76**	**0.039**	**148**	**3.18**	**0**	**1,960**	**1,991**	
Percent by Category	83%	5%	0.6%	8%	3%	0%			

	Total lb CO2 eq	**% of Virgin**
Virgin PET production burdens (2010 resin data)	2,746	
Recycled PET flake		
PET - Cut-off, weight-based collection	764	28%
PET - Cut-off, volume-based collection (50% compaction)	802	29%
PET - Open-loop, weight-based collection	1,755	64%
PET - Open-loop, volume-based collection (50% compaction)	1,774	65%

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*GWP factors for methane and nitrous oxide in the IPCC Second Assessment Report (SAR) are 21 and 310, respectively.

**GWP factors for methane and nitrous oxide in the IPCC 2007 report are 25 and 298, respectively.

Source: Franklin Associates, A Division of ERG

Table 3-6. Greenhouse Gas Emissions for Recycled HDPE Resin
(pounds per 1,000 pounds of resin)

	Fuel-Related Emissions (lb)			Process Emissions (lb)			Global Warming Potential (lb CO2 equivalents)		
	Fossil CO2	**Methane**	**Nitrous Oxide**	**Fossil CO2**	**Methane**	**Nitrous Oxide**	**IPCC SAR***	**IPCC 2007****	**% of Total**
HDPE - Cut-off, weight-based collection									
Collection (weight-based)	92.2	0.12	0.0029	0	0	0	95.6	96.0	16%
Sorting/Separation	32.8	0.053	9.1E-04	0	0	0	34.2	34.4	6%
Reclaimer Processing to Pellet	456	0.98	0.011	0	0	0	480	484	79%
Total for HDPE Pellet	**581**	**1.16**	**0.015**	**0**	**0**	**0**	**609**	**614**	
Percent by Category	95%	4%	0.7%	0%	0%	0%			
HDPE - Cut-off, volume-based collection (50% compaction)									
Collection (50% compaction)	148	0.19	0.0048	0	0	0	153	154	23%
Sorting/Separation	32.8	0.053	9.1E-04	0	0	0	34.2	34.4	5%
Reclaimer Processing to Pellet	456	0.98	0.011	0	0	0	480	484	72%
Total for HDPE Pellet	**636**	**1.22**	**0.017**	**0**	**0**	**0**	**667**	**672**	
Percent by Category	95%	4%	0.8%	0%	0%	0%			
HDPE - Open-loop, weight-based collection									
Allocated Virgin Resin Production (2010)	689	2.13	0.010	38.46	6.47	0	911	945	75%
Collection (weight-based)	46.1	0.059	0.0015	0	0	0	47.8	48.0	4%
Sorting/Separation	16.4	0.027	4.6E-04	0	0	0	17.1	17.2	1.4%
Reclaimer Processing to Pellet	228	0.49	0.0054	0	0	0	240	242	19%
Total for HDPE Pellet	**979**	**2.71**	**0.017**	**38.46**	**6.47**	**0**	**1,216**	**1,252**	
Percent by Category	81%	5%	0.4%	3%	11%	0%			
HDPE - Open-loop, volume-based collection (50% compaction)									
Allocated Virgin Resin Production (2010)	689	2.13	0.010	38.46	6.47	0	911	945	74%
Collection (50% compaction)	74	0.09	0.0024	0	0	0	77	77	6%
Sorting/Separation	16.4	0.027	4.6E-04	0	0	0	17.1	17.2	1.3%
Reclaimer Processing to Pellet	228	0.49	0.0054	0	0	0	240	242	19%
Total for HDPE Pellet	**1007**	**2.74**	**0.018**	**38.46**	**6.47**	**0**	**1,244**	**1,281**	
Percent by Category	81%	5%	0.5%	3%	11%	0%			

	Total lb CO2 eq	**% of Virgin**
Virgin HDPE production burdens (2010 resin data)	1,822	
Recycled HDPE Pellet		
HDPE - Cut-off, weight-based collection	609	22%
HDPE - Cut-off, volume-based collection (50% compaction)	667	24%
HDPE - Open-loop, weight-based collection	1,216	44%
HDPE - Open-loop, volume-based collection (50% compaction)	1,244	45%

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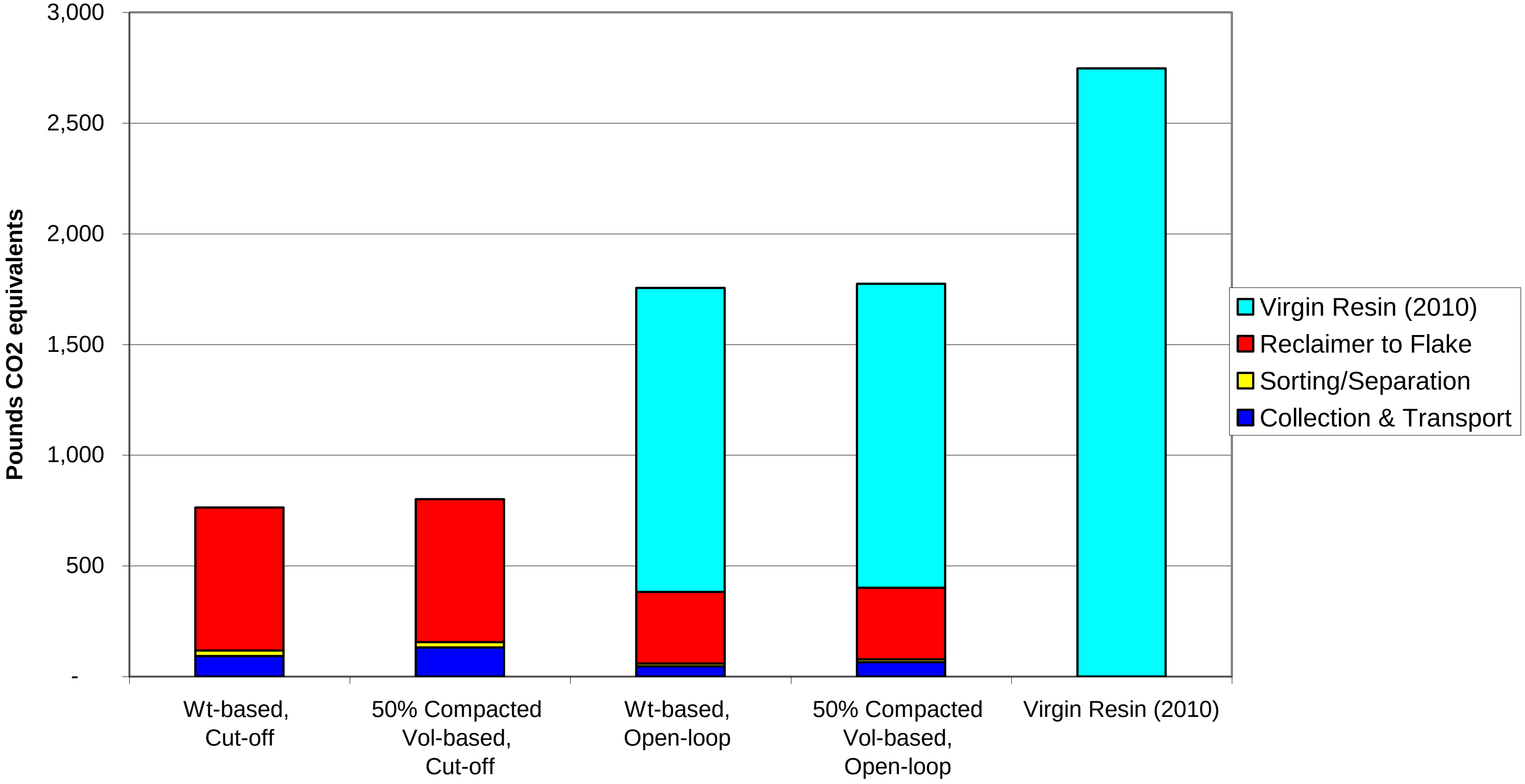
*GWP factors for methane and nitrous oxide in the IPCC Second Assessment Report (SAR) are 21 and 310, respectively.

**GWP factors for methane and nitrous oxide in the IPCC 2007 report are 25 and 298, respectively.

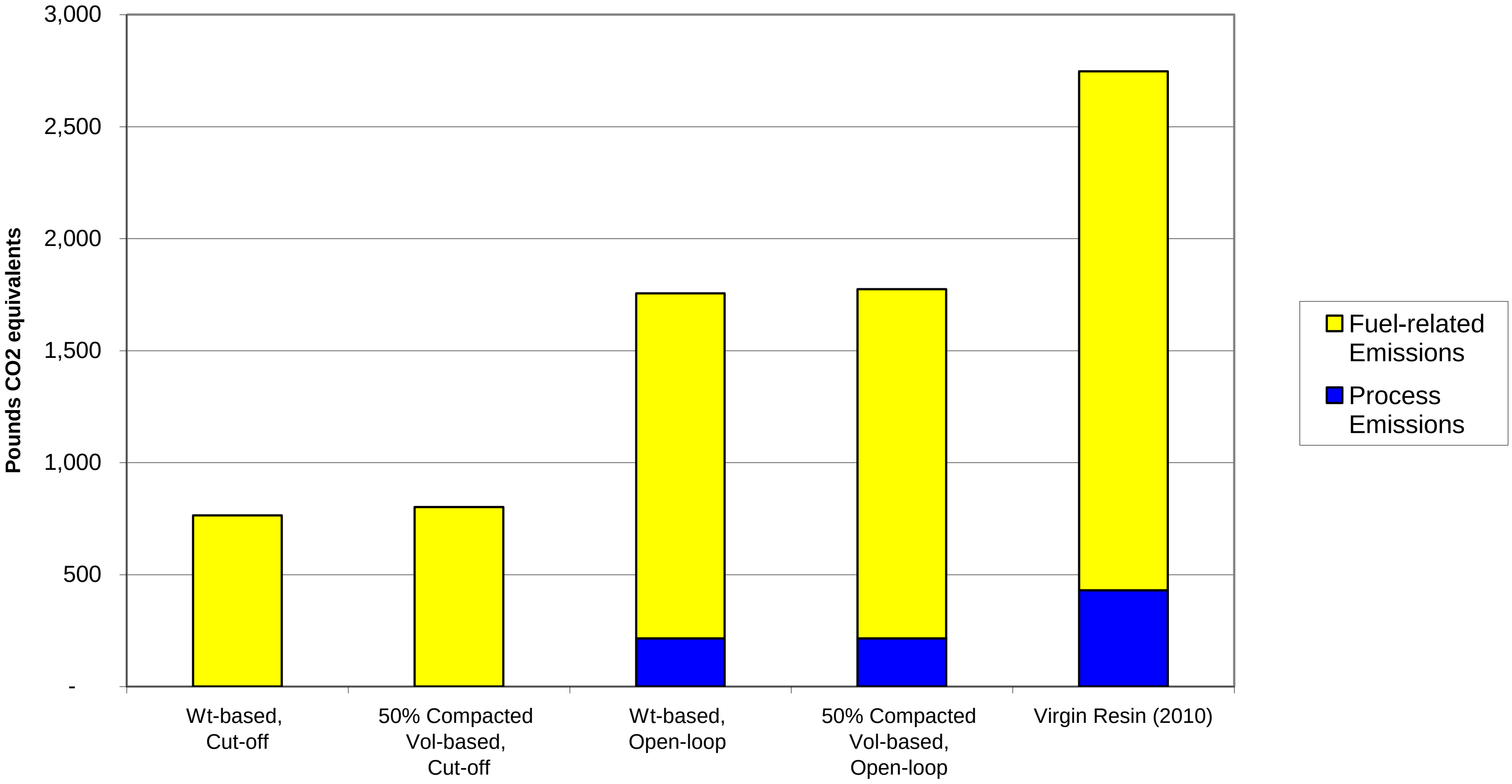
Source: Franklin Associates, A Division of ERG

Figure 3-5a. Greenhouse Gas Results by Life Cycle Stage for Production of Recycled PET Resin Flake (pounds CO2 equivalents per 1,000 pounds of resin)



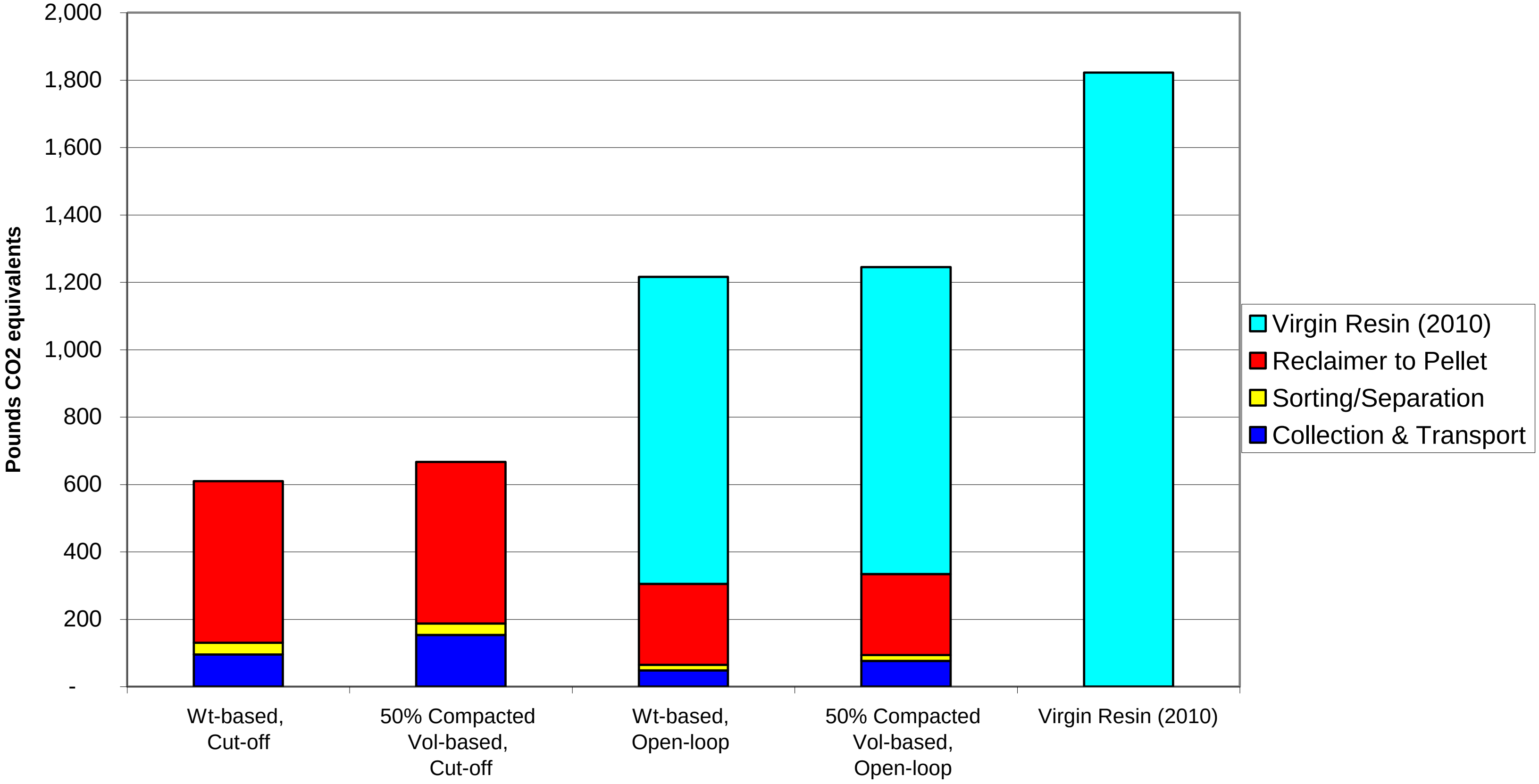
Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-5b. Greenhouse Gas Results by Emission Category for Production of Recycled PET Resin Flake (pounds CO2 equivalents per 1,000 pounds of resin)



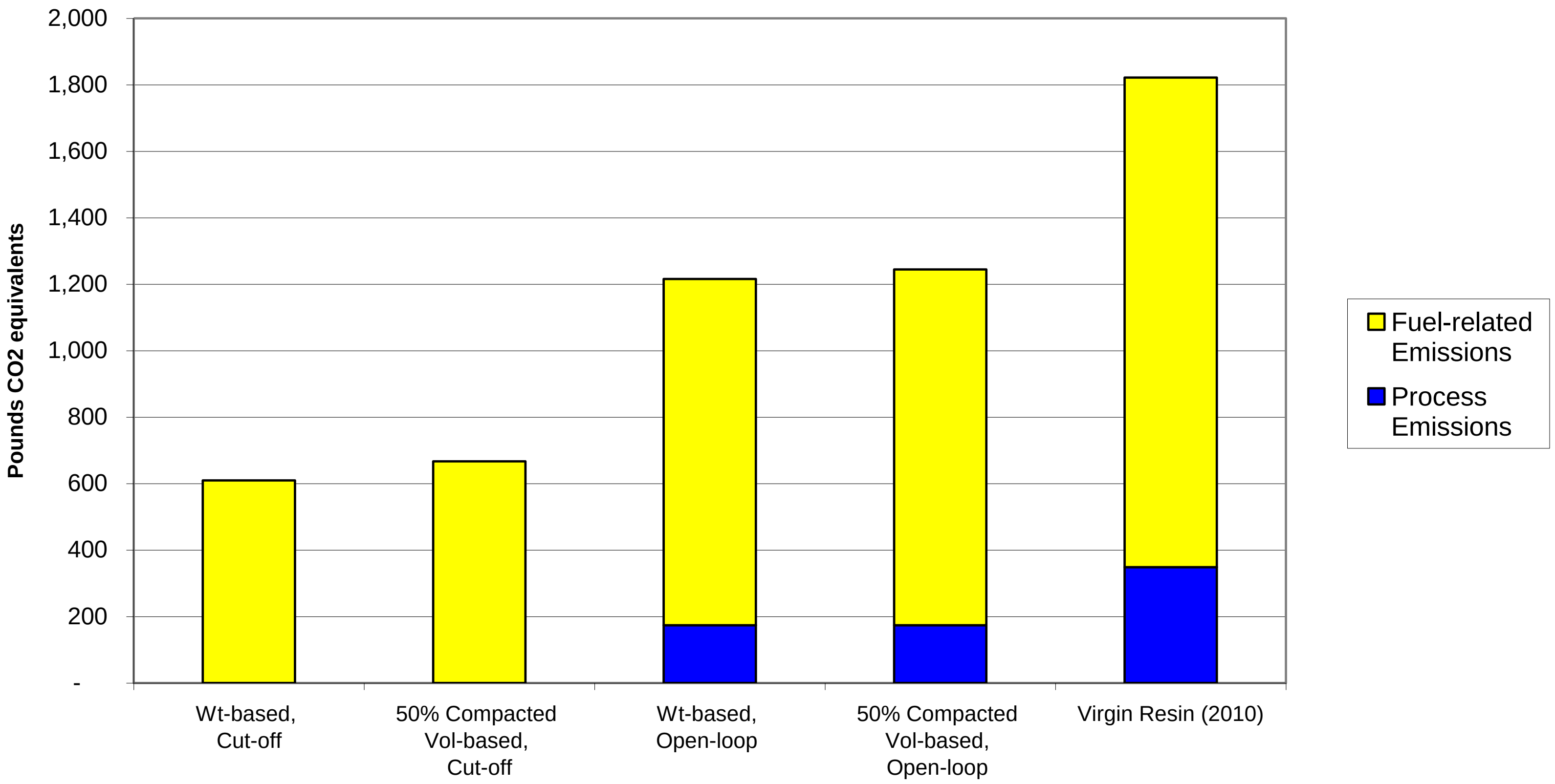
Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

**Figure 3-6a. Greenhouse Gas Results by Life Cycle Stage
for Production of Recycled HDPE Resin Pellet
(pounds CO2 equivalents per 1,000 pounds of resin)**



Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

Figure 3-6b. Greenhouse Gas Results by Emission Category for Production of Recycled HDPE Resin Pellet (pounds CO2 equivalents per 1,000 pounds of resin)



Cut-off method: Full burdens for collection, sorting, and reprocessing; no virgin resin burdens
Open-loop method: Half burdens for virgin resin production, collection, sorting, and reprocessing.

The tables and figures show that the majority of the GHG emissions are fuel-related. No process GHG emissions were reported for the collection, sorting and separation, and reclaimer processes; the only GHG emissions from these operations are associated with fuel use. There are process GHG emissions for production of virgin resins, so the open-loop recycled resin results include a share of these process emissions. Regardless of the recycling methodology used, the recycled resin systems show lower GHG emissions than virgin resin production.

Other Atmospheric and Waterborne Emissions. Tables showing the full list of atmospheric and waterborne emissions for each resin are shown at the end of this chapter in Tables 3-7 through 3-14. Tables 3-7 through 3-10 show emissions released directly from processes, while Tables 3-11 through 3-14 show emissions associated with production and combustion of fuels used for process energy and transportation. Fuel-related emissions include emissions from production and combustion of the fuels used to generate electricity used for process energy.

Each column in each table shows the **total** emissions for that resin scenario. Total emissions for the cut-off scenarios include the emissions for collection and transport, sorting and separation, and reprocessing. Total emissions for open-loop scenarios include half of the emissions for virgin resin production and half of the emissions for collection and transport, sorting and separation, and reprocessing.

In the PET fuel-related emissions tables 3-11 and 3-13, results are shown for flake and for pellet. The total fuel-related emissions for PET pellet include the fuel-related emissions from collection through flake production, plus the fuel-related emissions for the additional energy used to convert the flake to pellet. Since no process emissions were reported for pelletizing PET flake, the aggregated process emissions shown in Tables 3-7 and 3-9 are the same for flake or pellet.

USING THE DATA IN THIS REPORT FOR MODELING PRODUCT SYSTEMS

The results shown in the Chapter 3 tables are fully “rolled-up” data sets; that is, they include the burdens for all the processes required to produce recycled resin. Fully rolled-up datasets include not only the direct burdens for collecting, transporting, sorting, and reprocessing the material but also the upstream burdens for the production and combustion of all fuels used in these processes and the production of all materials used in the processes. 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 energy use for resin sorting or resin processing, or a change in the mix of fuels used to produce the grid electricity used in a process).

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 Chapter 2), rather than using fully rolled-up data sets like the data in the Chapter 3 tables. 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 plastic **product** LCI, the data sets for the resin used in the product are combined with the data for product fabrication, use, and end-of-life management. The choice of recycled resin modeling will depend on the product system being modeled and the allocation method chosen for the LCI (open-loop or cut-off). If a practitioner is using rolled-up recycled resin data sets (from the Chapter 3 tables), it is important that the practitioner use the rolled-up data sets that are consistent with the way recycling is being modeled throughout the product LCI. The following sections describe how to use the Chapter 2 unit process data sets for constructing LCI models of plastic product systems that use recycled resin.

Modeling a Product System with the Open-loop Recycling Methodology

As described earlier in this chapter, in the **open-loop** recycling methodology, a share of the virgin resin production burdens are allocated to each useful life of the material. The rolled-up open-loop results shown in the Chapter 3 tables represent one scenario for recycled resin that is based on **two** useful lives of the resin material (i.e., once in a virgin product, once in a recycled product, then disposed). The amount of postconsumer resin shown as an input to reprocessing in Table 2-9 or Table 2-10 is assigned **half** of its virgin resin production burdens (the other half is allocated to the first use of the material in a virgin product).

If the recycled resin is being used in a plastic product that is recovered and recycled at the end of its life, the total useful number of lives of the material would be **three** (virgin product, first recycled product, second recycled product, then disposed), and **one-third** of the virgin resin production burdens would be allocated to each useful life of the resin. In general, for “**n**” total useful lives of the material, each useful life of the material would be assigned **1/n** of the virgin material production burdens.

For open-loop recycling, the burdens for the collection, sorting, and reprocessing steps (shown in Tables 2-7 through 2-10) are allocated among **n** useful lives of the material, using an allocation factor of **(n-1)/n**. The number of collection, sorting, and reprocessing steps are one less than the total number of useful lives, since these steps are not required for the initial (virgin) use of the material.

Modeling a Product System with the Cut-off Recycling Methodology

If the recycled resin data are being used in an LCI that uses the **cut-off** methodology for recycling, the amount of postconsumer material shown as an input to reprocessing in Tables 2-9 and 2-10 would carry **no** virgin burdens, and the recycled resin system would be assigned **full** burdens for the collection, sorting, and reprocessing burdens shown in Tables 2-7 through 2-9 or 2-10. Since the cut-off method draws distinct boundaries between successive lives of the material, the number of previous and subsequent useful lives of the material do not influence the burdens assigned to an individual use of the material.

Modeling a Product System with a Mix of Virgin and Recycled Resin

In order to model a plastic product with less than 100% recycled resin, the recycled content of the product would be modeled using the appropriate open-loop or cut-off recycled resin modeling approach (corresponding to the methodology chosen for the LCI), and the remainder of the content of the product would be modeled as virgin material.

Table 3-7. Atmospheric Process Emissions for Recycled PET Resin*
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Particulates (unspecified)	0.037	0.037	0.16	0.16
Nitrogen Oxides	0	0	0.12	0.12
Non-Methane Hydrocarbons	0	0	3.36	3.36
Sulfur Oxides	1.3E-05	1.3E-05	3.53	3.53
Carbon Monoxide	0	0	6.66	6.66
Aldehydes (unspecified)	0	0	0.094	0.094
Methane	0	0	3.18	3.18
Other Organics	0	0	0.56	0.56
Ammonia	0	0	0.017	0.017
Mercury	6.0E-06	6.0E-06	3.0E-06	3.0E-06
Chlorine	3.3E-06	3.3E-06	1.2E-05	1.2E-05
Hydrogen Chloride	0	0	1.0E-07	1.0E-07
Carbon Dioxide - Fossil	0	0	148	148
Carbon Tetrachloride	0	0	3.4E-09	3.4E-09
Trichloroethane	0	0	2.7E-08	2.7E-08
Toluene	0	0	0.018	0.018
VOC	0.037	0.037	0.11	0.11
Particulates (PM10)	0	0	0.010	0.010
HCFC-22	0	0	1.0E-07	1.0E-07
Hydrogen	0	0	3.9E-04	3.9E-04
Ethylbenzene	0	0	0.0014	0.0014
Benzene	0	0	0.011	0.011
TOC	0	0	0.040	0.040
Ethylene Oxide	0	0	0.012	0.012
Acetic Acid	0	0	0.026	0.026
Bromine	0	0	0.040	0.040
Methyl Acetate	0	0	0.020	0.020
Xylene	0	0	0.031	0.031
Methanol	0	0	7.4E-04	7.4E-04

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* No process emissions were reported for pelletizing flake, so the emissions in this table apply to flake or pellet.

Source: Franklin Associates, A Division of ERG

Table 3-8. Atmospheric Process Emissions for Recycled HDPE Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Particulates (unspecified)	0	0	0.050	0.050
Nitrogen Oxides	0	0	0.065	0.065
Non-Methane Hydrocarbon	0	0	0.57	0.57
Sulfur Oxides	0	0	11.8	11.8
Carbon Monoxide	0	0	2.11	2.11
Aldehydes (unspecified)	0	0	0.0064	0.0064
Methane	0	0	6.47	6.47
Other Organics	0	0	0.0055	0.0055
Ammonia	0	0	0.0032	0.0032
Chlorine	0	0	5.0E-05	5.0E-05
Hydrogen Chloride	0	0	5.0E-07	5.0E-07
Carbon Dioxide - Fossil	0	0	38.5	38.5
Carbon Tetrachloride	0	0	1.8E-09	1.8E-09
Trichloroethane	0	0	1.5E-08	1.5E-08
Toluene	0	0	0.070	0.070
VOC	0	0	0.37	0.37
Particulates (PM2.5)	0.015	0.015	0.013	0.013
Particulates (PM10)	0.023	0.023	0.081	0.081
HCFC-22	0	0	5.0E-07	5.0E-07
Hydrogen	0	0	0.0020	0.0020
Ethylbenzene	0	0	0.0056	0.0056
Benzene	0	0	0.045	0.045
Xylene	0	0	0.041	0.041

Source: Franklin Associates, A Division of ERG

Table 3-9. Waterborne Process Emissions for Recycled PET Resin*
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Acid (unspecified)	0	0	0.018	0.018
Metal Ion (unspecified)	0	0	2.3E-06	2.3E-06
Fluorides	0	0	2.5E-05	2.5E-05
Dissolved Solids	0.055	0.055	69.4	69.4
Suspended Solids	2.98	2.98	4.70	4.70
BOD	7.26	7.26	4.35	4.35
COD	20.2	20.2	11.4	11.4
Phenol/ Phenolic Compounds	0	0	8.6E-04	8.6E-04
Sulfides	1.6E-06	1.6E-06	5.4E-05	5.4E-05
Oil	0	0	0.034	0.034
Iron	0	0	0.21	0.21
Cyanide	0	0	1.1E-07	1.1E-07
Alkalinity	0	0	0.12	0.12
Chromium (unspecified)	0	0	0.0061	0.0061
Chromium (hexavalent)	0	0	1.0E-05	1.0E-05
Aluminum	0	0	0.10	0.10
Nickel	1.2E-08	1.2E-08	3.8E-04	3.8E-04
Mercury	1.7E-08	1.7E-08	1.1E-06	1.1E-06
Lead	1.2E-08	1.2E-08	7.8E-04	7.8E-04
Phosphates	0	0	2.6E-04	2.6E-04
Zinc	1.2E-08	1.2E-08	0.0064	0.0064
Ammonia	0	0	0.082	0.082
Sulfates	0	0	0.11	0.11
1-Methylfluorene	0	0	1.8E-07	1.8E-07
2,4-Dimethylphenol	0	0	4.4E-05	4.4E-05
2-Hexanone	0	0	1.0E-05	1.0E-05
2-Methylnaphthalene	0	0	2.5E-05	2.5E-05
4-Methyl-2-Pentanone	0	0	6.5E-06	6.5E-06
Acetone	0	0	1.6E-05	1.6E-05
Alkylated benzenes	0	0	5.6E-05	5.6E-05
Alkylated fluorenes	0	0	3.2E-06	3.2E-06
Alkylated naphthalenes	0	0	9.2E-07	9.2E-07
Alkylated phenanthrenes	0	0	3.8E-07	3.8E-07
Antimony	0	0	6.4E-05	6.4E-05
Arsenic	0	0	4.0E-04	4.0E-04
Barium	0	0	1.42	1.42
Benzene	0	0	0.0026	0.0026
Acid (benzoic)	0	0	0.0016	0.0016
Beryllium	0	0	2.1E-05	2.1E-05
Boron	0	0	0.0049	0.0049
Bromide	0	0	0.33	0.33
Cadmium	0	0	5.9E-05	5.9E-05
Calcium	0	0	5.00	5.00
Chlorides	0	0	56.3	56.3
Cobalt	0	0	3.5E-05	3.5E-05
Copper	0	0	3.7E-04	3.7E-04

Table 3-9. Waterborne Process Emissions for Recycled PET Resin*
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Dibenzofuran	0	0	3.0E-07	3.0E-07
Dibenzothiophene	0	0	2.4E-07	2.4E-07
Ethylbenzene	0	0	1.5E-04	1.5E-04
Fluorine	0	0	1.6E-06	1.6E-06
Hardness	0	0	15.4	15.4
Acid (hexanoic)	0	0	3.3E-04	3.3E-04
Lead 210	0	0	1.6E-13	1.6E-13
Lithium	0	0	0.56	0.56
Magnesium	0	0	0.98	0.98
Manganese	0	0	0.0016	0.0016
Methyl Chloride	0	0	6.3E-08	6.3E-08
Methyl Ethyl Ketone	0	0	1.3E-07	1.3E-07
Molybdenum	0	0	3.6E-05	3.6E-05
Xylene	0	0	4.7E-05	4.7E-05
Naphthalene	0	0	2.8E-05	2.8E-05
n-Decane	0	0	4.5E-05	4.5E-05
n-Docosane	0	0	1.7E-06	1.7E-06
n-Dodecane	0	0	8.6E-05	8.6E-05
n-Eicosane	0	0	2.4E-05	2.4E-05
n-Hexacosane	0	0	1.0E-06	1.0E-06
n-Hexadecane	0	0	9.4E-05	9.4E-05
n-Octadecane	0	0	2.3E-05	2.3E-05
n-Tetradecane	0	0	3.8E-05	3.8E-05
o + p-Xyxlene	0	0	3.4E-05	3.4E-05
o-Cresol	0	0	4.5E-05	4.5E-05
p-Cresol	0	0	4.8E-05	4.8E-05
p-Cymene	0	0	1.6E-07	1.6E-07
Pentamethylbenzene	0	0	1.2E-07	1.2E-07
Phenanthrene	0	0	3.6E-07	3.6E-07
Radium 226	0	0	5.6E-11	5.6E-11
Radium 228	0	0	2.9E-13	2.9E-13
Selenium	0	0	1.2E-05	1.2E-05
Silver	0	0	0.0033	0.0033
Sodium	0	0	15.9	15.9
Strontium	0	0	0.085	0.085
Sulfur	0	0	0.0041	0.0041
Surfactants	0	0	0.0014	0.0014
Thallium	0	0	1.3E-05	1.3E-05
Tin	0	0	2.9E-04	2.9E-04
Titanium	0	0	9.8E-04	9.8E-04
Toluene	0	0	0.0025	0.0025
Total biphenyls	0	0	3.6E-06	3.6E-06
Total dibenzothiophenes	0	0	1.1E-08	1.1E-08
Vanadium	0	0	4.2E-05	4.2E-05
Xylene	0	0	0.0012	0.0012
Yttrium	0	0	1.0E-05	1.0E-05
Styrene	0	0	1.0E-07	1.0E-07
TOC	0	0	0.022	0.022

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* No process emissions were reported for pelletizing flake, so the emissions in this table apply to flake or pellet.
Source: Franklin Associates, A Division of ERG

Table 3-10. Waterborne Process Emissions for Recycled HDPE Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Dissolved Solids	0.0091	0.0091	101	101
Suspended Solids	0.29	0.29	2.43	2.43
BOD	0.30	0.30	0.55	0.55
COD	0.0015	0.0015	0.69	0.69
Phenol/ Phenolic Compoun	0	0	0.0015	0.0015
Sulfides	0	0	2.9E-05	2.9E-05
Oil	0	0	0.048	0.048
Iron	0	0	0.18	0.18
Cyanide	0	0	1.6E-07	1.6E-07
Alkalinity	0	0	0.18	0.18
Chromium (unspecified)	0	0	0.0020	0.0020
Chromium (hexavalent)	0	0	5.6E-06	5.6E-06
Aluminum	0	0	0.070	0.070
Nickel	0	0	4.3E-04	4.3E-04
Mercury	0	0	7.5E-07	7.5E-07
Lead	0	0	8.2E-04	8.2E-04
Phosphorus	0	0	5.0E-05	5.0E-05
Zinc	0	0	0.0018	0.0018
Ammonia	0	0	0.031	0.031
Sulfates	0	0	0.17	0.17
1-Methylfluorene	0	0	2.6E-07	2.6E-07
2,4-Dimethylphenol	0	0	6.3E-05	6.3E-05
2-Hexanone	0	0	1.5E-05	1.5E-05
2-Methylnaphthalene	0	0	3.6E-05	3.6E-05
4-Methyl-2-Pentanone	0	0	9.5E-06	9.5E-06
Acetone	0	0	2.3E-05	2.3E-05
Alkylated benzenes	0	0	3.7E-05	3.7E-05
Alkylated fluorenes	0	0	2.2E-06	2.2E-06
Alkylated naphthalenes	0	0	6.1E-07	6.1E-07
Alkylated phenanthrenes	0	0	2.5E-07	2.5E-07
Antimony	0	0	4.3E-05	4.3E-05
Arsenic	0	0	5.2E-04	5.2E-04
Barium	0	0	1.01	1.01
Benzene	0	0	0.0038	0.0038
Acid (benzoic)	0	0	0.0023	0.0023
Beryllium	0	0	2.5E-05	2.5E-05
Boron	0	0	0.0071	0.0071
Bromide	0	0	0.48	0.48
Cadmium	0	0	7.6E-05	7.6E-05
Calcium	0	0	7.26	7.26
Chlorides	0	0	81.6	81.6
Cobalt	0	0	5.0E-05	5.0E-05
Copper	0	0	3.8E-04	3.8E-04

Table 3-10. Waterborne Process Emissions for Recycled HDPE Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Dibenzofuran	0	0	4.3E-07	4.3E-07
Dibenzothiophene	0	0	3.5E-07	3.5E-07
Ethylbenzene	0	0	2.2E-04	2.2E-04
Fluorine	0	0	1.2E-06	1.2E-06
Hardness	0	0	22.4	22.4
Acid (hexanoic)	0	0	4.7E-04	4.7E-04
Lead 210	0	0	2.3E-13	2.3E-13
Lithium	0	0	2.01	2.01
Magnesium	0	0	1.42	1.42
Manganese	0	0	0.0023	0.0023
Methyl Chloride	0	0	9.1E-08	9.1E-08
Methyl Ethyl Ketone	0	0	1.8E-07	1.8E-07
Molybdenum	0	0	5.2E-05	5.2E-05
Xylene	0	0	6.8E-05	6.8E-05
Naphthalene	0	0	4.1E-05	4.1E-05
n-Decane	0	0	6.6E-05	6.6E-05
n-Docosane	0	0	2.4E-06	2.4E-06
n-Dodecane	0	0	1.2E-04	1.2E-04
n-Eicosane	0	0	3.4E-05	3.4E-05
n-Hexacosane	0	0	1.5E-06	1.5E-06
n-Hexadecane	0	0	1.4E-04	1.4E-04
n-Octadecane	0	0	3.4E-05	3.4E-05
n-Tetradecane	0	0	5.5E-05	5.5E-05
o + p-Xyxlene	0	0	5.0E-05	5.0E-05
o-Cresol	0	0	6.5E-05	6.5E-05
p-Cresol	0	0	7.0E-05	7.0E-05
p-Cymene	0	0	2.3E-07	2.3E-07
Pentamethylbenzene	0	0	1.7E-07	1.7E-07
Phenanthrene	0	0	3.5E-07	3.5E-07
Radium 226	0	0	8.2E-11	8.2E-11
Radium 228	0	0	4.2E-13	4.2E-13
Selenium	0	0	8.4E-06	8.4E-06
Silver	0	0	0.0047	0.0047
Sodium	0	0	23.0	23.0
Strontium	0	0	0.12	0.12
Sulfur	0	0	0.0060	0.0060
Surfactants	0	0	0.0022	0.0022
Thallium	0	0	9.0E-06	9.0E-06
Tin	0	0	2.9E-04	2.9E-04
Titanium	0	0	6.6E-04	6.6E-04
Toluene	0	0	0.0036	0.0036
Total biphenyls	0	0	2.4E-06	2.4E-06
Total dibenzothiophenes	0	0	7.5E-09	7.5E-09
Vanadium	0	0	6.1E-05	6.1E-05
Xylene	0	0	0.0018	0.0018
Yttrium	0	0	1.5E-05	1.5E-05
Styrene	0	0	5.0E-07	5.0E-07
TOC	0	0	5.0E-04	5.0E-04

Source: Franklin Associates, A Division of ERG

Table 3-11. Fuel-related Atmospheric Emissions for Recycled PET Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing. For open-loop, includes 1/2 of virgin resin production emissions.

	PET Flake	PET Pellet	PET Flake	PET Pellet	PET Flake	PET Pellet	PET Flake	PET Pellet
	Cut-off, weight-based collection	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)	Open-loop, volume-based collection (50% compaction)
Fossil CO2	718	1,072	755	1,108	1,439	1,615	1,457	1,634
Methane	1.92	2.70	1.96	2.75	4.34	4.73	4.36	4.76
Nitrous Oxide	0.017	0.026	0.018	0.027	0.034	0.038	0.034	0.039
Non-Fossil CO2	6.72	13.0	6.74	13.0	9.48	12.6	9.49	12.6
Particulates (unspecified)	0.24	0.46	0.25	0.46	0.38	0.48	0.38	0.49
Particulates (PM10)	0.072	0.11	0.077	0.11	0.17	0.19	0.18	0.19
Nitrogen Oxides	2.28	3.21	2.54	3.47	4.10	4.56	4.23	4.69
Sulfur Dioxide	4.12	6.50	4.14	6.52	8.73	9.92	8.74	9.93
Sulfur Oxides	0.28	0.38	0.31	0.41	0.71	0.76	0.72	0.77
VOC (unspecified)	0.15	0.17	0.16	0.19	0.29	0.31	0.30	0.31
TNMOC (unspecified)	0.0077	0.015	0.0077	0.015	0.013	0.017	0.013	0.017
Hydrocarbons (unspecified)	0.12	0.13	0.14	0.15	0.20	0.20	0.21	0.21
Carbon Monoxide	1.39	1.59	1.57	1.77	2.29	2.39	2.38	2.48
1,3 Butadiene	1.5E-07	2.3E-07	1.5E-07	2.3E-07	4.8E-07	5.2E-07	4.8E-07	5.3E-07
2,4-Dinitrotoluene	1.6E-10	1.7E-10	1.6E-10	1.7E-10	2.6E-09	2.6E-09	2.6E-09	2.6E-09
2-Chloroacetophenone	4.1E-09	4.3E-09	4.1E-09	4.3E-09	6.5E-08	6.5E-08	6.5E-08	6.5E-08
5-Methyl Chrysene	1.5E-09	2.9E-09	1.5E-09	2.9E-09	2.3E-09	3.0E-09	2.3E-09	3.0E-09
Acenaphthene	3.5E-08	6.8E-08	3.5E-08	6.8E-08	5.4E-08	7.1E-08	5.4E-08	7.1E-08
Acenaphthylene	1.7E-08	3.3E-08	1.7E-08	3.3E-08	2.7E-08	3.5E-08	2.7E-08	3.5E-08
Acetophenone	8.8E-09	9.2E-09	8.8E-09	9.2E-09	1.4E-07	1.4E-07	1.4E-07	1.4E-07
Acrolein	1.6E-04	3.1E-04	1.6E-04	3.1E-04	2.3E-04	3.0E-04	2.3E-04	3.0E-04
Aldehydes (Acetaldehyde)	3.3E-05	6.1E-05	3.3E-05	6.2E-05	5.9E-05	7.3E-05	5.9E-05	7.3E-05
Aldehydes (Formaldehyde)	3.6E-04	5.8E-04	3.7E-04	5.8E-04	9.6E-04	0.0011	9.6E-04	0.0011
Aldehydes (Propionaldehyde)	2.2E-07	2.3E-07	2.2E-07	2.3E-07	3.5E-06	3.5E-06	3.5E-06	3.5E-06
Aldehydes (unspecified)	0.0024	0.0028	0.0029	0.0032	0.0041	0.0043	0.0043	0.0045
Ammonia	0.0012	0.0014	0.0014	0.0016	0.0020	0.0021	0.0021	0.0022
Ammonia Chloride	5.3E-05	1.0E-04	5.3E-05	1.0E-04	7.5E-05	9.9E-05	7.5E-05	9.9E-05
Anthracene	1.4E-08	2.8E-08	1.5E-08	2.8E-08	2.2E-08	2.9E-08	2.2E-08	2.9E-08
Antimony	1.5E-06	2.9E-06	1.5E-06	2.9E-06	2.3E-06	3.0E-06	2.3E-06	3.0E-06
Arsenic	3.1E-05	5.9E-05	3.1E-05	5.9E-05	5.3E-05	6.7E-05	5.3E-05	6.7E-05
Benzene	0.0086	0.011	0.0086	0.011	0.023	0.024	0.023	0.024
Benzo(a)anthracene	5.5E-09	1.1E-08	5.5E-09	1.1E-08	8.5E-09	1.1E-08	8.5E-09	1.1E-08
Benzo(a)pyrene	2.6E-09	5.1E-09	2.6E-09	5.1E-09	4.0E-09	5.3E-09	4.0E-09	5.3E-09
Benzo(b,j,k)fluroanthene	7.6E-09	1.5E-08	7.6E-09	1.5E-08	1.2E-08	1.5E-08	1.2E-08	1.5E-08
Benzo(g,h,i) perylene	1.9E-09	3.6E-09	1.9E-09	3.6E-09	2.9E-09	3.7E-09	2.9E-09	3.7E-09
Benzyl Chloride	4.1E-07	4.3E-07	4.1E-07	4.3E-07	6.5E-06	6.5E-06	6.5E-06	6.5E-06
Beryllium	1.6E-06	3.1E-06	1.6E-06	3.1E-06	2.9E-06	3.6E-06	2.9E-06	3.7E-06
Biphenyl	1.2E-07	2.3E-07	1.2E-07	2.3E-07	1.8E-07	2.4E-07	1.8E-07	2.4E-07
Bis(2-ethylhexyl) Phthalate (DEHP)	4.3E-08	4.5E-08	4.3E-08	4.5E-08	6.8E-07	6.8E-07	6.8E-07	6.8E-07
Bromoform	2.3E-08	2.4E-08	2.3E-08	2.4E-08	3.6E-07	3.6E-07	3.6E-07	3.6E-07
Cadmium	6.1E-06	1.0E-05	6.2E-06	1.0E-05	1.4E-05	1.6E-05	1.4E-05	1.6E-05
Carbon Disulfide	7.6E-08	8.0E-08	7.6E-08	8.0E-08	1.2E-06	1.2E-06	1.2E-06	1.2E-06
Carbon Tetrachloride	1.6E-06	3.0E-06	1.6E-06	3.0E-06	2.2E-06	2.9E-06	2.2E-06	2.9E-06
CFC12	6.5E-09	7.3E-09	7.7E-09	8.4E-09	1.1E-08	1.1E-08	1.2E-08	1.2E-08
Chlorobenzene	1.3E-08	1.4E-08	1.3E-08	1.4E-08	2.0E-07	2.1E-07	2.0E-07	2.1E-07
Chloroform	3.5E-08	3.6E-08	3.5E-08	3.6E-08	5.5E-07	5.5E-07	5.5E-07	5.5E-07
Chorine	2.7E-05	5.3E-05	2.7E-05	5.3E-05	3.8E-05	5.1E-05	3.8E-05	5.1E-05
Chromium	2.2E-05	4.1E-05	2.2E-05	4.1E-05	4.0E-05	5.0E-05	4.0E-05	5.0E-05
Chromium (VI)	5.4E-06	1.1E-05	5.5E-06	1.1E-05	8.4E-06	1.1E-05	8.4E-06	1.1E-05
Chrysene	6.9E-09	1.3E-08	6.9E-09	1.3E-08	1.1E-08	1.4E-08	1.1E-08	1.4E-08
Cobalt	1.3E-05	2.3E-05	1.3E-05	2.3E-05	4.8E-05	5.3E-05	4.8E-05	5.3E-05
Copper	1.5E-07	2.6E-07	1.6E-07	2.6E-07	9.2E-07	9.7E-07	9.2E-07	9.7E-07
Cumene	3.1E-09	3.3E-09	3.1E-09	3.3E-09	4.9E-08	4.9E-08	4.9E-08	4.9E-08
Cyanide	1.5E-06	1.5E-06	1.5E-06	1.5E-06	2.3E-05	2.3E-05	2.3E-05	2.3E-05

Table 3-11. Fuel-related Atmospheric Emissions for Recycled PET Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing. For open-loop, includes 1/2 of virgin resin production emissions.

	PET Flake	PET Pellet	PET Flake	PET Pellet	PET Flake	PET Pellet	PET Flake	PET Pellet
	Cut-off, weight-based collection	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)	Open-loop, volume-based collection (50% compaction)
Dimethyl Sulfate	2.8E-08	3.0E-08	2.8E-08	3.0E-08	4.5E-07	4.5E-07	4.5E-07	4.5E-07
Dioxins (unspecified)	5.8E-08	1.1E-07	5.8E-08	1.1E-07	8.1E-08	1.1E-07	8.1E-08	1.1E-07
Ethyl Chloride	2.5E-08	2.6E-08	2.5E-08	2.6E-08	3.9E-07	3.9E-07	3.9E-07	3.9E-07
Ethylbenzene	9.9E-04	0.0012	0.0010	0.0012	0.0026	0.0028	0.0026	0.0028
Ethylene Dibromide	7.0E-10	7.4E-10	7.0E-10	7.4E-10	1.1E-08	1.1E-08	1.1E-08	1.1E-08
Ethylene Dichloride	2.3E-08	2.5E-08	2.3E-08	2.5E-08	3.7E-07	3.7E-07	3.7E-07	3.7E-07
Fluoranthene	4.9E-08	9.5E-08	4.9E-08	9.5E-08	7.5E-08	9.8E-08	7.6E-08	9.8E-08
Fluorene	6.3E-08	1.2E-07	6.3E-08	1.2E-07	9.7E-08	1.3E-07	9.7E-08	1.3E-07
Fluorides	3.0E-05	3.6E-05	3.0E-05	3.6E-05	4.2E-04	4.2E-04	4.2E-04	4.2E-04
Furans (unspecified)	1.8E-10	3.4E-10	1.8E-10	3.4E-10	3.7E-10	4.6E-10	3.7E-10	4.6E-10
HCl	0.084	0.16	0.084	0.16	0.13	0.17	0.13	0.17
Hexane	3.9E-08	4.1E-08	3.9E-08	4.1E-08	6.2E-07	6.3E-07	6.2E-07	6.3E-07
HF	0.010	0.020	0.010	0.020	0.016	0.020	0.016	0.020
Indeno(1,2,3-cd)pyrene	4.2E-09	8.1E-09	4.2E-09	8.1E-09	6.5E-09	8.4E-09	6.5E-09	8.4E-09
Isophorone (C9H14O)	3.4E-07	3.6E-07	3.4E-07	3.6E-07	5.4E-06	5.4E-06	5.4E-06	5.4E-06
Kerosene	9.5E-05	1.8E-04	9.5E-05	1.8E-04	1.3E-04	1.8E-04	1.3E-04	1.8E-04
Lead	3.5E-05	6.5E-05	3.5E-05	6.6E-05	9.0E-05	1.0E-04	9.0E-05	1.0E-04
Magnesium	7.6E-04	0.0015	7.6E-04	0.0015	0.0012	0.0015	0.0012	0.0015
Manganese	9.2E-05	1.8E-04	9.3E-05	1.8E-04	1.5E-04	1.9E-04	1.5E-04	1.9E-04
Mercaptan	1.3E-04	1.3E-04	1.3E-04	1.3E-04	0.0020	0.0020	0.0020	0.0020
Mercury	7.2E-06	1.3E-05	7.2E-06	1.3E-05	2.3E-05	2.6E-05	2.3E-05	2.6E-05
Metals (unspecified)	0.0015	0.0029	0.0015	0.0029	0.0021	0.0028	0.0021	0.0028
Methyl Bromide	9.4E-08	9.9E-08	9.4E-08	9.9E-08	1.5E-06	1.5E-06	1.5E-06	1.5E-06
Methyl Chloride	3.1E-07	3.3E-07	3.1E-07	3.3E-07	4.9E-06	4.9E-06	4.9E-06	4.9E-06
Methyl Ethyl Ketone	2.3E-07	2.4E-07	2.3E-07	2.4E-07	3.6E-06	3.6E-06	3.6E-06	3.6E-06
Methyl Hydrazine	9.9E-08	1.0E-07	9.9E-08	1.0E-07	1.6E-06	1.6E-06	1.6E-06	1.6E-06
Methyl Methacrylate	1.2E-08	1.2E-08	1.2E-08	1.2E-08	1.9E-07	1.9E-07	1.9E-07	1.9E-07
Methyl Tert Butyl Ether (MTBE)	2.0E-08	2.2E-08	2.0E-08	2.2E-08	3.3E-07	3.3E-07	3.3E-07	3.3E-07
Methylene Chloride	3.6E-05	6.8E-05	3.6E-05	6.8E-05	8.0E-05	9.6E-05	8.0E-05	9.6E-05
Naphthalene	6.4E-06	1.2E-05	6.5E-06	1.2E-05	1.6E-05	2.0E-05	1.6E-05	2.0E-05
Nickel	1.0E-04	1.7E-04	1.0E-04	1.7E-04	5.5E-04	5.8E-04	5.5E-04	5.9E-04
Organics (unspecified)	4.2E-04	8.1E-04	4.2E-04	8.1E-04	5.9E-04	7.9E-04	5.9E-04	7.9E-04
Perchloroethylene	3.1E-06	5.9E-06	3.1E-06	5.9E-06	5.1E-06	6.5E-06	5.1E-06	6.5E-06
Phenanthrene	1.9E-07	3.6E-07	1.9E-07	3.6E-07	2.9E-07	3.7E-07	2.9E-07	3.7E-07
Phenols	6.7E-06	1.2E-05	6.9E-06	1.2E-05	3.0E-05	3.2E-05	3.0E-05	3.2E-05
Polyaromatic Hydrocarbons (total)	2.1E-06	3.8E-06	2.1E-06	3.8E-06	4.3E-06	5.2E-06	4.3E-06	5.2E-06
Propylene	9.6E-06	1.5E-05	1.0E-05	1.5E-05	3.2E-05	3.5E-05	3.2E-05	3.5E-05
Pyrene	2.3E-08	4.4E-08	2.3E-08	4.4E-08	3.5E-08	4.6E-08	3.5E-08	4.6E-08
Radionuclides (unspecified) (Ci)	0.0053	0.010	0.0054	0.010	0.0076	0.010	0.0076	0.010
Selenium	9.1E-05	1.8E-04	9.1E-05	1.8E-04	1.4E-04	1.9E-04	1.5E-04	1.9E-04
Styrene	1.5E-08	1.5E-08	1.5E-08	1.5E-08	2.3E-07	2.3E-07	2.3E-07	2.3E-07
Toluene	0.013	0.016	0.013	0.016	0.034	0.036	0.034	0.036
Trichloroethane	1.7E-08	1.8E-08	1.8E-08	1.9E-08	2.0E-07	2.0E-07	2.0E-07	2.0E-07
Vinyl Acetate	4.4E-09	4.7E-09	4.4E-09	4.7E-09	7.1E-08	7.1E-08	7.1E-08	7.1E-08
Xylenes	0.0074	0.0092	0.0075	0.0092	0.020	0.021	0.020	0.021
Zinc	1.0E-07	1.8E-07	1.0E-07	1.8E-07	6.1E-07	6.5E-07	6.1E-07	6.5E-07

Source: Franklin Associates, A Division of ERG

Table 3-12. Fuel-related Atmospheric Emissions for Recycled HDPE Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
Fossil CO2	581	636	979	1,007
Methane	1.16	1.22	2.71	2.74
Nitrous Oxide	0.015	0.017	0.017	0.018
Non-Fossil CO2	6.81	6.85	5.85	5.87
Particulates (unspecified)	0.24	0.25	0.21	0.22
Particulates (PM10)	0.060	0.068	0.073	0.077
Nitrogen Oxides	2.10	2.49	2.21	2.41
Sulfur Dioxide	2.77	2.80	5.44	5.45
Sulfur Oxides	0.29	0.34	0.31	0.33
VOC (unspecified)	0.10	0.13	0.19	0.20
TNMOC (unspecified)	0.0076	0.0077	0.0066	0.0066
Hydrocarbons (unspecified)	0.12	0.15	0.089	0.10
Carbon Monoxide	1.40	1.68	1.34	1.48
1,3 Butadiene	1.1E-07	1.2E-07	5.4E-07	5.5E-07
2,4-Dinitrotoluene	9.4E-12	9.4E-12	8.1E-12	8.1E-12
2-Chloroacetophenone	2.3E-10	2.4E-10	2.0E-10	2.0E-10
5-Methyl Chrysene	1.5E-09	1.5E-09	1.3E-09	1.3E-09
Acenaphthene	3.5E-08	3.6E-08	3.1E-08	3.1E-08
Acenaphthylene	1.7E-08	1.7E-08	1.5E-08	1.5E-08
Acetophenone	5.0E-10	5.0E-10	4.3E-10	4.3E-10
Acrolein	1.6E-04	1.6E-04	1.4E-04	1.4E-04
Aldehydes (Acetaldehyde)	3.2E-05	3.2E-05	4.2E-05	4.3E-05
Aldehydes (Formaldehyde)	2.6E-04	2.7E-04	6.0E-04	6.0E-04
Aldehydes (Propionaldehyde)	1.3E-08	1.3E-08	1.1E-08	1.1E-08
Aldehydes (unspecified)	0.0026	0.0032	0.0019	0.0022
Ammonia	0.0013	0.0016	9.3E-04	0.0011
Ammonia Chloride	5.3E-05	5.4E-05	4.6E-05	4.6E-05
Anthracene	1.5E-08	1.5E-08	1.3E-08	1.3E-08
Antimony	1.5E-06	1.5E-06	1.3E-06	1.3E-06
Arsenic	3.1E-05	3.1E-05	2.8E-05	2.8E-05
Benzene	0.0031	0.0032	0.015	0.015
Benzo(a)anthracene	5.6E-09	5.6E-09	4.8E-09	4.8E-09
Benzo(a)pyrene	2.6E-09	2.7E-09	2.3E-09	2.3E-09
Benzo(b,j,k)fluroanthene	7.6E-09	7.7E-09	6.6E-09	6.6E-09
Benzo(g,h,i) perylene	1.9E-09	1.9E-09	1.6E-09	1.6E-09
Benzyl Chloride	2.3E-08	2.4E-08	2.0E-08	2.0E-08
Beryllium	1.6E-06	1.6E-06	1.5E-06	1.5E-06
Biphenyl	1.2E-07	1.2E-07	1.0E-07	1.0E-07
Bis(2-ethylhexyl) Phthalate (DEHP)	2.4E-09	2.5E-09	2.1E-09	2.1E-09
Bromoform	1.3E-09	1.3E-09	1.1E-09	1.1E-09
Cadmium	4.8E-06	4.9E-06	7.3E-06	7.3E-06
Carbon Disulfide	4.3E-09	4.4E-09	3.8E-09	3.8E-09
Carbon Tetrachloride	1.6E-06	1.6E-06	1.4E-06	1.4E-06
CFC12	6.9E-09	8.7E-09	5.0E-09	5.9E-09
Chlorobenzene	7.4E-10	7.4E-10	6.4E-10	6.4E-10
Chloroform	2.0E-09	2.0E-09	1.7E-09	1.7E-09
Chorine	2.8E-05	2.8E-05	2.4E-05	2.4E-05
Chromium	2.1E-05	2.1E-05	2.2E-05	2.2E-05
Chromium (VI)	5.5E-06	5.5E-06	4.7E-06	4.8E-06
Chrysene	6.9E-09	7.0E-09	6.0E-09	6.0E-09
Cobalt	1.3E-05	1.4E-05	1.6E-05	1.6E-05
Copper	1.3E-07	1.3E-07	2.0E-07	2.0E-07
Cumene	1.8E-10	1.8E-10	1.5E-10	1.5E-10
Cyanide	8.4E-08	8.4E-08	7.2E-08	7.2E-08

Table 3-12. Fuel-related Atmospheric Emissions for Recycled HDPE Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	**Cut-off, volume-based collection (50% compaction)**	**Open-loop, weight-based collection**	**Open-loop, volume-based collection (50% compaction)**
Dimethyl Sulfate	1.6E-09	1.6E-09	1.4E-09	1.4E-09
Dioxins (unspecified)	5.8E-08	5.9E-08	5.0E-08	5.0E-08
Ethyl Chloride	1.4E-09	1.4E-09	1.2E-09	1.2E-09
Ethylbenzene	3.4E-04	3.5E-04	0.0017	0.0017
Ethylene Dibromide	4.0E-11	4.0E-11	3.5E-11	3.5E-11
Ethylene Dichloride	1.3E-09	1.3E-09	1.2E-09	1.2E-09
Fluoranthene	4.9E-08	5.0E-08	4.3E-08	4.3E-08
Fluorene	6.3E-08	6.4E-08	5.5E-08	5.5E-08
Fluorides	5.9E-06	5.9E-06	5.1E-06	5.1E-06
Furans (unspecified)	1.8E-10	1.8E-10	2.0E-10	2.0E-10
HCl	0.085	0.085	0.074	0.074
Hexane	2.2E-09	2.3E-09	1.9E-09	1.9E-09
HF	0.010	0.010	0.0090	0.0090
Indeno(1,2,3-cd)pyrene	4.2E-09	4.3E-09	3.7E-09	3.7E-09
Isophorone (C9H14O)	1.9E-08	2.0E-08	1.7E-08	1.7E-08
Kerosene	9.6E-05	9.6E-05	8.3E-05	8.3E-05
Lead	3.3E-05	3.4E-05	3.1E-05	3.1E-05
Magnesium	7.6E-04	7.7E-04	6.6E-04	6.6E-04
Manganese	9.3E-05	9.4E-05	8.3E-05	8.4E-05
Mercaptan	6.8E-06	6.8E-06	5.9E-06	5.9E-06
Mercury	6.3E-06	6.3E-06	6.2E-06	6.2E-06
Metals (unspecified)	0.0015	0.0015	0.0013	0.0013
Methyl Bromide	5.4E-09	5.4E-09	4.6E-09	4.6E-09
Methyl Chloride	1.8E-08	1.8E-08	1.5E-08	1.5E-08
Methyl Ethyl Ketone	1.3E-08	1.3E-08	1.1E-08	1.1E-08
Methyl Hydrazine	5.7E-09	5.7E-09	4.9E-09	4.9E-09
Methyl Methacrylate	6.7E-10	6.7E-10	5.8E-10	5.8E-10
Methyl Tert Butyl Ether (MTBE)	1.2E-09	1.2E-09	1.0E-09	1.0E-09
Methylene Chloride	3.6E-05	3.7E-05	3.5E-05	3.5E-05
Naphthalene	5.8E-06	5.9E-06	7.6E-06	7.6E-06
Nickel	1.1E-04	1.1E-04	1.5E-04	1.6E-04
Organics (unspecified)	4.2E-04	4.3E-04	3.7E-04	3.7E-04
Perchloroethylene	3.1E-06	3.1E-06	2.7E-06	2.7E-06
Phenanthrene	1.9E-07	1.9E-07	1.6E-07	1.6E-07
Phenols	7.0E-06	7.2E-06	8.8E-06	8.9E-06
Polyaromatic Hydrocarbons (total)	1.9E-06	2.0E-06	3.7E-06	3.7E-06
Propylene	7.6E-06	8.0E-06	3.6E-05	3.6E-05
Pyrene	2.3E-08	2.3E-08	2.0E-08	2.0E-08
Radionuclides (unspecified) (Ci)	0.0054	0.0054	0.0047	0.0047
Selenium	9.1E-05	9.2E-05	8.0E-05	8.0E-05
Styrene	8.4E-10	8.4E-10	7.2E-10	7.2E-10
Toluene	0.0044	0.0045	0.022	0.023
Trichloroethane	6.5E-09	8.0E-09	4.8E-09	5.5E-09
Vinyl Acetate	2.5E-10	2.6E-10	2.2E-10	2.2E-10
Xylenes	0.0026	0.0026	0.013	0.013
Zinc	8.4E-08	8.6E-08	1.3E-07	1.4E-07

Source: Franklin Associates, A Division of ERG

Table 3-13. Fuel-related Waterborne Emissions for Recycled PET Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing. For open-loop, includes 1/2 of virgin resin production emissions.

	PET Flake	PET Pellet	PET Flake	PET Pellet	PET Flake	PET Pellet	PET Flake	PET Pellet
	Cut-off, weight-based collection	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)	Open-loop, volume-based collection (50% compaction)
1-methylfluorene	6.5E-08	7.7E-08	6.9E-08	8.1E-08	1.5E-07	1.6E-07	1.5E-07	1.6E-07
2,4 dimethylphenol	1.6E-05	1.9E-05	1.7E-05	2.0E-05	3.7E-05	3.9E-05	3.8E-05	3.9E-05
2-Hexanone	3.7E-06	4.4E-06	4.0E-06	4.7E-06	8.7E-06	9.0E-06	8.8E-06	9.1E-06
2-methyl naphthalene	9.0E-06	1.1E-05	9.6E-06	1.1E-05	2.1E-05	2.2E-05	2.1E-05	2.2E-05
4-methyl-2-pentanone	2.4E-06	2.9E-06	2.6E-06	3.0E-06	5.6E-06	5.8E-06	5.6E-06	5.9E-06
Acetone	5.7E-06	6.8E-06	6.1E-06	7.2E-06	1.3E-05	1.4E-05	1.3E-05	1.4E-05
Acid (benzoic)	5.8E-04	6.9E-04	6.2E-04	7.3E-04	0.0013	0.0014	0.0014	0.0014
Acid (hexanoic)	1.2E-04	1.4E-04	1.3E-04	1.5E-04	2.8E-04	2.9E-04	2.8E-04	2.9E-04
Acid (unspecified)	4.5E-04	5.6E-04	4.5E-04	5.6E-04	0.0012	0.0013	0.0012	0.0013
Alkylated Benzenes	1.4E-05	1.5E-05	1.5E-05	1.7E-05	2.6E-05	2.7E-05	2.7E-05	2.8E-05
Alkylated Fluorenes	7.8E-07	9.0E-07	8.9E-07	1.0E-06	1.5E-06	1.6E-06	1.6E-06	1.6E-06
Alkylated Naphthalenes	2.2E-07	2.5E-07	2.5E-07	2.8E-07	4.3E-07	4.5E-07	4.5E-07	4.6E-07
Alkylated Phenanthrenes	9.2E-08	1.1E-07	1.0E-07	1.2E-07	1.8E-07	1.9E-07	1.9E-07	1.9E-07
Aluminum	0.025	0.029	0.029	0.032	0.049	0.051	0.051	0.053
Ammonia	0.0092	0.011	0.010	0.012	0.021	0.022	0.021	0.022
Ammonium	4.2E-05	8.2E-05	4.2E-05	8.2E-05	6.0E-05	8.0E-05	6.0E-05	8.0E-05
Antimony	1.5E-05	1.8E-05	1.7E-05	2.0E-05	3.0E-05	3.1E-05	3.1E-05	3.2E-05
Arsenic	1.4E-04	1.6E-04	1.5E-04	1.7E-04	3.1E-04	3.3E-04	3.2E-04	3.3E-04
Barium	0.35	0.40	0.40	0.45	0.70	0.73	0.72	0.75
Benzene	9.6E-04	0.0011	0.0010	0.0012	0.0022	0.0023	0.0023	0.0023
Beryllium	6.8E-06	8.0E-06	7.4E-06	8.6E-06	1.5E-05	1.6E-05	1.5E-05	1.6E-05
BOD	0.13	0.21	0.13	0.21	0.27	0.31	0.27	0.31
Boron	0.0018	0.0021	0.0019	0.0022	0.0042	0.0043	0.0042	0.0044
Bromide	0.12	0.15	0.13	0.15	0.28	0.30	0.29	0.30
Cadmium	2.1E-05	2.5E-05	2.2E-05	2.7E-05	4.7E-05	4.9E-05	4.7E-05	4.9E-05
Calcium	1.83	2.18	1.95	2.30	4.26	4.43	4.32	4.49
Chlorides (methyl chloride)	2.3E-08	2.7E-08	2.4E-08	2.9E-08	5.3E-08	5.6E-08	5.4E-08	5.6E-08
Chlorides (unspecified)	20.6	24.5	21.9	25.9	47.9	49.8	48.5	50.5
Chromium (unspecified)	7.0E-04	8.0E-04	7.9E-04	8.9E-04	0.0014	0.0014	0.0014	0.0015
Cobalt	1.3E-05	1.5E-05	1.3E-05	1.6E-05	2.9E-05	3.1E-05	3.0E-05	3.1E-05
COD	0.12	0.15	0.12	0.15	0.31	0.32	0.31	0.32
Copper	1.2E-04	1.5E-04	1.3E-04	1.6E-04	2.5E-04	2.7E-04	2.6E-04	2.7E-04
Cresols	3.3E-05	4.0E-05	3.6E-05	4.2E-05	7.7E-05	8.1E-05	7.8E-05	8.2E-05
Cyanide	4.1E-08	4.9E-08	4.4E-08	5.2E-08	9.6E-08	1.0E-07	9.7E-08	1.0E-07
Cymene	5.7E-08	6.8E-08	6.1E-08	7.2E-08	1.3E-07	1.4E-07	1.3E-07	1.4E-07
Dibenzofuran	1.1E-07	1.3E-07	1.2E-07	1.4E-07	2.5E-07	2.6E-07	2.6E-07	2.7E-07
Dibenzothiophene	8.8E-08	1.0E-07	9.4E-08	1.1E-07	2.0E-07	2.1E-07	2.1E-07	2.2E-07
Dissolved Solids	25.4	30.2	27.1	31.9	59.0	61.5	59.9	62.3
Ethylbenzene	5.4E-05	6.4E-05	5.7E-05	6.8E-05	1.3E-04	1.3E-04	1.3E-04	1.3E-04
Fluorine/Fluorides	6.8E-04	0.0013	6.9E-04	0.0013	9.7E-04	0.0013	9.7E-04	0.0013
Hardness	5.64	6.71	6.01	7.09	13.1	13.7	13.3	13.8
Hydrocarbons	1.1E-04	1.4E-04	1.2E-04	1.4E-04	2.7E-04	2.8E-04	2.7E-04	2.8E-04
Iron	0.060	0.072	0.067	0.078	0.12	0.13	0.13	0.13
Lead	2.4E-04	2.8E-04	2.6E-04	3.0E-04	5.2E-04	5.4E-04	5.3E-04	5.5E-04
Lithium	0.40	0.49	0.40	0.49	1.06	1.10	1.06	1.10
Magnesium	0.36	0.43	0.38	0.45	0.83	0.87	0.84	0.88
Manganese	0.0015	0.0025	0.0015	0.0025	0.0027	0.0032	0.0028	0.0032
Mercury	2.8E-07	3.4E-07	3.2E-07	3.7E-07	5.5E-07	5.8E-07	5.7E-07	5.9E-07
Methyl Ethyl Ketone (MEK)	4.6E-08	5.5E-08	4.9E-08	5.8E-08	1.1E-07	1.1E-07	1.1E-07	1.1E-07
Molybdenum	1.3E-05	1.6E-05	1.4E-05	1.6E-05	3.0E-05	3.2E-05	3.1E-05	3.2E-05
Naphthalene	1.0E-05	1.2E-05	1.1E-05	1.3E-05	2.4E-05	2.5E-05	2.4E-05	2.5E-05
Nickel	1.2E-04	1.4E-04	1.3E-04	1.5E-04	2.7E-04	2.8E-04	2.7E-04	2.8E-04
Nitrates	1.1E-04	2.0E-04	1.1E-04	2.0E-04	1.5E-04	2.0E-04	1.5E-04	2.0E-04
Nitrogen (ammonia)	3.7E-05	7.1E-05	3.7E-05	7.1E-05	5.2E-05	6.9E-05	5.2E-05	6.9E-05
Oil	0.012	0.014	0.013	0.015	0.027	0.028	0.027	0.028
Organic Carbon	0.0019	0.0023	0.0019	0.0023	0.0050	0.0052	0.0050	0.0052
Pentamethyl benzene	4.3E-08	5.1E-08	4.6E-08	5.4E-08	9.9E-08	1.0E-07	1.0E-07	1.0E-07
Phenanthrene	1.0E-07	1.2E-07	1.2E-07	1.3E-07	2.2E-07	2.3E-07	2.3E-07	2.4E-07
Phenol/Phenolic Compounds	2.7E-04	3.2E-04	2.9E-04	3.4E-04	6.1E-04	6.4E-04	6.2E-04	6.5E-04
Radionuclides (unspecified) (Ci)	7.5E-08	1.4E-07	7.5E-08	1.4E-07	1.1E-07	1.4E-07	1.1E-07	1.4E-07
Selenium	1.8E-05	3.2E-05	1.8E-05	3.3E-05	2.7E-05	3.4E-05	2.7E-05	3.4E-05
Silver	0.0012	0.0014	0.0013	0.0015	0.0028	0.0029	0.0028	0.0029
Sodium	5.80	6.91	6.19	7.29	13.5	14.1	13.7	14.2
Strontium	0.031	0.037	0.033	0.039	0.072	0.075	0.073	0.076
Sulfates	0.11	0.18	0.11	0.19	0.19	0.23	0.20	0.23
Sulfides	1.1E-05	1.2E-05	1.2E-05	1.4E-05	1.8E-05	1.8E-05	1.9E-05	1.9E-05
Sulfur	0.0015	0.0018	0.0016	0.0019	0.0035	0.0037	0.0036	0.0037
Surfactants	5.3E-04	6.4E-04	5.7E-04	6.7E-04	0.0013	0.0013	0.0013	0.0013
Suspended Solids	0.80	0.93	0.90	1.03	1.59	1.65	1.64	1.70
Thallium	3.3E-06	3.7E-06	3.7E-06	4.1E-06	6.4E-06	6.6E-06	6.6E-06	6.8E-06
Tin	8.6E-05	1.0E-04	9.4E-05	1.1E-04	1.9E-04	1.9E-04	1.9E-04	2.0E-04
Titanium	2.4E-04	2.7E-04	2.7E-04	3.0E-04	4.6E-04	4.8E-04	4.8E-04	5.0E-04
Toluene	9.0E-04	0.0011	9.6E-04	0.0011	0.0021	0.0022	0.0021	0.0022
Total Alkalinity	0.046	0.054	0.048	0.057	0.11	0.11	0.11	0.11
Total Biphenyls	8.8E-07	1.0E-06	9.9E-07	1.1E-06	1.7E-06	1.8E-06	1.8E-06	1.8E-06
Total Dibenzo-thiophenes	2.7E-09	3.1E-09	3.1E-09	3.4E-09	5.3E-09	5.5E-09	5.5E-09	5.7E-09
Vanadium	1.5E-05	1.8E-05	1.6E-05	1.9E-05	3.6E-05	3.7E-05	3.6E-05	3.8E-05
Xylenes	4.8E-04	5.7E-04	5.1E-04	6.0E-04	0.0011	0.0012	0.0011	0.0012
Yttrium	3.8E-06	4.6E-06	4.1E-06	4.8E-06	8.9E-06	9.3E-06	9.1E-06	9.4E-06
Zinc	6.2E-04	7.3E-04	6.9E-04	8.0E-04	0.0012	0.0013	0.0013	0.0013

Source: Franklin Associates, A Division of ERG

Table 3-14. Fuel-related Waterborne Emissions for Recycled HDPE Resin
(Pounds per 1,000 pounds of resin)
Includes emissions from postconsumer collection, transport, sorting, and reprocessing.
For open-loop, includes 1/2 of virgin resin production emissions.

	Cut-off, weight-based collection	Cut-off, volume-based collection (50% compaction)	Open-loop, weight-based collection	Open-loop, volume-based collection (50% compaction)
1-methylfluorene	3.9E-08	4.5E-08	9.1E-08	9.5E-08
2,4 dimethylphenol	9.5E-06	1.1E-05	2.2E-05	2.3E-05
2-Hexanone	2.2E-06	2.6E-06	5.2E-06	5.4E-06
2-methyl naphthalene	5.4E-06	6.3E-06	1.3E-05	1.3E-05
4-methyl-2-pentanone	1.4E-06	1.7E-06	3.4E-06	3.5E-06
Acetone	3.4E-06	4.0E-06	8.0E-06	8.3E-06
Acid (benzoic)	3.5E-04	4.0E-04	8.1E-04	8.4E-04
Acid (hexanoic)	7.1E-05	8.4E-05	1.7E-04	1.7E-04
Acid (unspecified)	1.6E-04	1.6E-04	7.9E-04	8.0E-04
Alkylated Benzenes	1.2E-05	1.4E-05	1.4E-05	1.5E-05
Alkylated Fluorenes	6.8E-07	8.4E-07	8.1E-07	8.9E-07
Alkylated Naphthalenes	1.9E-07	2.4E-07	2.3E-07	2.5E-07
Alkylated Phenanthrenes	8.0E-08	9.8E-08	9.5E-08	1.0E-07
Aluminum	0.022	0.027	0.026	0.029
Ammonia	0.0059	0.0069	0.013	0.013
Ammonium	4.3E-05	4.3E-05	3.7E-05	3.7E-05
Antimony	1.3E-05	1.6E-05	1.6E-05	1.7E-05
Arsenic	8.8E-05	1.0E-04	1.9E-04	1.9E-04
Barium	0.30	0.37	0.37	0.41
Benzene	5.7E-04	6.7E-04	0.0013	0.0014
Beryllium	4.6E-06	5.5E-06	8.9E-06	9.3E-06
BOD	0.092	0.094	0.17	0.17
Boron	0.0011	0.0012	0.0025	0.0026
Bromide	0.073	0.085	0.17	0.18
Cadmium	1.3E-05	1.6E-05	2.8E-05	2.9E-05
Calcium	1.09	1.28	2.58	2.67
Chlorides (methyl chloride)	1.4E-08	1.6E-08	3.2E-08	3.3E-08
Chlorides (unspecified)	12.3	14.4	29.0	30.0
Chromium (unspecified)	6.1E-04	7.5E-04	7.2E-04	7.9E-04
Cobalt	7.5E-06	8.8E-06	1.8E-05	1.8E-05
COD	0.051	0.055	0.20	0.20
Copper	9.0E-05	1.1E-04	1.5E-04	1.5E-04
Cresols	2.0E-05	2.3E-05	4.7E-05	4.9E-05
Cyanide	2.5E-08	2.9E-08	5.8E-08	6.0E-08
Cymene	3.4E-08	4.0E-08	8.0E-08	8.3E-08
Dibenzofuran	6.5E-08	7.6E-08	1.5E-07	1.6E-07
Dibenzothiophene	5.2E-08	6.1E-08	1.2E-07	1.3E-07
Dissolved Solids	15.2	17.7	35.8	37.1
Ethylbenzene	3.2E-05	3.8E-05	7.6E-05	7.8E-05
Fluorine/Fluorides	6.9E-04	7.0E-04	6.0E-04	6.0E-04
Hardness	3.37	3.94	7.95	8.23
Hydrocarbons	6.8E-05	8.0E-05	1.6E-04	1.7E-04
Iron	0.048	0.058	0.068	0.073
Lead	1.7E-04	2.0E-04	3.0E-04	3.1E-04
Lithium	0.14	0.14	0.70	0.70
Magnesium	0.21	0.25	0.50	0.52
Manganese	0.0013	0.0013	0.0016	0.0016
Mercury	2.5E-07	3.0E-07	2.9E-07	3.2E-07
Methyl Ethyl Ketone (MEK)	2.7E-08	3.2E-08	6.5E-08	6.7E-08
Molybdenum	7.8E-06	9.1E-06	1.8E-05	1.9E-05
Naphthalene	6.2E-06	7.2E-06	1.5E-05	1.5E-05
Nickel	8.1E-05	9.6E-05	1.6E-04	1.6E-04
Nitrates	1.1E-04	1.1E-04	9.2E-05	9.2E-05
Nitrogen (ammonia)	3.7E-05	3.8E-05	3.2E-05	3.2E-05
Oil	0.0074	0.0087	0.016	0.017
Organic Carbon	6.5E-04	6.6E-04	0.0033	0.0033
Pentamethyl benzene	2.6E-08	3.0E-08	6.0E-08	6.2E-08
Phenanthrene	7.7E-08	9.3E-08	1.3E-07	1.4E-07
Phenol/Phenolic Compounds	1.7E-04	1.9E-04	3.7E-04	3.8E-04
Radionuclides (unspecified) (Ci)	7.6E-08	7.6E-08	6.5E-08	6.6E-08
Selenium	1.8E-05	1.8E-05	1.6E-05	1.6E-05
Silver	7.1E-04	8.3E-04	0.0017	0.0017
Sodium	3.47	4.05	8.18	8.47
Strontium	0.019	0.022	0.044	0.045
Sulfates	0.094	0.099	0.12	0.12
Sulfides	1.1E-05	1.4E-05	8.1E-06	9.5E-06
Sulfur	9.0E-04	0.0011	0.0021	0.0022
Surfactants	3.0E-04	3.5E-04	7.7E-04	8.0E-04
Suspended Solids	0.68	0.83	0.85	0.93
Thallium	2.8E-06	3.5E-06	3.4E-06	3.7E-06
Tin	6.2E-05	7.4E-05	1.1E-04	1.1E-04
Titanium	2.1E-04	2.5E-04	2.4E-04	2.7E-04
Toluene	5.4E-04	6.3E-04	0.0013	0.0013
Total Alkalinity	0.027	0.032	0.064	0.067
Total Biphenyls	7.6E-07	9.3E-07	9.0E-07	9.9E-07
Total Dibenzo-thiophenes	2.3E-09	2.9E-09	2.8E-09	3.1E-09
Vanadium	9.2E-06	1.1E-05	2.2E-05	2.3E-05
Xylenes	2.9E-04	3.3E-04	6.8E-04	7.0E-04
Yttrium	2.3E-06	2.7E-06	5.4E-06	5.6E-06
Zinc	5.2E-04	6.4E-04	6.6E-04	7.1E-04

Source: Franklin Associates, A Division of ERG