FINAL PEER-REVIEWED APPENDIX TO LIFE CYCLE INVENTORY OF PACKAGING OPTIONS FOR SHIPMENT OF RETAIL MAIL-ORDER SOFT GOODS

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APPENDIX A

ENERGY REQUIREMENTS AND ENVIRONMENTAL EMISSIONS FOR FUEL CONSUMPTION

INTRODUCTION

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

This version of Appendix A was last completely updated in 1998 using the most current data sources that were available at that time. Most of the public data sources for fuel use and emissions were 1995-1997 publications. Combustion energy values are 1995 values. Average fuel use for electricity generation is 1996 data. Crude oil production data are 1994 values, while refinery data are 1993 values. Specific sources of data on the production and combustion of each fuel and for electricity generation are clearly referenced in the text and tables, with full source information (including age) provided in the References section at the end of the appendix.

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

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

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

Primary Fuel Production

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

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

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

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

The environmental emissions can be divided into two sources:

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

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

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

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

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

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

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

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

Primary Fuel Combustion

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

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

The list of emissions reported and level of speciation (e.g., in categories such as acid and metal ion) reported in these appendix tables is limited by the published data sources that are available and may vary for different fuels and combustion source. Combustion emissions for a given primary fuel will vary according to how it is combusted; for example, coal burned in utility boilers will have different emission factors from coal burned in industrial boilers. Different types of boilers and engines vary in completeness of combustion, resulting in different emissions of carbon dioxide, carbon monoxide, and methane for the same type of fuel. The types and efficiencies of emission control systems used with various combustion sources also vary, affecting the quantities of controlled emissions that are reported in these tables. Major types of combustion sources for the primary fuels, both stationary and mobile, are included in this appendix.

To summarize, the topics included in this appendix are:

- Primary fuel production (precombustion process energy requirements and precombustion process emissions data)
    - Coal
    - Natural gas
    - Petroleum fuels
    - Nuclear fuel
- Energy for transportation
- Fuels consumed for electricity generation
    - Calculation of the composite kilowatt-hour
- Precombustion energy and precombustion process and fuel-related emissions
    - Coal
    - Natural gas
    - Petroleum fuels
    - Nuclear fuel
- Primary fuel combustion

  Energy content of fuels

  Environmental emissions (precombustion and combustion)
    - Coal
        - Utility boilers
        - Industrial boilers
    - Residual fuel oil
        - Utility boilers
        - Industrial boilers
    - Distillate fuel oil - Industrial boilers
    - Natural gas
        - Utility boilers
        - Industrial boilers
        - Industrial equipment
    - Diesel fuel - Industrial equipment
    - Gasoline - Industrial equipment
    - Liquefied petroleum gases (LPG) - Industrial equipment
    - Uranium
    - Wood wastes
    - Mobile sources
        - Truck
        - Locomotive
        - Barges and ocean freighters

Data Quality Indicators

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

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

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

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

The Franklin Associates methodology involves the assignment of data quality indicators (DQIs) to the variables used as inputs to our computer models. This allows the determination of a distribution of input values, rather than a single point estimate. This distribution more accurately reflects the level of confidence in the values. The deterministic model is therefore changed into a stochastic model. This means that the output of the model is also a distribution of values, rather than a single point estimate. It is then easier to judge, for example, whether two values for total solid waste are the same or different. This approach requires considerable additional modeling time and expense, however, and is outside the scope of this project. Data quality indicators are reported here for informational purposes only.

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

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

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

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

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

PRIMARY FUEL PRODUCTION

Precombustion Energy and Process Emissions

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

Precombustion process emissions include all environmental emissions that are released as a direct result of activities associated with producing the primary fuels. The process emissions listed in this fuel production section do not, however, include emissions from the combustion of fuels used to produce process energy. These fuel-related process emissions are calculated and presented in a different section of this appendix. The energy values presented in Tables A-1 through A-4 are the basis for these fuel-related precombustion emissions calculations.

Coal

Coal is used as a fuel for electric power generation and industrial heating and steam generation. Energy is required and environmental consequences are incurred in acquiring coal for fuel. Table A-1 presents the energy requirements and the process-related environmental emissions involved in mining and preparing coal for fuel consumption.

Coal Mining. Coal may be obtained by surface mining of outcrops or seams that are near the earth's surface or by underground mining of deeper deposits. In surface mining, also called strip mining, the overburden (soil and rock covering the ore) is removed from shallow seams, the deposit is broken up, and the coal is loaded for transport. The overburden is generally returned to the mine (eventually) and is not considered as a solid waste in this appendix. Underground mining is done primarily by one of two methods—room-and-pillar mining or longwall mining. Underground mining is a complex undertaking, and is much more labor and energy intensive than surface mining. The data in Table A-1 are based on the portion of coal mined by surface and underground methods in the U.S. in 1994.

Coal Production. After the coal is mined, it goes through various preparation processes before it is used as fuel. These processes vary depending on the quality of the coal and the use for which it is intended. Coal preparation usually involves some type of size reduction, such as crushing and screening, and the removal of extraneous material introduced during mining. In addition, coal is often cleaned to upgrade the quality and heating value of the coal by removing or reducing the sulfur, clay, rock, and other ash-producing materials (Reference A-18).

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

Natural Gas

Natural gas is a widely used energy resource, since it is a relatively clean, efficient, and versatile fuel. The major component of natural gas is methane (CH_4). Other components of natural gas include ethane, propane, butane, and other heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen and hydrogen sulfides. Table A-2 contains the combined energy requirements and environmental emissions for producing, processing, and transporting natural gas used as a fuel. The data are based on the portion of natural gas extracted on-shore and off-shore in 1994.

Natural Gas Production. Natural gas is extracted from deep underground wells and is frequently co-produced with crude oil. Because of its gaseous nature, natural gas flows quite freely from wells, which produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface.

Atmospheric emissions from natural gas production result primarily from unflared venting. The waterborne wastes result from brines that occur when natural gas is produced in combination with oil.

Natural Gas Processing. Once the raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG). Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the natural gas has a high hydrogen sulfide content, it is considered "sour."

Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as "sweetening."

Atmospheric emissions result from gas sweetening plants if the acid waste gas is flared or incinerated.

Table A-1

DATA FOR MINING AND PROCESSING 1,000 POUNDS OF COAL

Energy Usage			**DQI**
Process Energy			
Electricity	9.6	kwh	B
Natural Gas	0.79	cubic feet	B
Residual Oil	0.028	gal	C
Distillate Oil	0.30	gal	C
Gasoline	0.024	gal	C
Coal	0.48	lb	B
Transportation Energy			
Combination Truck	2.0	ton-miles	C
Diesel	0.020	gal	C
Rail	200	ton-miles	C
Diesel	0.56	gal	C
Barge	20	ton-miles	D
Diesel	0.040	gal	D
Residual Oil	0.016	gal	D
Pipeline-coal slurry	1.4	ton-miles	C
Electricity	0.32	kwh	C
Process Atmospheric Emissions			
Particulates	2.5	lb	D
Methane	4.7	lb	B
Process Waterborne Emissions			
Suspended Solids	1.4	lb	E
Manganese	0.078	lb	E
Iron	0.12	lb	E
Process Solid Wastes	342	lbs	C

References: A-2, A-6, A-9, A-19, A-21, A-22, A-23, A-40, A-41, and A-54 through A-57

Source: Franklin Associates, Ltd.

Table A-2

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

Energy Usage			**DQI**
Process Energy			
Electricity	0.82	kwh	B
Natural Gas	51.0	cubic feet	B
Residual Oil	0.013	gallons	B
Distillate Oil	0.011	gallons	B
Gasoline	0.046	gallons	B
Transportation Energy			
Natural Gas Pipeline	17.3	ton-miles	C
Natural Gas	39.9	cu ft	C
Combination Truck	0.64	ton-miles	C
Diesel	0.0064	gallons	C
Rail	1.93	ton-miles	C
Diesel	0.0054	gallons	C
Barge	0.64	ton-miles	C
Diesel	0.0013	gallons	C
Residual Oil	5.2E-04	gallons	C
Process Atmospheric Emissions			
Methane	0.35	lb	B
Hydrocarbons (other than methane)	0.46	lb	B
Sulfur Oxides	1.80	lb	B
Process Waterborne Emissions			
Dissolved Solids	2.8	lb	D
Suspended Solids	0.0014	lb	D
BOD	0.0025	lb	D
COD	0.016	lb	D
Oil/grease	0.05	lb	E
Chromium	1.3E-04	lb	E
Zinc	4.40E-05	lb	E
Chlorides	0.13	lb	E
Sulfates	0.10	lb	E
Cyanide	1.9E-07	lb	E
Mercury	1.0E-08	lb	E
Cadmium	1.3E-04	lb	E
Other Organics	0.0081	lb	E
Process Solid Waste	5.1	lb	C

References: A-2, A-6, A-9, A-20, A-21, A-24 through A-30, A-51, A-52, A-54, and A-57.

Source: Franklin Associates, Ltd.

Natural gas is transported primarily by pipeline. Sometimes it is compressed and transported by insulated railcars and tankers.

Petroleum Fuels

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

The American Petroleum Institute identifies three categories of oil extraction wastes: produced water, drilling waste, and associated waste.

The water that is extracted with crude oil is called the “oil field brine”. The brine goes through a separator at or near the wellhead in order to remove the oil from the water. According to the American Petroleum Institute (API), it is estimated that 17.9 billion barrels of brine water were produced from crude oil production in 1995. This quantity of water equates to a ratio of 3.3 barrels of water for each barrel of oil. The majority of this water (85 percent) is injected into separate wells specifically designed to accept production-related waters. This represents all waters produced by onshore oil production facilities, which are not permitted to discharge “oil field brine” to surface waters (Reference A-29). The remainder of the produced water is from offshore oil production facilities and is assumed to be discharged to the ocean. Therefore, the waterborne wastes represent the brine wastes present in this 15 percent of brine water (Reference A-50). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (Reference A-20).

The second type of oil extraction waste is drilling waste. Drilling waste includes the rock cuttings and fluids produced from drilling a wellbore. Drilling mud, a viscous fluid, is a particular kind of drilling fluid that is commonly used for drilling wellbores.

The third source of waste is associated waste, which is a broad category of small volume wastes. Associated wastes include atmospheric emissions, which are primarily hydrocarbons. These atmospheric emissions originate from the natural gas produced from combination wells and result in line losses and unflared venting.

Petroleum Refining. A petroleum refinery processes crude oil into thousands of products using physical and/or chemical processing technology. Gasoline is the primary output from refineries; however, other major products include kerosene, aviation fuel, diesel fuel, fuel oils, lubricating oil, and feedstocks for the petrochemical industry.

A petroleum refinery receives crude oil, which is comprised of mixtures of many hydrocarbon compounds and uses distillation processes to separate out pure product streams. Because the crude oil is contaminated (to variable degrees) with compounds of sulfur, nitrogen, oxygen, and metals, cleaning operations are common in all refineries. Also, the natural hydrocarbon components that comprise the crude oil are often chemically changed to give products for which there is higher demand. These processes, such as polymerization, alkylation, reforming, and visbreaking, are utilized to convert light or heavy crude oil fractions into intermediate weight products, which are more easily handled and utilized as fuels and/or feedstocks (Reference A-8).

Air pollution is caused by various petroleum refining processes, including: vacuum distillation, catalytic cracking, thermal cracking processes, and sulfur recovery. Fugitive emissions are also significant contributors to air emissions. These may be leaks from valves, seals, flanges, and drains, as well as leaks escaping from storage tanks or during transfer operations. The wastewater treatment plant for a refinery is also a source of fugitive emissions (Reference A-6).

The energy and emissions data for crude oil exploration and drilling are combined with refinery operations to present total precombustion energy for refined products in Tables A-3a through A-3d. The same refinery data are used for each petroleum fuel and allocation of energy emissions to the different refinery products is done on a mass basis. Differences in these values for different refinery products shown in Tables A-3a through A-3d are the result of converting from pounds of product to gallons using the specific gravity for each type of product.

Nuclear Fuel

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

Mining. Uranium ore can be extracted from the earth by either open-pit or underground mining; these methods are referred to as “conventional” mining. In addition, significant amounts of concentrated uranium ore can be produced by “nonconventional” methods such as solution mining (in-situ leaching), and recovery as a byproduct of phosphate, copper, and beryllium production. Since 1993, no conventional mining of uranium ore has occurred in the United States; all of the domestic uranium concentrate has come from nonconventional methods.

Milling. Uranium ore is processed in mills where uranium oxide (U_3O_8, also known as yellowcake) is extracted from the ore by a series of crushing, grinding, and concentration operations. Uranium mills are located near uranium mines due to the large quantities of ore that must be milled to produce concentrated uranium oxide. The most significant waste stream from the milling operations is called “tailings.” Tailings are liquid sludge from the concentration operations. The solids portion of the tailings is separated from the liquid and usually returned to the earth. Unlike overburden from mining operations, tailing solids are reported as in Table A-4 as solid wastes because they result from ore processing operations.

Table A-3a

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Energy Usage			**DQI**
Process Energy			
Electricity	199	kwh	B
Natural Gas	8,969	cu ft	B
Residual Oil	11.5	gal	B
Distillate Oil	1.67	gal	B
Gasoline	0.74	gal	B
LPG	1.33	gal	B
Transportation Energy			
Combination Truck	79.2	ton-miles	C
Diesel	0.79	gal	C
Ocean Freighter	16,065	ton-miles	C
Diesel	1.61	gal	C
Residual Oil	28.9	gal	C
Petroleum Pipeline	1,125	ton-miles	C
Electricity	24.8	kwh	C
Process Atmospheric Emissions			
Particulates	0.47	lb	B
Hydrocarbons (other than methane)	48.1	lb	B
Sulfur Oxides	1.58	lb	B
Aldehydes	0.32	lb	D
Ammonia	0.041	lb	D
Lead	1.1E-05	lb	C
Chlorine	0.0016	lb	D
Hydrochloric Acid	0.0012	lb	D
Process Waterborne Emissions			
Acid	9.0E-06	lb	E
Metal Ion	0.19	lb	E
Dissolved Solids	7.38	lb	D
Suspended Solids	0.10	lb	D
BOD	0.11	lb	D
COD	0.52	lb	D
Phenol	6.2E-04	lb	E
Oil	0.35	lb	E
Iron	0.0033	lb	E
Ammonia	0.014	lb	E
Chromium	3.6E-05	lb	E
Lead	1.6E-05	lb	E
Zinc	2.3E-04	lb	E
Process Solid Waste	31.2	lb	C

References: A-6, A-8, A-11, A-20, A-25 through A-28, A-32 through A-36, A-38, A-42 through A-48, and A-53.

Source: Franklin Associates, Ltd.

Table A-3b

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF DISTILLATE OIL

Energy Usage			**DQI**
Process Energy			
Electricity	183	kwh	B
Natural Gas	8,235	cu ft	B
Residual Oil	10.6	gal	B
Distillate Oil	1.53	gal	B
Gasoline	0.68	gal	B
LPG	1.23	gal	B
Transportation Energy			
Combination Truck	72.7	ton-miles	C
Diesel	0.72	gal	C
Ocean Freighter	14,750	ton-miles	C
Diesel	1.48	gal	C
Residual Oil	26.6	gal	C
Petroleum Pipeline	1,033	ton-miles	C
Electricity	22.7	kwh	C
Process Atmospheric Emissions			
Particulates	0.43	lb	B
Hydrocarbons (other than methane)	44.2	lb	B
Sulfur Oxides	1.45	lb	B
Aldehydes	0.29	lb	D
Ammonia	0.038	lb	D
Lead	1.0E-05	lb	C
Chlorine	0.0015	lb	D
Hydrochloric Acid	0.0011	lb	D
Process Waterborne Emissions			
Acid	8.2E-06	lb	E
Metal Ion	0.17	lb	E
Dissolved Solids	6.78	lb	D
Suspended Solids	0.092	lb	D
BOD	0.10	lb	D
COD	0.48	lb	D
Phenol	5.7E-04	lb	E
Oil	0.32	lb	E
Iron	0.0030	lb	E
Ammonia	0.013	lb	E
Chromium	3.3E-05	lb	E
Lead	1.5E-05	lb	E
Zinc	2.1E-04	lb	E
Process Solid Waste	28.7	lb	C

References: A-6, A-8, A-11, A-20, A-25 through A-28, A-32 through A-36, A-38, A-42 through A-48, and A-53.

Source: Franklin Associates, Ltd.

Table A-3c

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF GASOLINE

Energy Usage			**DQI**
Process Energy			
Electricity	156	kwh	B
Natural Gas	7,017	cu ft	B
Residual Oil	9.00	gal	B
Distillate Oil	1.30	gal	B
Gasoline	0.58	gal	B
LPG	1.04	gal	B
Transportation Energy			
Combination Truck	62.0	ton-miles	C
Diesel	0.61	gal	C
Ocean Freighter	12,569	ton-miles	C
Diesel	1.26	gal	C
Residual Oil	22.6	gal	C
Petroleum Pipeline	880	ton-miles	C
Electricity	19.4	kwh	C
Process Atmospheric Emissions			
Particulates	0.37	lb	B
Hydrocarbons (other than methane)	37.7	lb	B
Sulfur Oxides	1.23	lb	B
Aldehydes	0.25	lb	D
Ammonia	0.032	lb	D
Lead	8.9E-06	lb	C
Chlorine	0.0013	lb	D
Hydrochloric Acid	9.5E-04	lb	D
Process Waterborne Emissions			
Acid	7.0E-06	lb	E
Metal Ion	0.15	lb	E
Dissolved Solids	5.78	lb	D
Suspended Solids	0.079	lb	D
BOD	0.086	lb	D
COD	0.41	lb	D
Phenol	4.8E-04	lb	E
Oil	0.27	lb	E
Iron	0.0026	lb	E
Ammonia	0.011	lb	E
Chromium	2.8E-05	lb	E
Lead	1.2E-05	lb	E
Zinc	1.8E-04	lb	E
Process Solid Waste	24.4	lb	C

References: A-6, A-8, A-11, A-20, A-25 through A-28, A-32 thourgh A-36, A-38, A-42 through A-48, and A-53.

Source: Franklin Associates, Ltd.

Table A-3d

DATA FOR THE PRODUCTION AND PROCESSING OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Energy Usage			**DQI**
Process Energy			
Electricity	114	kwh	B
Natural Gas	5,148	cu ft	B
Residual Oil	6.60	gal	B
Distillate Oil	0.95	gal	B
Gasoline	0.43	gal	B
LPG	0.77	gal	B
Transportation Energy			
Combination Truck	45.5	ton-miles	C
Diesel	0.45	gal	C
Ocean Freighter	9,221	ton-miles	C
Diesel	0.92	gal	C
Residual Oil	16.6	gal	C
Petroleum Pipeline	646	ton-miles	C
Electricity	14.2	kwh	C
Process Atmospheric Emissions			
Particulates	0.27	lb	B
Hydrocarbons (other than methane)	27.6	lb	B
Sulfur Oxides	0.90	lb	B
Aldehydes	0.18	lb	D
Ammonia	0.024	lb	D
Lead	6.5E-06	lb	D
Chlorine	9.3E-04	lb	D
Hydrochloric Acid	7.0E-04	lb	D
Process Waterborne Emissions			
Acid	5.2E-06	lb	E
Metal Ion	0.11	lb	E
Dissolved Solids	4.24	lb	D
Suspended Solids	0.058	lb	D
BOD	0.063	lb	D
COD	0.30	lb	D
Phenol	3.5E-04	lb	E
Oil	0.20	lb	E
Iron	0.0019	lb	E
Ammonia	0.0083	lb	E
Chromium	2.0E-05	lb	E
Lead	9.1E-06	lb	E
Zinc	1.3E-04	lb	E
Process Solid Waste	17.9	lb	C

References: A-6, A-8, A-11, A-20, A-25 through A-28, A-32 through A-36, A-38, A-42 through A-48, and A-53.

Source: Franklin Associates, Ltd.

Table A-4

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL GRADE URANIUM

Energy Usage			**DQI**
Process Energy			
Electricity	4,290,000	kwh	B
Natural Gas	1,900,000	cu ft	B
Residual Oil	561	gal	B
Transportation Energy			
Combination Truck	3,440	ton-miles	D
Diesel	34.13	gal	D
Process Atmospheric Emissions			
Particulates	36,500	lb	B
Nitrogen Oxides	33,300	lb	B
Hydrocarbons (other than methane)	957	lb	B
Sulfur Oxides	120,000	lb	B
Carbon Monoxide	960	lb	B
Carbon Dioxide	11,900	lb	B
Kerosene	221	lb	C
Process Waterborne Emissions			
Chloride	950	lb	E
Sodium	350	lb	E
Calcium	190	lb	E
Iron	4,100	lb	E
Sulfates	110,000	lb	E
Ammonia	330	lb	E
Manganese	201	lb	E
Fluorides	880	lb	E
Nitrates	83	lb	E
Process Solid Waste	5,600,000	lb	C

References: A-11 through A-19, and A-31.

Source: Franklin Associates, Ltd.

Since 1993, all conventional uranium mills in the United States are either inactive, are being decommissioned, or are permanently closed. Only nonconventional uranium plants (in-situ leaching or phosphate byproduct) were producing uranium concentrate in 1995.

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

Enrichment. Gaseous diffusion and gas centrifuge are the two most common methods used to commercially produce enriched uranium. These enrichment processes increase the fissionable portion of the fuel (^{235}U) from its natural abundance of 0.7 percent to a fuel-grade abundance of around 3 percent. Gaseous diffusion is currently used in the United States, while in Europe the gas centrifuge is the commercially used enrichment process.

In the gaseous diffusion process, gaseous UF_6 is passed through a series of porous membrane filters. In the filtering process, UF_6 molecules containing the ^{235}U isotope diffuse through the filters more readily than the molecules containing the larger ^{238}U isotope. A typical gaseous diffusion enrichment process requires more than 1,200 stages to produce uranium enriched to 3 percent. Enrichment is necessary for uranium used as fuel in light-water nuclear reactors, because the amount of fissile ^{235}U in natural uranium is too low to sustain a nuclear chain reaction.

Fuel Fabrication. Enriched UF_6 is next taken to a fuel fabrication plant, where it is converted to uranium dioxide (UO_2) powder. The powder is then compressed into small cylindrical pellets, which are loaded and sealed into hollow rods made of a zirconium-stainless steel alloy. These fuel rods are then shipped to nuclear power plants for use as nuclear reactor fuel.

The energy and emissions for mining and processing uranium to form fuel rods are shown in Table A-4. Almost all of the energy used and environmental emissions released are due to the enrichment step.

Energy for Transportation

Transportation, an important step, occurs often in the production of the primary fuels. The energy requirements associated with the transportation of products are shown in Table A-5. Transportation modes included are: truck, rail, barge, ocean transport, and pipeline. Energy requirements are reported as the quantity of fuel or electricity required per 1,000 ton-miles. Statistical data were used for rail, barge, and pipeline transportation energy (Reference A-4). The energy usage for combination trucks (tractor trailers) weighing greater than 14,000 pounds is calculated based upon the following data:

1. Average miles per gallon for tractor-trailers = 5.9 miles per gallon. These gallons are distributed based on the following fuel usage split: 19.4 percent gasoline tractor-trailers and 80.6 percent diesel tractor-trailers (Reference A-4).

2. A fully loaded tractor-trailer carries a maximum of 45,000 pounds (Reference A-35). It is more common for a load to be volume limited than weight limited.

3. Accounting for empty backhauling and trucks that are not fully loaded increases fuel usage by approximately 25 percent (Reference A-35).

Table A-5

1993 TRANSPORTATION FUEL REQUIREMENTS

		Fuel Consumed per 1,000 Ton-Miles	Energy Consumed (1) (Btu/ton-mile)	DQI
Combination truck (tractor trailer)				
Diesel	gal	9.4	1,465	B
Gasoline	gal	9.4	1,308	B
Single unit truck				
Diesel	gal	26.5	4,129	B
Gasoline	gal	26.5	3,689	B
Rail				
Diesel	gal	2.4	374	B
Barge (2)				
Diesel	gal	2.0	316	C
Residual	gal	0.8	131	C
Total			447	
Ocean freighter (2)				
Diesel	gal	0.1	23	C
Residual	gal	1.8	307	C
Total			330	C
Pipeline - natural gas				
Natural gas	cuft	2,300	2,581	C
Pipeline - petroleum products				
Electricity	kwh	22	241	C
Pipeline - coal slurry				
Electricity	kwh	235	2,578	C

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(1) Includes precombustion energy for fuel acquisition.

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

References: A-4 and A-57.

Source: Franklin Associates, Ltd.

The energy usage for single unit trucks weighing less than 14,000 pounds is calculated based upon the following data:

1. Average miles per gallon for single unit trucks = 6.8 miles per gallon. These gallons are distributed based on the following fuel usage split: 19.4 percent gasoline trucks and 80.6 percent diesel trucks (Reference A-4).
2. A fully loaded single unit truck carries 15,000 pounds maximum of freight (Reference A-35).
3. These types of trucks are used for local deliveries. These trucks will either deliver and pick-up throughout the day and will only be empty at the end of the day or will deliver until empty and then go back to the warehouse for more deliveries. Therefore, calculations are based on single-unit trucks having an average load of 65 percent (References A-16 and A-35).

Fuels used for barge and ocean freighter transportation are diesel and residual fuel oil, with diesel being the dominant fuel for barges and residual oil the dominant fuel for ocean freighters. The Btu per ton-mile values are additive as shown in Table A-5.

Energy Sources for Electricity Generation

To accurately account for the fuels used in the production and processing of the primary fuels, the fuel mix for electricity generation in the U.S., (the composite kilowatt-hour), must be determined.

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

A national fuel grid was developed to relate electricity generation to the average quantities of individual energy sources used to produce electricity in the United States. In general, detailed data do not exist on the energy sources used to generate the electricity consumed by each industry. Electricity production and distribution systems in the United States are interlinked and cannot be separated from one another. Users of electricity, in general, cannot specify the energy sources used to produce their share of the electric power grid. Therefore, the energy sources used to produce the national average electricity grid are used for most industries.

The exception to this is the electricity used by aluminum processes in the aluminum industry. The electricity data for the aluminum industry is developed using region-specific data for that industry. This is because the aluminum industry influenced the building of hydropower facilities in many locations.

Calculation of the U.S. Composite Kilowatt-Hour

Representative fuel and other energy requirements for the average generation of electrical energy are calculated by first determining the requirements to generate one composite kilowatt-hour. A composite kilowatt-hour is defined as a kilowatt-hour of electrical energy produced using the national average fuel mix for electricity production in the United States.

In Table A-6 the total electricity generated from the various types of fuel and other energy sources is presented for both utility and non-utility generators (Reference A-1). The percentage of total electricity generated in the U.S. from each energy source is also calculated in Table A-6.

The data in Table A-6 were used to calculate the quantity of each fossil fuel required to generate one kilowatt-hour of electricity if only that fuel were being used. The results of these calculations are presented in Table A-7. For example, by converting 873,700,000 tons of coal to pounds and dividing by the quantity of kilowatt-hours of electricity generated (1735×10^9 kWh), the quantity of coal to produce one kilowatt-hour by utility generators is determined to be 1.01 pound in 1996. Similarly, the quantity of coal to produce one kilowatt-hour by industrial generators is 1.53 pounds. This is one way to evaluate the average efficiency of converting fossil fuels into electricity.

Table A-8 shows the results of the calculations to determine the total fuel requirements for the generation and delivery of one composite kilowatt-hour for 1996 conditions in the United States. For the fossil fuels, the combustion energy of the fuel is multiplied by the quantity of fuel required to generate one kilowatt-hour. This gives the total energy to generate one kilowatt-hour. Multiplying this value by the percent of total electricity generated by the specific fuel results in the quantity of energy contributed by that fuel to the generation of the composite kilowatt-hour.

The contribution of nuclear energy and wood or other renewable fuels to the composite kilowatt-hour is calculated in a similar manner to the calculations used for fossil fuels.

Nuclear power plants generate electricity by harnessing the thermal energy from a controlled nuclear reaction. The reaction is used to produce steam, which in turn drives a turbine-generator to produce electric power.

The thermal efficiency for producing electricity from nuclear reactions is roughly 32 percent. Taking into account this thermal efficiency for electricity generation, the heat factor for nuclear power-derived electricity is 10,740 Btu per kWh of generated electricity (Reference A-1). This translates to 985,000,000 Btu per pound of fuel grade uranium, which is added to precombustion energy and multiplied in Table A-7 by the pounds of uranium needed to produce one kilowatt-hour of electricity and by the percentage of total electricity generated from nuclear power to obtain the energy contribution to the composite kilowatt-hour from nuclear power.

Table A-6

1996 U.S. NATIONAL ELECTRICITY GENERATION BY ENERGY SOURCE

Source	Quantity of Fuel Consumed		Electricity Production (million kwh)	Reference	Percent of Total Generation
Utility Sources					
Coal	873,700,000	tons	1,735,000	1	49.9
Natural gas	2,737,000	million cuft	263,300	1	7.57
Residual oil	110,000,000	barrels	64,500	1, 2 (1)	1.85
Distillate oil	7,800,000	barrels	3,400	1, 2 (1)	0.10
Total Oil	117,800,000	barrels	67,900	1	1.95
Fossil Fuel Subtotal			2,066,200		59.4
Nuclear			674,800	1	19.4
Hydroelectric			328,800	1	9.45
Geothermal			5,200	39	0.15
Biomass			2,000	39	0.057
Photovoltaic			3	39	0.0001
Total (Utility)			**3,077,003**	1	**88.42**
Non-Utility Sources					
Natural gas	2,500,000	million cuft	220,000	2, 3 (1)	6.32
Other gas	1,600,000	million cuft	7,201	39	0.21
Wood	25,900,000	tons (2)	38,800	2, 3 (1)	1.11
Coal	49,100,000	tons	64,000	2, 3 (1)	1.84
Petroleum (3)	42,000,000	barrels	20,400	2, 3 (1)	0.59
Hydroelectric			11,050	2, 3 (1)	0.32
Waste			23,300	39	0.67
Geothermal			11,000	39	0.32
Wind			2,009	39	0.058
Solar			900	39	0.026
Other (4)			4,380	39	0.13
Total (Non-utility)			**403,040**		**11.58**
TOTAL			**3,480,043**		**100.0**

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(1) Value calculated using data from two sources.

(2) Assuming 4,500 Btu/lb and 10,400 Btu/kwh (33% thermal efficiency in generation of electricity from wood).

(3) This petroleum product is assumed to be distillate oil.

(4) Other includes hydrogen, sulfur, batteries, chemicals, and spent sulfite liquor.

References: A-1, A-2, A-3, A-39, A-49, and A-50.

Source: Franklin Associates, Ltd.

Table A-7

CALCULATION OF ENERGY CONSUMPTION FOR THE GENERATION AND DELIVERY OF ONE COMPOSITE KILOWATT-HOUR, 1996

		Total Energy (1)		**Quantity of Each Fuel to Generate One Kwh (2)**	**Percent of Composite Kwh (3)**	**Btu of Fuel Consumed per Composite Kwh**
Utility Sources						
Coal	Pre-Combustion	264	Btu/lb			
	Combustion	10,402	Btu/lb			
	Total Energy	10,666	Btu/lb	1.01 lb	49.9	5,243
Natural gas	Pre-Combustion	129	Btu/cuft			
	Combustion	1,022	Btu/cuft			
	Total Energy	1,151	Btu/cuft	10.4 cuft	7.57	805
Residual fuel oil	Pre-Combustion	21,000	Btu/gal			
	Combustion	149,700	Btu/gal			
	Total Energy	170,700	Btu/gal	0.068 gal	1.85	188
Distillate fuel oil	Pre-Combustion	19,300	Btu/gal			
	Combustion	138,700	Btu/gal			
	Total Energy	158,000	Btu/gal	0.091 gal	0.10	13
Subtotal (fossil fuels)					59.4	6,248
Uranium	Pre-Combustion	50,600,000	Btu/lb			
	Combustion	985,321,000	Btu/lb			
	Total Energy	1,035,921,000	Btu/lb	1.09E-05 lb	19.4	2,084
Hydropower	Total energy	3,414	Btu/kwh	--	9.45	323
Other utility (geothermal, biomass, solar, etc.)	Total energy	10,350	Btu/kwh (4)	--	0.21	21
Total (Utility)					**88.5**	**8,676**
Non-utility Sources						
Natural gas	Pre-Combustion	129	Btu/cuft			
	Combustion	1,031	Btu/cuft			
	Total Energy	1,160	Btu/cuft	12.0 cuft	6.32	779
Wood wastes		10,350	Btu/kwh (4)		1.11	115
Coal	Pre-Combustion	264	Btu/lb			
	Combustion	11,157	Btu/lb			
	Total Energy	11,421	Btu/lb	1.53 lb	1.84	314
Distillate	Pre-Combustion	19,300	Btu/gal			
	Combustion	138,700	Btu/gal			
	Total Energy	158,000	Btu/gal	0.11	0.59	92
Hydropower	Total energy	3,414	Btu/kwh	--	0.32	11
Other non-utility	Total energy	10,350	Btu/kwh (4)	--	1.41	146
Total (Non-utility)					**11.6**	**1,458**
TOTAL (U.S. AVERAGE)					**100**	**10,134**
Line loss adjustment: (5)		**Multiply by 1.08**				**10,944**

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(1) From Table 9.
(2) From Table 6.
(3) From Table 6.
(4) 3,413 Btu/kwh divided by 0.33 thermal efficiency
(5) Adjusts energy requirements to account for power losses in transmission lines (i.e., the difference between net electricity generation and sales.) References A-1 and A-2.

Source: Franklin Associates, Ltd.

Table A-8

MIX OF FUEL REQUIRED TO GENERATE ONE KILOWATT-HOUR (1996 U.S. average)

			DQI
Coal	0.53	lb	A
Natural gas	1.52	cuft	A
Residual oil	0.0012	gal	A
Distillate oil	0.00071	gal	A
Fuel grade uranium (1)	2.0E-06	lb	A
Hydroelectric	338	Btu	A
Other (2)	234	Btu	A

Includes line loss adjustment.

(1) Calculated.

(2) Other includes wood, waste, geothermal, wind, solar, hydrogen, other gases, batteries, and other small sources of electricity.

Source: Calculated from data presented in Table A-6.

Efficiency calculations for energy sources other than fossil fuels are less meaningful. The quantity of water needed to produce one kilowatt-hour of electricity using hydropower is not an issue in this study. Water for hydropower is a finite, yet renewable, resource. Assigning an efficiency to this source of electricity would be an arbitrary procedure. Therefore, the portion of the composite kilowatt-hour from hydropower is determined using the standard conversion of 3,413 Btu per kilowatt-hour and multiplying by the percentage of total electricity generated from hydropower.

Electricity from wind energy and from photovoltaic cells using solar power falls into the same category as hydroelectric energy. The standard conversion of 3,413 Btu per kilowatt-hour is used to measure energy produced from these sources. Currently, very little electricity is actually being produced using wind energy or photovoltaic cells. Therefore, the contributions of these energy sources to the composite kilowatt-hour do not show up in the national fuel grid.

Renewable energy sources other than hydroelectricity, such as geothermal energy, solar energy for steam generation, and biomass energy, produced less than one percent of the total electricity generated in the U.S. in 1996. These energy sources are presented in Table A-8 under the heading of Other. The contribution from these energy sources is calculated by using the standard conversion factor of 3,413 Btu per kilowatt-hour and assuming an average thermal efficiency of 33 percent for converting the steam produced by these energy sources to electricity. This gives an energy factor of 10,350 Btu per kWh of generated electricity. This energy factor is then multiplied by the percentage of total electricity generated from unconventional energy sources. The energy factor of 10,350 Btu per kWh is consistent with that reported in the November 1993 issue of the U.S. Department of Energy publication, **Monthly Energy Review**.

Adding the energy components of the composite kilowatt-hour shown in Table A-7 gives the total energy required to generate a composite kilowatt-hour of electricity, expressed in total Btu. An adjustment must be made to account for line losses in the transmission of electricity to consumers in order to reflect the true energy requirements for the use of electricity. This line loss adjustment is calculated to be the difference between net electricity generation and sales (Reference A-1). Net electricity generation is the total electricity produced by utilities minus the electricity used in-plant plus the net electricity purchased from non-utility generators and other countries.

In 1996, non-utility generated electricity was about 11 percent of the total U.S. electricity generation (Reference A-2, page 43). Non-utility generated electricity is produced using roughly 55 percent natural gas, 19 percent wood or renewable fuel sources, and 16 percent coal (Reference A-3, page 211).

Precombustion Energy and Emissions for Primary Fuels

Precombustion energy is the summation of all energy inputs into the production of a fuel that is subsequently used as a source of energy. Calculation of precombustion energy requires the tabulation of the fuel requirements for each of the energy sources used in fuel production. Each of these fuel inputs also had energy requirements for production and transportation. This series of inputs creates a complex and technically infinite set of inter-dependent steps. Iterative calculations were employed to evaluate this inter-dependency.

Precombustion energy requirements for primary fuels were calculated using the process and transportation energy requirements presented in Tables A-1 through A-4, the transportation energy requirements in Table A-5, and the electricity production data presented in Tables A-6 through A-8. The results of these iterative calculations are presented in Tables A-10, A-11, A-12a through A-12d, and A-13 for coal, natural gas, petroleum fuels, and nuclear fuels, respectively. The energy requirements shown in Tables A-10 through A-13 include both the process and precombustion energy to produce the fuel.

The environmental emissions that result from producing and combusting fuels used for energy to produce other fuels are also presented in Tables A-10 through A-13. The emissions shown in these tables only include the precombustion emissions, not the process emissions. These fuel-related precombustion emissions are added to the process emissions presented in Tables A-1 through A-4 to obtain total precombustion emissions for each energy source in Tables A-14 through A-31 in the next section of this appendix.

PRIMARY FUEL COMBUSTION

Energy Content of Fuels

The precombustion, combustion, and total energy associated with the consumption of 1,000 units of the various types of fuels used by mobile and stationary sources are reported in Table A-9. Stationary sources include industrial and utility boilers, and other types of stationary industrial equipment such as compressors and pumps. Mobile sources include various modes of transportation such as truck, rail, barge, and ocean freighter.

Table A-9

ENERGY FACTORS FOR VARIOUS FUELS
1996

		Pre-Combustion Energy (Million Btu)	**Combustion Energy** (Million Btu)	**Total Energy** (Million Btu)
Mobile Sources				
Diesel	1,000 gal	19.3	139	158
Gasoline	1,000 gal	16.4	125	142
Residual fuel oil	1,000 gal	21.0	150	171
Industrial Heating				
Coal	1,000 lb	0.26	11.2	11.4
Diesel	1,000 gal	19.3	139	158
Distillate fuel oil	1,000 gal	19.3	139	158
Gasoline	1,000 gal	16.4	125	142
LPG	1,000 gal	12.1	95.5	108
Natural gas	1,000 cuft	0.13	1.03	1.16
Residual fuel oil	1,000 gal	21.0	150	171
Utility Heating				
Coal	1,000 lb	0.26	10.4	10.7
Natural gas	1,000 cuft	0.13	1.02	1.15
Residual fuel oil	1,000 gal	21.0	150	171
Distillate fuel oil	1,000 gal	19.3	139	158
Fuel grade uranium	1,000 lb	50,600	985,320	1,035,920

References: A-1, A-2, and A-4

Source: Franklin Associates, Ltd.

Table A-10

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF COAL

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	6.3	lb	B
Natural gas	30.0	cuft	B
Residual oil	0.098	gal	B
Distillate oil	0.86	gal	B
Gasoline	0.027	gal	B
Liquefied petroleum gas	0.0013	gal	B
Uranium (nuclear power)	2.4E-05	lb	B
Hydropower	3,780	Btu	B
Wood and wood wastes	1,310	Btu	B
Other renewable energy	2,030	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	0.059	lb	B
Nitrogen Oxides	0.23	lb	B
Hydrocarbons (other than methane)	0.085	lb	C
Sulfur Oxides	0.23	lb	B
Carbon Monoxide	0.18	lb	B
Fossil Carbon Dioxide	40.7	lb	A
Non-Fossil Carbon Dioxide	0.30	lb	C
Formaldehyde	9.6E-07	lb	C
Othr Aldehydes	0.0035	lb	C
Other Organics	0.0063	lb	E
Ammonia	8.7E-05	lb	C
Lead	2.7E-06	lb	B
Methane	0.039	lb	B
Kerosene	5.0E-06	lb	D
Chlorine	1.7E-06	lb	D
Hydrochloric Acid	0.0011	lb	C
Hydrogen Fluoride	1.5E-04	lb	C
Metals	1.2E-04	lb	D
Antimony	1.0E-06	lb	E
Arsenic	2.7E-06	lb	E
Beryllium	2.2E-07	lb	E
Cadmium	3.3E-06	lb	E
Chrominum	3.5E-06	lb	E
Cobalt	2.9E-06	lb	E
Manganese	5.4E-06	lb	E
Mercury	8.5E-07	lb	E
Nickel	4.6E-05	lb	E
Selenium	2.5E-06	lb	E
Acreolin	2.1E-07	lb	E
Nitrous Oxide	1.7E-04	lb	E
Benzene	9.3E-07	lb	E
Perchloroethylene	2.3E-07	lb	E
Trichloroethylene	2.0E-07	lb	E
Methylene Chloride	1.0E-06	lb	E
Carbon Tetrachloride	2.3E-06	lb	E
Phenols	5.9E-06	lb	E
Naphthalene	3.4E-07	lb	E
Dioxins	1.1E-12	lb	E
n-nitrodimethylamine	4.4E-08	lb	E
Radionuclides	3.9E-06	Ci	E

(continued)

Table A-10 (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF COAL

Waterborne Emissions			**DQI**
Acid	3.2E-09	lb	E
Metal Ion	6.9E-05	lb	E
Dissolved Solids	0.082	lb	D
Suspended Solids	0.012	lb	D
BOD	1.2E-04	lb	D
COD	0.0013	lb	D
Phenol	2.2E-07	lb	E
Oil	0.0015	lb	E
Sulfuric Acid	2.5E-04	lb	E
Iron	8.3E-04	lb	E
Ammonia	1.4E-05	lb	E
Chromium	3.6E-06	lb	E
Lead	5.7E-09	lb	E
Zinc	1.3E-06	lb	E
Chlorides	0.0037	lb	E
Sodium	8.0E-06	lb	E
Calcium	4.3E-06	lb	E
Sulfates	0.0053	lb	E
Manganese	4.8E-04	lb	E
Fluorides	2.0E-05	lb	E
Nitrates	1.9E-06	lb	E
Phosphates	1.2E-04	lb	E
Boron	0.0010	lb	E
Other Organics	4.2E-04	lb	E
Chromates	2.6E-06	lb	E
Cyanide	5.3E-09	lb	E
Mercury	2.8E-10	lb	E
Cadmium	3.6E-06	lb	E
Solid Waste	2.91	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Table A-11

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 CUBIC FEET OF NATURAL GAS

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	0.54	lb	B
Natural gas	104	cuft	B
Residual oil	0.021	gal	B
Distillate oil	0.028	gal	B
Gasoline	0.053	gal	B
Liquefied petroleum gas	1.4E-04	gal	B
Uranium (nuclear power)	2.2E-06	lb	B
Hydropower	347	Btu	B
Wood and wood wastes	187	Btu	B
Other renewable energy	121	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	0.0038	lb	B
Nitrogen Oxides	0.12	lb	B
Hydrocarbons (other than methane)	0.071	lb	C
Sulfur Oxides	0.13	lb	B
Carbon Monoxide	0.23	lb	B
Fossil Carbon Dioxide	15.7	lb	A
Non-Fossil Carbon Dioxide	0.028	lb	C
Formaldehyde	8.8E-08	lb	C
Othr Aldehydes	3.5E-04	lb	C
Other Organics	8.7E-04	lb	E
Ammonia	9.5E-06	lb	C
Lead	2.8E-07	lb	B
Methane	0.024	lb	B
Kerosene	4.8E-07	lb	D
Chlorine	2.2E-07	lb	D
Hydrochloric Acid	9.8E-05	lb	C
Hydrogen Fluoride	1.3E-05	lb	C
Metals	1.1E-05	lb	E
Antimony	8.9E-08	lb	E
Arsenic	1.9E-07	lb	E
Beryllium	1.4E-08	lb	E
Cadmium	2.7E-07	lb	E
Chrominum	2.3E-07	lb	E
Cobalt	2.5E-07	lb	E
Manganese	3.6E-07	lb	E
Mercury	7.4E-08	lb	E
Nickel	3.8E-06	lb	E
Selenium	2.2E-07	lb	E
Acreolin	1.9E-08	lb	E
Nitrous Oxide	1.2E-05	lb	E
Benzene	6.8E-08	lb	E
Perchloroethylene	2.0E-08	lb	E
Trichloroethylene	1.8E-08	lb	E
Methylene Chloride	8.8E-08	lb	E
Carbon Tetrachloride	1.1E-07	lb	E
Phenols	5.6E-07	lb	E
Naphthalene	3.2E-08	lb	E
Dioxins	1.1E-13	lb	E
n-nitrodimethylamine	4.1E-09	lb	E
Radionuclides	3.6E-07	Ci	E

(continued)

Table A-11 (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 CUBIC FEET OF NATURAL GAS

Waterborne Emissions			**DQI**
Acid	6.4E-10	lb	E
Metal Ion	1.4E-05	lb	E
Dissolved Solids	0.17	lb	D
Suspended Solids	0.0039	lb	D
BOD	1.8E-04	lb	D
COD	0.0024	lb	D
Phenol	4.4E-08	lb	E
Oil	0.0031	lb	E
Sulfuric Acid	2.1E-05	lb	E
Iron	7.3E-05	lb	E
Ammonia	4.9E-06	lb	E
Chromium	7.9E-06	lb	E
Lead	1.1E-09	lb	E
Zinc	2.7E-06	lb	E
Chlorides	0.0079	lb	E
Sodium	7.6E-07	lb	E
Calcium	4.1E-07	lb	E
Sulfates	0.0063	lb	E
Manganese	4.2E-05	lb	E
Fluorides	1.9E-06	lb	E
Nitrates	1.8E-07	lb	E
Phosphates	1.1E-05	lb	E
Boron	8.4E-05	lb	E
Other Organics	5.1E-04	lb	E
Chromates	2.2E-07	lb	E
Cyanide	1.2E-08	lb	E
Mercury	6.1E-10	lb	E
Cadmium	7.9E-06	lb	E
Solid Waste	0.55	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Table A-12a

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	141	lb	B
Natural gas	11,000	cuft	B
Residual oil	43.0	gal	B
Distillate oil	4.90	gal	B
Gasoline	1.40	gal	B
Liquefied petroleum gas	1.40	gal	B
Uranium (nuclear power)	5.7E-04	lb	B
Hydropower	91,500	Btu	B
Wood and wood wastes	49,300	Btu	B
Other renewable energy	31,800	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	1.34	lb	B
Nitrogen Oxides	9.23	lb	B
Hydrocarbons (other than methane)	6.59	lb	C
Sulfur Oxides	26.6	lb	B
Carbon Monoxide	6.92	lb	B
Fossil Carbon Dioxide	2,860	lb	A
Non-Fossil Carbon Dioxide	6.64	lb	C
Formaldehyde	2.3E-05	lb	C
Othr Aldehydes	0.19	lb	C
Other Organics	0.33	lb	E
Ammonia	0.0024	lb	C
Lead	1.4E-04	lb	B
Methane	4.41	lb	B
Kerosene	1.1E-04	lb	D
Chlorine	5.2E-05	lb	D
Hydrochloric Acid	0.026	lb	C
Hydrogen Fluoride	0.0035	lb	C
Metals	0.0027	lb	D
Antimony	4.1E-05	lb	E
Arsenic	8.6E-05	lb	E
Beryllium	6.0E-06	lb	E
Cadmium	1.3E-04	lb	E
Chrominum	9.8E-05	lb	E
Cobalt	1.2E-04	lb	E
Manganese	1.2E-04	lb	E
Mercury	2.8E-05	lb	E
Nickel	0.0018	lb	E
Selenium	7.9E-05	lb	E
Acreolin	5.1E-06	lb	E
Nitrous Oxide	0.0031	lb	E
Benzene	1.6E-05	lb	E
Perchloroethylene	5.0E-06	lb	E
Trichloroethylene	4.8E-06	lb	E
Methylene Chloride	2.2E-05	lb	E
Carbon Tetrachloride	2.1E-05	lb	E
Phenols	1.3E-04	lb	E
Naphthalene	7.6E-06	lb	E
Dioxins	2.8E-11	lb	E
n-nitrodimethylamine	1.1E-06	lb	E
Radionuclides	9.5E-05	Ci	E

(continued)

Table A-12a (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF RESIDUAL FUEL OIL

Waterborne Emissions			**DQI**
Acid	1.5E-07	lb	E
Metal Ion	0.0031	lb	E
Dissolved Solids	30.6	lb	D
Suspended Solids	0.76	lb	D
BOD	0.031	lb	D
COD	0.43	lb	D
Phenol	1.0E-05	lb	E
Oil	0.54	lb	E
Sulfuric Acid	0.0075	lb	E
Iron	0.017	lb	E
Ammonia	9.7E-04	lb	E
Chromium	0.0014	lb	E
Lead	2.6E-07	lb	E
Zinc	4.7E-04	lb	E
Chlorides	1.39	lb	E
Sodium	1.8E-04	lb	E
Calcium	9.7E-05	lb	E
Sulfates	1.13	lb	E
Manganese	0.010	lb	E
Fluorides	4.5E-04	lb	E
Nitrates	4.3E-05	lb	E
Phosphates	0.0038	lb	E
Boron	0.030	lb	E
Other Organics	0.093	lb	E
Chromates	1.1E-04	lb	E
Cyanide	2.0E-06	lb	E
Mercury	1.1E-07	lb	E
Cadmium	0.0014	lb	E
Solid Waste	113	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Table A-12b

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF DISTILLATE FUEL OIL

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	130	lb	B
Natural gas	10,100	cuft	B
Residual oil	40.0	gal	B
Distillate oil	4.50	gal	B
Gasoline	1.30	gal	B
Liquefied petroleum gas	1.30	gal	B
Uranium (nuclear power)	5.3E-04	lb	B
Hydropower	84,000	Btu	B
Wood and wood wastes	45,300	Btu	B
Other renewable energy	29,200	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	1.23	lb	B
Nitrogen Oxides	8.47	lb	B
Hydrocarbons (other than methane)	6.05	lb	C
Sulfur Oxides	24.4	lb	B
Carbon Monoxide	6.36	lb	B
Fossil Carbon Dioxide	2,630	lb	A
Non-Fossil Carbon Dioxide	6.10	lb	C
Formaldehyde	2.1E-05	lb	C
Othr Aldehydes	0.18	lb	C
Other Organics	0.30	lb	E
Ammonia	0.0022	lb	C
Lead	1.2E-04	lb	B
Methane	4.05	lb	B
Kerosene	1.0E-04	lb	D
Chlorine	4.7E-05	lb	D
Hydrochloric Acid	0.024	lb	C
Hydrogen Fluoride	0.0033	lb	C
Metals	0.0025	lb	D
Antimony	3.8E-05	lb	E
Arsenic	7.9E-05	lb	E
Beryllium	5.5E-06	lb	E
Cadmium	1.2E-04	lb	E
Chrominum	9.0E-05	lb	E
Cobalt	1.1E-04	lb	E
Manganese	1.1E-04	lb	E
Mercury	2.6E-05	lb	E
Nickel	0.0017	lb	E
Selenium	7.2E-05	lb	E
Acreolin	4.7E-06	lb	E
Nitrous Oxide	0.0028	lb	E
Benzene	1.5E-05	lb	E
Perchloroethylene	4.6E-06	lb	E
Trichloroethylene	4.4E-06	lb	E
Methylene Chloride	2.1E-05	lb	E
Carbon Tetrachloride	1.9E-05	lb	E
Phenols	1.2E-04	lb	E
Naphthalene	7.0E-06	lb	E
Dioxins	2.5E-11	lb	E
n-nitrodimethylamine	9.9E-07	lb	E
Radionuclides	8.7E-05	Ci	E

(continued)

Table A-12b (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF DISTILLATE FUEL OIL

Waterborne Emissions			**DQI**
Acid	1.4E-07	lb	E
Metal Ion	0.0029	lb	E
Dissolved Solids	28.1	lb	D
Suspended Solids	0.70	lb	D
BOD	0.029	lb	D
COD	0.40	lb	D
Phenol	9.3E-06	lb	E
Oil	0.50	lb	E
Sulfuric Acid	0.0069	lb	E
Iron	0.016	lb	E
Ammonia	8.9E-04	lb	E
Chromium	0.0013	lb	E
Lead	2.4E-07	lb	E
Zinc	4.4E-04	lb	E
Chlorides	1.28	lb	E
Sodium	1.6E-04	lb	E
Calcium	9.0E-05	lb	E
Sulfates	1.03	lb	E
Manganese	0.0092	lb	E
Fluorides	4.1E-04	lb	E
Nitrates	3.9E-05	lb	E
Phosphates	0.0035	lb	E
Boron	0.028	lb	E
Other Organics	0.085	lb	E
Chromates	9.8E-05	lb	E
Cyanide	1.9E-06	lb	E
Mercury	9.8E-08	lb	E
Cadmium	0.0013	lb	E
Solid Waste	104	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Table A-12c

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF GASOLINE

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	110	lb	B
Natural gas	8,620	cuft	B
Residual oil	34.0	gal	B
Distillate oil	3.80	gal	B
Gasoline	1.10	gal	B
Liquefied petroleum gas	1.10	gal	B
Uranium (nuclear power)	4.5E-04	lb	B
Hydropower	71,600	Btu	B
Wood and wood wastes	38,600	Btu	B
Other renewable energy	24,900	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	1.05	lb	B
Nitrogen Oxides	7.22	lb	B
Hydrocarbons (other than methane)	5.16	lb	C
Sulfur Oxides	20.8	lb	B
Carbon Monoxide	5.42	lb	B
Fossil Carbon Dioxide	2,239	lb	A
Non-Fossil Carbon Dioxide	5.20	lb	C
Formaldehyde	1.8E-05	lb	C
Othr Aldehydes	0.15	lb	C
Other Organics	0.26	lb	E
Ammonia	0.0019	lb	C
Lead	1.1E-04	lb	B
Methane	3.45	lb	B
Kerosene	8.9E-05	lb	D
Chlorine	4.0E-05	lb	D
Hydrochloric Acid	0.020	lb	C
Hydrogen Fluoride	0.0028	lb	C
Metals	0.0021	lb	D
Antimony	3.2E-05	lb	E
Arsenic	6.7E-05	lb	E
Beryllium	4.7E-06	lb	E
Cadmium	1.0E-04	lb	E
Chrominum	7.6E-05	lb	E
Cobalt	9.2E-05	lb	E
Manganese	9.1E-05	lb	E
Mercury	2.2E-05	lb	E
Nickel	0.0014	lb	E
Selenium	6.2E-05	lb	E
Acreolin	4.0E-06	lb	E
Nitrous Oxide	0.0024	lb	E
Benzene	1.3E-05	lb	E
Perchloroethylene	3.9E-06	lb	E
Trichloroethylene	3.8E-06	lb	E
Methylene Chloride	1.8E-05	lb	E
Carbon Tetrachloride	1.6E-05	lb	E
Phenols	1.0E-04	lb	E
Naphthalene	6.0E-06	lb	E
Dioxins	2.2E-11	lb	E
n-nitrodimethylamine	8.4E-07	lb	E
Radionuclides	7.4E-05	Ci	E

(continued)

Table A-12c (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF GASOLINE

Waterborne Emissions			**DQI**
Acid	1.2E-07	lb	E
Metal Ion	0.0024	lb	E
Dissolved Solids	23.9	lb	D
Suspended Solids	0.60	lb	D
BOD	0.025	lb	D
COD	0.34	lb	D
Phenol	7.9E-06	lb	E
Oil	0.42	lb	E
Sulfuric Acid	0.0059	lb	E
Iron	0.014	lb	E
Ammonia	7.6E-04	lb	E
Chromium	0.0011	lb	E
Lead	2.0E-07	lb	E
Zinc	3.7E-04	lb	E
Chlorides	1.09	lb	E
Sodium	1.4E-04	lb	E
Calcium	7.6E-05	lb	E
Sulfates	0.88	lb	E
Manganese	0.0078	lb	E
Fluorides	3.5E-04	lb	E
Nitrates	3.3E-05	lb	E
Phosphates	0.0030	lb	E
Boron	0.024	lb	E
Other Organics	0.072	lb	E
Chromates	8.3E-05	lb	E
Cyanide	1.6E-06	lb	E
Mercury	8.4E-08	lb	E
Cadmium	0.0011	lb	E
Solid Waste	88.6	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Table A-12d

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	81.0	lb	B
Natural gas	6,300	cuft	B
Residual oil	25.0	gal	B
Distillate oil	2.80	gal	B
Gasoline	0.80	gal	B
Liquefied petroleum gas	0.80	gal	B
Uranium (nuclear power)	3.3E-04	lb	B
Hydropower	52,500	Btu	B
Wood and wood wastes	28,300	Btu	B
Other renewable energy	18,300	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	0.77	lb	B
Nitrogen Oxides	5.30	lb	B
Hydrocarbons (other than methane)	3.78	lb	C
Sulfur Oxides	15.2	lb	B
Carbon Monoxide	3.97	lb	B
Fossil Carbon Dioxide	1,642	lb	A
Non-Fossil Carbon Dioxide	3.81	lb	C
Formaldehyde	1.3E-05	lb	C
Othr Aldehydes	0.11	lb	C
Other Organics	0.19	lb	E
Ammonia	0.0014	lb	C
Lead	7.8E-05	lb	B
Methane	2.53	lb	B
Kerosene	6.5E-05	lb	D
Chlorine	3.0E-05	lb	D
Hydrochloric Acid	0.015	lb	C
Hydrogen Fluoride	0.0020	lb	C
Metals	0.0016	lb	D
Antimony	2.4E-05	lb	E
Arsenic	4.9E-05	lb	E
Beryllium	3.4E-06	lb	E
Cadmium	7.4E-05	lb	E
Chrominum	5.6E-05	lb	E
Cobalt	6.7E-05	lb	E
Manganese	6.7E-05	lb	E
Mercury	1.6E-05	lb	E
Nickel	0.0010	lb	E
Selenium	4.5E-05	lb	E
Acreolin	2.9E-06	lb	E
Nitrous Oxide	0.0018	lb	E
Benzene	9.4E-06	lb	E
Perchloroethylene	2.9E-06	lb	E
Trichloroethylene	2.8E-06	lb	E
Methylene Chloride	1.3E-05	lb	E
Carbon Tetrachloride	1.2E-05	lb	E
Phenols	7.7E-05	lb	E
Naphthalene	4.4E-06	lb	E
Dioxins	1.6E-11	lb	E
n-nitrodimethylamine	6.2E-07	lb	E
Radionuclides	5.4E-05	Ci	E

(continued)

Table A-12d (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 GALLONS OF LIQUEFIED PETROLEUM GAS (LPG)

Waterborne Emissions			**DQI**
Acid	8.5E-08	lb	E
Metal Ion	0.0018	lb	E
Dissolved Solids	17.5	lb	D
Suspended Solids	0.44	lb	D
BOD	0.018	lb	D
COD	0.25	lb	D
Phenol	5.8E-06	lb	E
Oil	0.31	lb	E
Sulfuric Acid	0.0043	lb	E
Iron	0.010	lb	E
Ammonia	5.6E-04	lb	E
Chromium	8.0E-04	lb	E
Lead	1.5E-07	lb	E
Zinc	2.7E-04	lb	E
Chlorides	0.80	lb	E
Sodium	1.0E-04	lb	E
Calcium	5.6E-05	lb	E
Sulfates	0.65	lb	E
Manganese	0.0057	lb	E
Fluorides	2.6E-04	lb	E
Nitrates	2.4E-05	lb	E
Phosphates	0.0022	lb	E
Boron	0.017	lb	E
Other Organics	0.053	lb	E
Chromates	6.1E-05	lb	E
Cyanide	1.2E-06	lb	E
Mercury	6.1E-08	lb	E
Cadmium	8.0E-04	lb	E
Solid Waste	65.0	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Table A-13

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL-GRADE URANIUM

Total Precombustion Fuel Use and Process Energy			**DQI**
Coal	2,500,000	lb	B
Natural gas	9,800,000	cuft	B
Residual oil	7,300	gal	B
Distillate oil	5,800	gal	B
Gasoline	610	gal	B
Liquefied petroleum gas	23.0	gal	B
Uranium (nuclear power)	10.0	lb	B
Hydropower	1.6E+09	Btu	B
Wood and wood wastes	8.6E+08	Btu	B
Other renewable energy	5.5E+08	Btu	B
Precombustion Fuel Related Emissions Only			
Atmospheric Emissions			
Particulates	7,500	lb	B
Nitrogen Oxides	25,200	lb	B
Hydrocarbons (other than methane)	5,500	lb	C
Sulfur Oxides	54,000	lb	B
Carbon Monoxide	4,800	lb	B
Fossil Carbon Dioxide	6,750,000	lb	A
Non-Fossil Carbon Dioxide	129,000	lb	C
Formaldehyde	0.41	lb	C
Othr Aldehydes	18.9	lb	C
Other Organics	45.8	lb	E
Ammonia	30.7	lb	C
Lead	0.36	lb	B
Methane	14,900	lb	B
Kerosene	2.21	lb	D
Chlorine	0.50	lb	D
Hydrochloric Acid	447	lb	C
Hydrogen Fluoride	61.8	lb	C
Metals	52.7	lb	D
Antimony	0.049	lb	E
Arsenic	0.21	lb	E
Beryllium	0.023	lb	E
Cadmium	0.055	lb	E
Chrominum	0.27	lb	E
Cobalt	0.13	lb	E
Manganese	1.16	lb	E
Mercury	0.17	lb	E
Nickel	1.38	lb	E
Selenium	0.64	lb	E
Acreolin	0.089	lb	E
Nitrous Oxide	50.4	lb	E
Benzene	0.30	lb	E
Perchloroethylene	0.085	lb	E
Trichloroethylene	0.084	lb	E
Methylene Chloride	0.37	lb	E
Carbon Tetrachloride	0.15	lb	E
Phenols	2.57	lb	E
Naphthalene	0.15	lb	E
Dioxins	4.8E-07	lb	E
n-nitrodimethylamine	0.019	lb	E
Radionuclides	1.65	Ci	E

(continued)

Table A-13 (cont)

TOTAL PRECOMBUSTION FUEL USE AND FUEL RELATED EMISSIONS FOR THE PRODUCTION OF 1,000 POUNDS OF FUEL-GRADE URANIUM

Waterborne Emissions			**DQI**
Acid	1.0E-04	lb	E
Metal Ion	2.11	lb	E
Dissolved Solids	27,400	lb	D
Suspended Solids	4,270	lb	D
BOD	27.9	lb	D
COD	385	lb	D
Phenol	0.0068	lb	E
Oil	484	lb	E
Sulfuric Acid	57.5	lb	E
Iron	337	lb	E
Ammonia	3.96	lb	E
Chromium	1.25	lb	E
Lead	1.8E-04	lb	E
Zinc	0.43	lb	E
Chlorides	1,280	lb	E
Sodium	3.49	lb	E
Calcium	1.90	lb	E
Sulfates	2,060	lb	E
Manganese	194	lb	E
Fluorides	8.78	lb	E
Nitrates	0.83	lb	E
Phosphates	28.7	lb	E
Boron	230	lb	E
Other Organics	122	lb	E
Chromates	0.079	lb	E
Cyanide	0.0018	lb	E
Mercury	9.6E-05	lb	E
Cadmium	1.25	lb	E
Solid Waste	1,150,000	lb	C

Calculated from data in Tables A-1 through A-9.

Source: Franklin Associates, Ltd.

Total Environmental Emissions for Process, Utility, and Transportation Fuels

The environmental emissions associated with the consumption of 1,000 units of the various types of fuels by mobile and stationary sources are reported in Tables A-14 through A-32. Precombustion and combustion emissions are shown separately and also totaled. Mobile sources include various modes of transportation such as truck, rail, barge, etc. Stationary sources include industrial and utility boilers, and other types of stationary industrial equipment such as compressors and pumps.

Coal

Utility Boilers. Coal is most commonly burned by utilities as their primary fuel, followed by oil and natural gas. The environmental effects of coal combustion are dependent upon the ash and sulfur content of the coal, the type of boiler, and the firing mechanism used. The sulfur content of coal received by utilities in 1994 ranged from 0.27 weight percent to 4.50 weight percent, and the ash content ranged from 4.10 weight percent to 21.43 weight percent. (Reference A-5, page 66). A national average ash content of 9.87 percent by weight and a sulfur content of 1.18 percent by weight are used in this appendix.

Table A-14 presents the emissions associated with the combustion of 1,000 pounds of coal in utility boilers. Utilities use a mix of coal-fired boilers to produce electricity, and the data in Table A-14 represents a national average of 77 percent pulverized dry-bottom boilers, 11 percent pulverized wet-bottom boilers, 11 percent cyclone boilers, and one percent stoker boilers. Air emissions from coal-fired boilers are mainly particulates, sulfur oxides, and other gaseous products of combustion.

Coal-fired power plants commonly employ particulate control devices, which range in efficiency from about 80 percent for multiple cyclones to more than 99 percent for electrostatic precipitators and bag filters (Reference A-6). It was assumed that an average of 99 percent of the fly ash is collected in particulate control devices. This collected fly ash becomes solid waste along with the bottom ash from the boiler furnaces.

The sulfur oxide emissions from burning coal for utility power generation were calculated using the average sulfur content of coal received by utilities. The sulfur oxide emissions were reduced to appropriately account for the desulfurization units employed by 33 percent of the coal-fired generating units (Reference A-60). Since only 33 percent of utilities have desulfurization units, the sulfur oxide emissions from utility boilers are not significantly lower than the sulfur oxide emissions from industrial boilers. Furthermore, desulfurization units do not remove 100 percent of the sulfur oxides in an effluent stream. On average, utility desulfurization units remove 85 percent of the sulfur oxides emitted from coal combustion.

Some solid waste byproducts from utility coal combustion (fly ash, bottom ash, boiler slag, and flue gas desulfurization material) are now being diverted from the landfill by being incorporated in other useful products, such as cement and concrete products, mineral filler in asphalt, grouting, and wallboard. These diverted materials are not included as solid waste in Table A-14.

Industrial Boilers. In 1994, 11 percent of the coal consumed in the U.S. was used by industry. Industrial combustion of coal is treated separately from combustion of coal for utility boilers because pollutants are often different. Industries often do not burn coal in boilers as large as or of the same type as the utility boilers. They also do not always burn the same kinds of coal. The emissions presented in Table A-15 represent a national average of 44 percent pulverized dry-bottom boilers, 10 percent pulverized wet-bottom boilers, 2 percent cyclone boilers, and 44 percent stoker boilers.

Average ash and sulfur content for coal used by industry was assumed to be the same as for coal being received by utilities. Statistics on the quality of industrial and utility coal show that there is very little difference in the ash and sulfur content (Reference A-39). However, particulate control is generally less efficient for industrial coal boilers, and it is assumed that sulfur oxide control is not employed.

Residual Oil

Utility Boilers. The fuel oil consumed by utilities is mainly residual oil. Emissions from the combustion of residual oil are dependent on the composition of the fuel, the type of boiler, and the firing practices used. Pollutants from oil-fired boilers include ash, sulfur oxides, and other gaseous emissions. For residual oil, both particulate emissions and sulfur oxide emissions are proportional to the sulfur content of the fuel. A national average of 1.2 weight percent was used (Reference A-5, page 212).

About 30 percent of the total ash from combustion of oil is bottom ash. The remaining 70 percent of the ash will travel up the stack. It has been estimated that 42 percent of all oil-fired utility boilers had particulate control devices in 1994. These have an average efficiency of about 60 percent. Therefore, of the ash generated, about 48 percent is collected and will result in solid waste. The remaining 52 percent is released as air emissions (Reference A-8).

Sulfur oxide emissions were calculated based upon the average sulfur content of the fuel oil. Utilities using oil-fired boilers do not currently employ flue gas desulfurization units (Reference A-5, pages 23 and 37). Emissions for the combustion of residual oil in utility boilers are reported in Table A-16. These data are based on use of sulfur oxide controls for 33 percent of utility boilers, and a control efficiency of 85 percent in reducing sulfur oxide emissions where controls are used (Reference 60).

Table A-14

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN UTILITY BOILERS
(pounds of pollutants per 1,000 pounds of coal)

	Precombustion (1)	Combustion	Total	DQI
Atmospheric Emissions				
Particulates	2.56	0.31	2.87	B
Nitrogen Oxides	0.23	7.90	8.13	B
Hydrocarbons (other than methane)	0.085	0.035	0.12	C
Sulfur Oxides	0.23	11.7	11.9	B
Carbon Monoxide	0.18	0.30	0.48	B
Fossil Carbon Dioxide	40.7	2,120	2,161	A
Non-Fossil Carbon Dioxide	0.30		0.30	B
Formaldehyde	9.6E-07	4.5E-05	4.6E-05	C
Other Aldehydes	0.0035	1.9E-04	0.0037	C
Other Organics	0.0063		0.0063	D
Ammonia	8.7E-05	2.4E-05	1.1E-04	C
Lead	2.7E-06	9.3E-05	9.6E-05	B
Methane	4.69	0.019	4.71	C
Kerosene	5.0E-06		5.0E-06	D
Chlorine	1.7E-06		1.7E-06	D
Hydrochloric Acid	0.0011	0.18	0.18	C
Hydrogen Fluoride	1.5E-04	0.025	0.025	C
Metals	1.2E-04		1.2E-04	D
Mercaptan				
Antimony	1.0E-06	1.4E-05	1.5E-05	E
Arsenic	2.7E-06	7.0E-05	7.3E-05	E
Beryllium	2.2E-07	8.5E-06	8.7E-06	E
Cadmium	3.3E-06	2.5E-06	5.8E-06	E
Chromium	3.5E-06	9.1E-05	9.4E-05	E
Cobalt	2.9E-06	2.7E-05	3.0E-05	E
Manganese	5.4E-06	2.3E-04	2.4E-04	E
Mercury	8.5E-07	6.6E-05	6.7E-05	E
Nickel	4.6E-05	6.2E-05	1.1E-04	E
Selenium	2.5E-06	2.5E-04	2.5E-04	E
Acreolin	2.1E-07	3.6E-05	3.6E-05	D
Nitrous Oxide	1.7E-04	0.020	0.020	D
Benzene	9.3E-07	2.7E-05	2.8E-05	D
Perchloroethylene	2.3E-07	3.4E-05	3.4E-05	D
Trichloroethylene	2.0E-07	3.4E-05	3.4E-05	D
Methylene Chloride	1.0E-06	1.4E-04	1.4E-04	D
Carbon Tetrachloride	2.3E-06	3.6E-05	3.8E-05	D
Phenols	5.9E-06	6.7E-05	7.3E-05	D
Naphthalene	3.4E-07		3.4E-07	D
Dioxins	1.1E-12	1.9E-10	1.9E-10	D
n-nitrodimethylamine	4.4E-08	7.6E-06	7.6E-06	D
Radionuclides (Ci)	3.9E-06	3.5E-04	3.5E-04	D

(continued)

Table A-14 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN UTILITY BOILERS

(pounds of pollutants per 1,000 pounds of coal)

	Precombustion (1)	**Combustion**	**Total**	**DQI**
Waterborne Emissions				
Acid	3.2E-09		3.2E-09	E
Metal Ion	6.9E-05		6.9E-05	E
Dissolved Solids	0.082		0.082	D
Suspended Solids	1.41	0.13	1.54	D
BOD	1.2E-04		1.2E-04	D
COD	0.0013		0.0013	D
Phenol	2.2E-07		2.2E-07	E
Sulfide				E
Oil	0.0015		0.0015	E
Sulfuric Acid	2.5E-04	0.022	0.022	E
Iron	0.12		0.12	E
Hydrocarbons				E
Ammonia	1.4E-05		1.4E-05	E
Chromium	3.6E-06		3.6E-06	E
Lead	5.7E-09		5.7E-09	E
Zinc	1.3E-06		1.3E-06	E
Chlorides	0.0037	0.0070	0.011	E
Sodium	8.0E-06		8.0E-06	E
Calcium	4.3E-06		4.3E-06	E
Sulfates	0.0053		0.0053	E
Manganese	0.078		0.078	E
Fluorides	2.0E-05		2.0E-05	E
Nitrates	1.9E-06		1.9E-06	E
Phosphates	1.2E-04	0.011	0.011	E
Boron	0.0010	0.088	0.089	E
Other Organics	4.2E-04	0.017	0.017	E
Chromates	2.6E-06		2.6E-06	E
Cyanide	5.3E-09		5.3E-09	E
Mercury	2.8E-10		2.8E-10	E
Cadmium	3.6E-06		3.6E-06	E
Solid Waste	345	79	424	B

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(1) Sum of precombustion process-related emissions from Table A-1 and precombustion fuel-related emissions from Table A-10.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-15

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 pounds of coal)

Atmospheric Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Particulates	2.56	0.61	3.17	B
Nitrogen Oxides	0.23	5.40	5.63	B
Hydrocarbons (other than methane)	0.085	0.066	0.15	C
Sulfur Oxides	0.23	16.2	16.4	B
Carbon Monoxide	0.18	0.76	0.94	B
Fossil Carbon Dioxide	40.7	2,360	2,401	A
Non-Fossil Carbon Dioxide	0.30		0.30	B
Formaldehyde	9.6E-07		9.6E-07	C
Other Aldehydes	0.0035		0.0035	C
Other Organics	0.0063		0.0063	D
Ammonia	8.7E-05	1.6E-04	2.5E-04	C
Lead	2.7E-06	1.0E-04	1.0E-04	B
Methane	4.69	0.079	4.77	C
Kerosene	5.0E-06		5.0E-06	D
Chlorine	1.7E-06		1.7E-06	D
Hydrochloric Acid	0.0011		0.0011	C
Hydrogen Fluoride	1.5E-04		1.5E-04	C
Metals	1.2E-04		1.2E-04	D
Mercaptan				
Antimony	1.0E-06		1.0E-06	E
Arsenic	2.7E-06	8.7E-04	8.7E-04	E
Beryllium	2.2E-07	1.0E-04	1.0E-04	E
Cadmium	3.3E-06	2.8E-04	2.8E-04	E
Chromium	3.5E-06	0.0018	0.0018	E
Cobalt	2.9E-06		2.9E-06	E
Manganese	5.4E-06	0.0029	0.0029	E
Mercury	8.5E-07	2.3E-05	2.3E-05	E
Nickel	4.6E-05	0.0010	0.0011	E
Selenium	2.5E-06	2.0E-12	2.5E-06	E
Acreolin	2.1E-07		2.1E-07	D
Nitrous Oxide	1.7E-04	0.039	0.039	D
Benzene	9.3E-07	3.5E-04	3.5E-04	D
Perchloroethylene	2.3E-07		2.3E-07	D
Trichloroethylene	2.0E-07		2.0E-07	D
Methylene Chloride	1.0E-06		1.0E-06	D
Carbon Tetrachloride	2.3E-06		2.3E-06	D
Phenols	5.9E-06		5.9E-06	D
Naphthalene	3.4E-07		3.4E-07	D
Dioxins	1.1E-12		1.1E-12	D
n-nitrodimethylamine	4.4E-08		4.4E-08	D
Radionuclides (Ci)	3.9E-06		3.9E-06	D

(continued)

Table A-15 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF COAL IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 pounds of coal)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	3.2E-09		3.2E-09	E
Metal Ion	6.9E-05		6.9E-05	E
Dissolved Solids	0.082		0.082	D
Suspended Solids	1.41	0.13	1.54	D
BOD	1.2E-04		1.2E-04	D
COD	0.0013		0.0013	D
Phenol	2.2E-07		2.2E-07	E
Sulfide				E
Oil	0.0015		0.0015	E
Sulfuric Acid	2.5E-04	0.022	0.022	E
Iron	0.12		0.12	E
Hydrocarbons				E
Ammonia	1.4E-05		1.4E-05	E
Chromium	3.6E-06		3.6E-06	E
Lead	5.7E-09		5.7E-09	E
Zinc	1.3E-06		1.3E-06	E
Chlorides	0.0037	0.0070	0.011	E
Sodium	8.0E-06		8.0E-06	E
Calcium	4.3E-06		4.3E-06	E
Sulfates	0.0053		0.0053	E
Manganese	0.078		0.078	E
Fluorides	2.0E-05		2.0E-05	E
Nitrates	1.9E-06		1.9E-06	E
Phosphates	1.2E-04	0.011	0.011	E
Boron	0.0010	0.088	0.089	E
Other Organics	4.2E-04	0.017	0.017	E
Chromates	2.6E-06		2.6E-06	E
Cyanide	5.3E-09		5.3E-09	E
Mercury	2.8E-10		2.8E-10	E
Cadmium	3.6E-06		3.6E-06	E
Solid Waste	345	105	450	B

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(1) Sum of precombustion process-related emissions from Table A-1 and precombustion fuel-related emissions from Table A-10.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-16

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN UTILITY BOILERS

(pounds of pollutants per 1,000 gallons of residual oil)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.8	1.9	3.7	B
Nitrogen Oxides	9.2	32	41	B
Hydrocarbons (other than methane)	55	0.013	55	C
Sulfur Oxides	28.1	95.9	124	B
Carbon Monoxide	6.9	4.0	10.9	B
Fossil Carbon Dioxide	2,861	25,495	28,356	A
Non-Fossil Carbon Dioxide	6.64		6.64	B
Formaldehyde	2.3E-05	0.0045	0.0045	C
Other Aldehydes	0.51	0.0012	0.51	C
Other Organics	0.33		0.33	D
Ammonia	0.044	1.73	1.77	C
Lead	1.5E-04	0.0056	0.0057	B
Methane	4.41	0.28	4.69	C
Kerosene	1.1E-04		1.1E-04	D
Chlorine	0.0017		0.0017	D
Hydrochloric Acid	0.027	0.68	0.71	C
Hydrogen Fluoride	0.0035	0.034	0.038	C
Metals	0.0027		0.0027	D
Antimony	4.1E-05		4.1E-05	E
Arsenic	8.6E-05	0.0012	0.0013	E
Beryllium	6.0E-06	1.1E-04	1.2E-04	E
Cadmium	1.3E-04	4.0E-04	5.3E-04	E
Chromium	9.8E-05	0.0011	0.0012	E
Cobalt	1.2E-04	0.0048	0.0049	E
Manganese	1.2E-04	0.0023	0.0024	E
Mercury	2.8E-05	6.0E-05	8.8E-05	E
Nickel	0.0018	0.095	0.097	E
Selenium	7.9E-05	4.0E-04	4.8E-04	E
Acreolin	5.1E-06		5.1E-06	D
Nitrous Oxide	0.0031	0.11	0.11	D
Benzene	1.6E-05	2.1E-04	2.3E-04	D
Perchloroethylene	5.0E-06	8.9E-05	9.4E-05	D
Trichloroethylene	4.8E-06		4.8E-06	D
Methylene Chloride	2.2E-05	0.0048	0.0048	D
Carbon Tetrachloride	2.1E-05	0.0063	0.0063	D
Phenols	1.3E-04	0.0036	0.0037	D
Naphthalene	7.6E-06	5.0E-05	5.8E-05	D
Dioxins	2.8E-11	2.6E-09	2.6E-09	D
n-nitrodimethylamine	1.1E-06		1.1E-06	D
Radionuclides (Ci)	9.5E-05	0.066	0.066	D

(continued)

Table A-16 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN UTILITY BOILERS

(pounds of pollutants per 1,000 gallons of residual oil)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	9.1E-06		9.1E-06	E
Metal Ion	0.19		0.19	E
Dissolved Solids	37.9		37.9	D
Suspended Solids	0.86	1.80	2.7	D
BOD	0.14		0.14	D
COD	0.95		0.95	D
Phenol	6.3E-04		6.3E-04	E
Oil	0.89		0.89	E
Sulfuric Acid	0.0075	0.30	0.31	E
Iron	0.021		0.021	E
Ammonia	0.015		0.015	E
Chromium	0.0014		0.0014	E
Lead	1.6E-05		1.6E-05	E
Zinc	7.1E-04		7.1E-04	E
Chlorides	1.39	0.094	1.5	E
Sodium	1.8E-04		1.8E-04	E
Calcium	9.7E-05		9.7E-05	E
Sulfates	1.13		1.1	E
Manganese	0.010		0.010	E
Fluorides	4.5E-04		4.5E-04	E
Nitrates	4.3E-05		4.3E-05	E
Phosphates	0.0038	0.15	0.15	E
Boron	0.030	1.2	1.2	E
Other Organics	0.093	0.24	0.33	E
Chromates	1.1E-04	0.0072	7.3E-03	E
Cyanide	2.0E-06		2.0E-06	E
Mercury	1.1E-07		1.1E-07	E
Cadmium	0.0014		0.0014	E
Solid Waste	144	33	177	B

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(1) Sum of precombustion process-related emissions from Table A-3a and precombustion fuel-related emissions from Table A-12a.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, A-58 and A-59.

Source: Franklin Associates, Ltd.

Industrial Boilers. As with the combustion of residual oil in utility boilers, the emissions from the combustion of residual oil in industrial boilers are dependent on the composition of the fuel, the type of boiler, and the firing practices used. Again, both particulate emissions and sulfur oxide emissions are proportional to the sulfur content of the fuel. The sulfur content of residual fuel for industrial boilers was assumed to be the same as that reported for utility boilers. Emissions from the combustion of residual oil in industrial boilers are reported in Table A-17.

Distillate Oil

Utility Boilers. Distillate oil is a small part of the fuel oil burned for utility boilers. Emissions from the combustion of distillate oil are dependent on the composition of the fuel, the type of boiler, and the firing practices used. Pollutants from distillate oil-fired boilers include ash, sulfur oxides, and other gaseous emissions.

Sulfur oxide emissions were calculated based upon the average sulfur content of the fuel oil–0.3 weight percent (Reference A-6, page 1.3-1). Utilities using oil-fired boilers do not currently employ flue gas desulfurization units (Reference A-5, pages 23 and 37). Emissions for the combustion of distillate oil in utility boilers are reported in Table A-18.

Industrial Boilers. Emissions from the combustion of distillate oil are dependent on the composition of the fuel, the type of boiler, and the firing practices used. Pollutants from distillate oil-fired boilers include ash, sulfur oxides, and other gaseous emissions. Both particulate emissions and sulfur oxide emissions are proportional to the sulfur content of the fuel. An average fuel sulfur content of 0.3 weight percent is used for the emissions presented in Table A-19 (Reference A-6, page 1.3-1).

Natural Gas

Utility Boilers. Although raw natural gas may contain high levels of sulfur, it is removed during processing. The major pollutants from the burning of natural gas are nitrogen oxides. Nitrogen oxide control (if employed) is typically carried out as a boiler operational parameter adjustment. Pollution control devices are not employed for natural gas-fired utility boilers. Table A-20 shows the precombustion and combustion emissions for 1,000 cubic feet of natural gas burned.

Industrial Boilers. The emissions for natural gas-fired industrial boilers are shown in Table A-21. Precombustion emissions, the emissions associated with acquiring and processing natural gas, are the same as those shown in Table A-20 for natural gas used in utility boilers. Combustion emissions differ, however, because industrial boilers are generally smaller than utility boilers and therefore have different operating conditions.

Table A-17

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 gallons of residual oil)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.81	1.9	3.7	B
Nitrogen Oxides	9.23	55.0	64.2	B
Hydrocarbons (other than methane)	54.7	0.28	55.0	C
Sulfur Oxides	28.1	95.9	124	B
Carbon Monoxide	6.92	5.00	11.9	B
Fossil Carbon Dioxide	2,861	25,494	28,355	A
Non-Fossil Carbon Dioxide	6.64		6.64	B
Formaldehyde	2.3E-05		2.3E-05	C
Other Aldehydes	0.51		0.51	C
Other Organics	0.33		0.33	D
Ammonia	0.044		0.044	C
Lead	1.5E-04	0.0087	0.0088	B
Methane	4.41	1.00	5.41	C
Kerosene	1.1E-04		1.1E-04	D
Chlorine	0.0017		0.0017	D
Hydrochloric Acid	0.027		0.027	C
Hydrogen Fluoride	0.0035		0.0035	C
Metals	0.0027		0.0027	D
Antimony	4.1E-05	0.0027	0.0028	E
Arsenic	8.6E-05	0.0052	0.0053	E
Beryllium	6.0E-06	3.3E-04	3.3E-04	E
Cadmium	1.3E-04	0.0089	0.0090	E
Chromium	9.8E-05	0.0058	0.0059	E
Cobalt	1.2E-04	0.0077	0.0078	E
Manganese	1.2E-04	0.0038	0.0039	E
Mercury	2.8E-05	0.0013	0.0013	E
Nickel	0.0018	0.12	0.13	E
Selenium	7.9E-05	0.0030	0.0030	E
Acreolin	5.1E-06		5.1E-06	D
Nitrous Oxide	0.0031		0.0031	D
Benzene	1.6E-05		1.6E-05	D
Perchloroethylene	5.0E-06		5.0E-06	D
Trichloroethylene	4.8E-06		4.8E-06	D
Methylene Chloride	2.2E-05		2.2E-05	D
Carbon Tetrachloride	2.1E-05		2.1E-05	D
Phenols	1.3E-04		1.3E-04	D
Naphthalene	7.6E-06		7.6E-06	D
Dioxins	2.8E-11		2.8E-11	D
n-nitrodimethylamine	1.1E-06		1.1E-06	D
Radionuclides(Ci)	9.5E-05		9.5E-05	D

(continued)

Table A-17 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF RESIDUAL FUEL OIL IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 gallons of residual oil)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	9.1E-06		9.1E-06	E
Metal Ion	0.19		0.19	E
Dissolved Solids	37.9		37.9	D
Suspended Solids	0.86	1.80	2.66	D
BOD	0.14		0.14	D
COD	0.95		0.95	D
Phenol	6.3E-04		6.3E-04	E
Oil	0.89		0.89	E
Sulfuric Acid	0.0075	0.30	0.31	E
Iron	0.021		0.021	E
Ammonia	0.015		0.015	E
Chromium	0.0014		0.0014	E
Lead	1.6E-05		1.6E-05	E
Zinc	7.1E-04		7.1E-04	E
Chlorides	1.39	0.094	1.49	E
Sodium	1.8E-04		1.8E-04	E
Calcium	9.7E-05		9.7E-05	E
Sulfates	1.13		1.13	E
Manganese	0.010		0.010	E
Fluorides	4.5E-04		4.5E-04	E
Nitrates	4.3E-05		4.3E-05	E
Phosphates	0.0038	0.15	0.15	E
Boron	0.030	1.20	1.23	E
Other Organics	0.093	0.24	0.33	E
Chromates	1.1E-04	0.0072	0.0073	E
Cyanide	2.0E-06		2.0E-06	E
Mercury	1.1E-07		1.1E-07	E
Cadmium	0.0014		0.0014	E
Solid Waste	144	33	177	B

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(1) Sum of precombustion process-related emissions from Table A-3a and precombustion fuel-related emissions from Table A-12a.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, A-58 and A-59.

Source: Franklin Associates, Ltd.

Table A-18

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN UTILITY BOILERS

(pounds of pollutants per 1,000 gallons of distillate oil)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.66	1.00	2.66	B
Nitrogen Oxides	8.47	24.0	32.5	B
Hydrocarbons (other than methane)	50.2	0.76	51.0	C
Sulfur Oxides	25.8	43	69	B
Carbon Monoxide	6.36	4.50	10.9	B
Fossil Carbon Dioxide	2,627	26,500	29,127	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05		2.1E-05	C
Other Aldehydes	0.47	0.015	0.48	C
Other Organics	0.30		0.30	D
Ammonia	0.040		0.040	C
Lead	1.4E-04	0.0049	0.0050	B
Methane	4.05	0.05	4.10	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05	0.0027	0.0027	E
Arsenic	7.9E-05	0.0052	0.0053	E
Beryllium	5.5E-06	3.3E-04	3.3E-04	E
Cadmium	1.2E-04	0.0089	0.0090	E
Chromium	9.0E-05	0.0058	0.0059	E
Cobalt	1.1E-04	0.0077	0.0078	E
Manganese	1.1E-04	0.0038	0.0039	E
Mercury	2.6E-05	0.0013	0.0013	E
Nickel	0.0017	0.12	0.12	E
Selenium	7.2E-05	0.0030	0.0031	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028	0.11	0.11	D
Benzene	1.5E-05	2.3E-04	2.4E-04	D
Perchloroethylene	4.6E-06	8.9E-05	9.4E-05	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05	5.2E-04	5.4E-04	D
Carbon Tetrachloride	1.9E-05	0.0063	0.0063	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

(continued)

Table A-18 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN UTILITY BOILERS

(pounds of pollutants per 1,000 gallons of distillate oil)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	8.4E-06		8.4E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	34.8		34.8	D
Suspended Solids	0.79	1.80	2.59	D
BOD	0.13		0.13	D
COD	0.87		0.87	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.81		0.81	E
Sulfuric Acid	0.0069	0.30	0.31	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.5E-04		6.5E-04	E
Chlorides	1.28	0.0094	1.29	E
Sodium	1.6E-04		1.6E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.03		1.03	E
Manganese	0.0092		0.0092	E
Fluorides	4.1E-04		4.1E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035	0.15	0.15	E
Boron	0.028	1.20	1.23	E
Other Organics	0.085	0.24	0.33	E
Chromates	9.8E-05	0.0072	0.0073	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.8E-08		9.8E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	133	33.0	166	B

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(1) Sum of precombustion process-related emissions from Table A-3b and precombustion fuel-related emissions from Table A-12b.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, A-58 and A-59.

Source: Franklin Associates, Ltd.

Table A-19

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 gallons of distillate oil)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.66	1.00	2.66	B
Nitrogen Oxides	8.47	24.0	32.5	B
Hydrocarbons (other than methane)	50.2	0.20	50.4	C
Sulfur Oxides	25.8	42.8	68.6	B
Carbon Monoxide	6.36	5.00	11.4	B
Fossil Carbon Dioxide	2,627	22,757	25,384	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05		2.1E-05	C
Other Aldehydes	0.47		0.47	C
Other Organics	0.30		0.30	D
Ammonia	0.040		0.040	C
Lead	1.4E-04	6.4E-04	7.8E-04	B
Methane	4.05	0.051	4.10	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		3.8E-05	E
Arsenic	7.9E-05	3.0E-04	3.8E-04	E
Beryllium	5.5E-06	1.8E-04	1.9E-04	E
Cadmium	1.2E-04	8.0E-04	9.2E-04	E
Chromium	9.0E-05	0.0042	0.0043	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04	0.0010	0.0011	E
Mercury	2.6E-05	2.2E-04	2.5E-04	E
Nickel	0.0017	0.0013	0.0030	E
Selenium	7.2E-05		7.2E-05	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028		0.0028	D
Benzene	1.5E-05	0.11	1.1E-01	D
Perchloroethylene	4.6E-06		4.6E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

(continued)

Table A-19 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DISTILLATE FUEL OIL IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 gallons of distillate oil)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	8.4E-06		8.4E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	34.8		34.8	D
Suspended Solids	0.79		0.79	D
BOD	0.13		0.13	D
COD	0.87		0.87	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.81		0.81	E
Sulfuric Acid	0.0069		0.0069	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.5E-04		6.5E-04	E
Chlorides	1.28		1.28	E
Sodium	1.6E-04		1.6E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.03		1.03	E
Manganese	0.0092		0.0092	E
Fluorides	4.1E-04		4.1E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.085		0.085	E
Chromates	9.8E-05		9.8E-05	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.8E-08		9.8E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	133		133	B

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(1) Sum of precombustion process-related emissions from Table A-3b and precombustion fuel-related emissions from Table A-12b.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, A-58 and A-59.

Source: Franklin Associates, Ltd.

Table A-20

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN UTILITY BOILERS

(pounds of pollutants per 1,000 cubic feet of natural gas)

Atmospheric Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Particulates	0.0038	6.7E-04	0.0045	B
Nitrogen Oxides	0.12	0.39	0.51	B
Hydrocarbons (other than methane)	0.53	0.0014	0.53	C
Sulfur Oxides	1.97	6.7E-04	1.97	B
Carbon Monoxide	0.23	0.035	0.26	B
Fossil Carbon Dioxide	15.7	121	137	A
Non-Fossil Carbon Dioxide	0.028		0.028	B
Formaldehyde	8.8E-08	4.0E-05	4.0E-05	C
Other Aldehydes	3.5E-04		3.5E-04	C
Other Organics	8.7E-04		8.7E-04	D
Ammonia	9.5E-06	0.0030	0.0030	C
Lead	2.8E-07	3.2E-07	6.0E-07	B
Methane	0.38	3.0E-04	0.38	C
Kerosene	4.8E-07		4.8E-07	D
Chlorine	2.2E-07		2.2E-07	D
Hydrochloric Acid	9.8E-05		9.8E-05	C
Hydrogen Fluoride	1.3E-05		1.3E-05	C
Metals	1.1E-05		1.1E-05	D
Antimony	8.9E-08		8.9E-08	E
Arsenic	1.9E-07	1.2E-07	3.1E-07	E
Beryllium	1.4E-08		1.4E-08	E
Cadmium	2.7E-07	3.9E-08	3.0E-07	E
Chromium	2.3E-07	8.6E-07	1.1E-06	E
Cobalt	2.5E-07	1.0E-07	3.5E-07	E
Manganese	3.6E-07	2.7E-07	6.3E-07	E
Mercury	7.4E-08	1.2E-09	7.5E-08	E
Nickel	3.8E-06	1.7E-07	4.0E-06	E
Selenium	2.2E-07	9.3E-07	1.2E-06	E
Acreolin	1.9E-08		1.9E-08	D
Nitrous Oxide	1.2E-05		1.2E-05	D
Benzene	6.8E-08	1.3E-06	1.4E-06	D
Perchloroethylene	2.0E-08		2.0E-08	D
Trichloroethylene	1.8E-08		1.8E-08	D
Methylene Chloride	8.8E-08		8.8E-08	D
Carbon Tetrachloride	1.1E-07		1.1E-07	D
Phenols	5.6E-07		5.6E-07	D
Naphthalene	3.2E-08	4.7E-07	5.0E-07	D
Dioxins	1.1E-13		1.1E-13	D
n-nitrodimethylamine	4.1E-09		4.1E-09	D
Radionuclides (Ci)	3.6E-07	6.1E-05	6.1E-05	D

(continued)

Table A-20 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN UTILITY BOILERS

(pounds of pollutants per 1,000 cubic feet of natural gas)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	6.4E-10		6.4E-10	E
Metal Ion	1.4E-05		1.4E-05	E
Dissolved Solids	3.04	0.047	3.08	D
Suspended Solids	0.0054	0.050	0.055	D
BOD	0.0027	2.8E-04	0.0030	D
COD	0.019	0.024	0.043	D
Phenol	4.4E-08		4.4E-08	E
Oil	0.054		0.054	E
Sulfuric Acid	2.1E-05		2.1E-05	E
Iron	7.3E-05		7.3E-05	E
Ammonia	4.9E-06	5.4E-05	5.9E-05	E
Chromium	1.4E-04		1.4E-04	E
Lead	1.1E-09		1.1E-09	E
Zinc	4.8E-05		4.8E-05	E
Chlorides	0.14		0.14	E
Sodium	7.6E-07		7.6E-07	E
Calcium	4.1E-07		4.1E-07	E
Sulfates	0.11		0.11	E
Manganese	4.2E-05		4.2E-05	E
Fluorides	1.9E-06		1.9E-06	E
Nitrates	1.8E-07		1.8E-07	E
Phosphates	1.1E-05		1.1E-05	E
Boron	8.4E-05		8.4E-05	E
Other Organics	0.0088		0.0088	E
Chromates	2.2E-07		2.2E-07	E
Cyanide	2.1E-07		2.1E-07	E
Mercury	1.1E-08		1.1E-08	E
Cadmium	1.4E-04		1.4E-04	E
Solid Waste	5.8		5.8	B

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(1) Sum of precombustion process-related emissions from Table A-2 and precombustion fuel-related emissions from Table A-11.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-21

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 cubic feet of natural gas)

Atmospheric Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Particulates	0.0038	0.0094	0.013	B
Nitrogen Oxides	0.12	0.31	0.43	B
Hydrocarbons (other than methane)	0.53	0.0095	0.54	C
Sulfur Oxides	1.97	0.075	2.04	B
Carbon Monoxide	0.23	0.060	0.29	B
Fossil Carbon Dioxide	15.7	118	134	A
Non-Fossil Carbon Dioxide	0.028		0.028	B
Formaldehyde	8.8E-08		8.8E-08	C
Other Aldehydes	3.5E-04		3.5E-04	C
Other Organics	8.7E-04		8.7E-04	D
Ammonia	9.5E-06		9.5E-06	C
Lead	2.8E-07		2.8E-07	B
Methane	0.38	0.0035	0.39	C
Kerosene	4.8E-07		4.8E-07	D
Chlorine	2.2E-07		2.2E-07	D
Hydrochloric Acid	9.8E-05		9.8E-05	C
Hydrogen Fluoride	1.3E-05		1.3E-05	C
Metals	1.1E-05		1.1E-05	D
Antimony	8.9E-08		8.9E-08	E
Arsenic	1.9E-07		1.9E-07	E
Beryllium	1.4E-08		1.4E-08	E
Cadmium	2.7E-07		2.7E-07	E
Chromium	2.3E-07		2.3E-07	E
Cobalt	2.5E-07		2.5E-07	E
Manganese	3.6E-07		3.6E-07	E
Mercury	7.4E-08		7.4E-08	E
Nickel	3.8E-06		3.8E-06	E
Selenium	2.2E-07		2.2E-07	E
Acreolin	1.9E-08		1.9E-08	D
Nitrous Oxide	1.2E-05		1.2E-05	D
Benzene	6.8E-08		6.8E-08	D
Perchloroethylene	2.0E-08		2.0E-08	D
Trichloroethylene	1.8E-08		1.8E-08	D
Methylene Chloride	8.8E-08		8.8E-08	D
Carbon Tetrachloride	1.1E-07		1.1E-07	D
Phenols	5.6E-07		5.6E-07	D
Naphthalene	3.2E-08		3.2E-08	D
Dioxins	1.1E-13		1.1E-13	D
n-nitrodimethylamine	4.1E-09		4.1E-09	D
Radionuclides (Ci)	3.6E-07		3.6E-07	D

(continued)

Table A-21 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 cubic feet of natural gas)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	6.4E-10		6.4E-10	E
Metal Ion	1.4E-05		1.4E-05	E
Dissolved Solids	3.04	0.047	3.08	D
Suspended Solids	0.0054	0.050	0.055	D
BOD	0.0027	2.8E-04	0.0030	D
COD	0.019	0.024	0.043	D
Phenol	4.4E-08		4.4E-08	E
Oil	0.054		0.054	E
Sulfuric Acid	2.1E-05		2.1E-05	E
Iron	7.3E-05		7.3E-05	E
Ammonia	4.9E-06	5.4E-05	5.9E-05	E
Chromium	1.4E-04		1.4E-04	E
Lead	1.1E-09		1.1E-09	E
Zinc	4.8E-05		4.8E-05	E
Chlorides	0.14		0.14	E
Sodium	7.6E-07		7.6E-07	E
Calcium	4.1E-07		4.1E-07	E
Sulfates	0.11		0.11	E
Manganese	4.2E-05		4.2E-05	E
Fluorides	1.9E-06		1.9E-06	E
Nitrates	1.8E-07		1.8E-07	E
Phosphates	1.1E-05		1.1E-05	E
Boron	8.4E-05		8.4E-05	E
Other Organics	0.0088		0.0088	E
Chromates	2.2E-07		2.2E-07	E
Cyanide	2.1E-07		2.1E-07	E
Mercury	1.1E-08		1.1E-08	E
Cadmium	1.4E-04		1.4E-04	E
Solid Waste	5.8		5.8	B

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(1) Sum of precombustion process-related emissions from Table A-2 and precombustion fuel-related emissions from Table A-11.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Industrial Equipment. Natural gas is also used to power industrial equipment. One application is the use of natural gas to power compressors used for the pipeline transportation of natural gas. Again, the major pollutants of concern when using natural gas as a fuel are nitrogen oxides. Lesser amounts of carbon monoxide and hydrocarbons are emitted. However, for each unit of natural gas burned, compressor engines emit significantly more of these pollutants than do external combustion boilers (Reference A-6, page 3.2-1). Emissions for the internal combustion of natural gas are presented in Table A-22.

Diesel

Industrial Equipment. Diesel is used in a wide variety of industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment. Table A-23 shows average emissions for the internal combustion of diesel in industrial equipment.

Gasoline

Industrial Equipment. Gasoline is also used in a wide variety of industrial applications such as mobile refrigeration units, generators, pumps, and portable well-drilling equipment. Table A-24 shows average emissions for the internal combustion of gasoline in industrial equipment.

Liquefied Petroleum Gases

Industrial Equipment. Liquefied petroleum gas (LPG) consists of propane, butane, or a mixture of the two. This gas is obtained both from natural gas liquids plants and as a byproduct of petroleum refinery operations.

Gaseous pollutants such as nitrogen oxides, carbon monoxide, and hydrocarbons are produced when LPG is burned as a fuel. Table A-25 shows the precombustion and combustion emissions for the combustion of 1,000 gallons of LPG.

Fuel Grade Uranium

Nuclear power plants generate electricity by harnessing the thermal energy from controlled nuclear fission reactions. These reactions are used to produce steam, which in turn drives a turbine-generator to produce electricity. Environmental emissions for combustion of fuel grade uranium are shown in Table A-26.

Wood Wastes

The combustion of wood waste in boilers is mostly confined to those industries where it is available as a byproduct. It is burned to obtain both heat energy and to alleviate possible solid waste disposal problems. In boilers, wood waste is normally burned in the form of hogged wood, sawdust, shavings, chips, sander dust, or wood trim.

Table A-22

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL EQUIPMENT

(pounds of pollutants per 1,000 cubic feet of natural gas)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	0.0038	0.0070	0.011	B
Nitrogen Oxides	0.12	1.9	2.0	B
Hydrocarbons (other than methane)	0.53	0.71	1.2	C
Sulfur Oxides	2.0	0.00060	2.0	B
Carbon Monoxide	0.23	0.275	0.50	B
Fossil Carbon Dioxide	16	127	143	A
Non-Fossil Carbon Dioxide	0.028		0.028	B
Formaldehyde	8.8E-08		8.8E-08	C
Other Aldehydes	3.5E-04		3.5E-04	C
Other Organics	8.7E-04		8.7E-04	D
Ammonia	9.5E-06		9.5E-06	C
Lead	2.8E-07		2.8E-07	B
Methane	0.38		0.38	C
Kerosene	4.8E-07		4.8E-07	D
Chlorine	2.2E-07		2.2E-07	D
Hydrochloric Acid	9.8E-05		9.8E-05	C
Hydrogen Fluoride	1.3E-05		1.3E-05	C
Metals	1.1E-05		1.1E-05	D
Antimony	8.9E-08		8.9E-08	E
Arsenic	1.9E-07		1.9E-07	E
Beryllium	1.4E-08		1.4E-08	E
Cadmium	2.7E-07		2.7E-07	E
Chromium	2.3E-07		2.3E-07	E
Cobalt	2.5E-07		2.5E-07	E
Manganese	3.6E-07		3.6E-07	E
Mercury	7.4E-08		7.4E-08	E
Nickel	3.8E-06		3.8E-06	E
Selenium	2.2E-07		2.2E-07	E
Acreolin	1.9E-08		1.9E-08	D
Nitrous Oxide	1.2E-05		1.2E-05	D
Benzene	6.8E-08		6.8E-08	D
Perchloroethylene	2.0E-08		2.0E-08	D
Trichloroethylene	1.8E-08		1.8E-08	D
Methylene Chloride	8.8E-08		8.8E-08	D
Carbon Tetrachloride	1.1E-07		1.1E-07	D
Phenols	5.6E-07		5.6E-07	D
Naphthalene	3.2E-08		3.2E-08	D
Dioxins	1.1E-13		1.1E-13	D
n-nitrodimethylamine	4.1E-09		4.1E-09	D
Radionuclides (Ci)	3.6E-07		3.6E-07	D

(continued)

Table A-22 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF NATURAL GAS IN INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 cubic feet of natural gas)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	6.4E-10		6.4E-10	E
Metal Ion	1.4E-05		1.4E-05	E
Dissolved Solids	3.0		3.0	D
Suspended Solids	0.0054		5.4E-03	D
BOD	0.0027		2.7E-03	D
COD	0.019		1.9E-02	D
Phenol	4.4E-08		4.4E-08	E
Oil	0.054		5.4E-02	E
Sulfuric Acid	2.1E-05		2.1E-05	E
Iron	7.3E-05		7.3E-05	E
Ammonia	4.9E-06		4.9E-06	E
Chromium	1.4E-04		1.4E-04	E
Lead	1.1E-09		1.1E-09	E
Zinc	4.8E-05		4.8E-05	E
Chlorides	0.14		1.4E-01	E
Sodium	7.6E-07		7.6E-07	E
Calcium	4.1E-07		4.1E-07	E
Sulfates	0.11		1.1E-01	E
Manganese	4.2E-05		4.2E-05	E
Fluorides	1.9E-06		1.9E-06	E
Nitrates	1.8E-07		1.8E-07	E
Phosphates	1.1E-05		1.1E-05	E
Boron	8.4E-05		8.4E-05	E
Other Organics	8.8E-03		8.8E-03	E
Chromates	2.2E-07		2.2E-07	E
Cyanide	2.1E-07		2.1E-07	E
Mercury	1.1E-08		1.1E-08	E
Cadmium	1.4E-04		1.4E-04	E
Solid Waste	5.8		5.8	B

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(1) Sum of precombustion process-related emissions from Table A-2 and precombustion fuel-related emissions from Table A-11.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-23

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DIESEL POWERED INDUSTRIAL EQUIPMENT

(pounds of pollutants per 1,000 gallons of diesel fuel)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.66	33.5	35.2	B
Nitrogen Oxides	8.47	469	477.5	B
Hydrocarbons (other than methane)	50.2	37.5	87.7	C
Sulfur Oxides	25.8	31.2	57	B
Carbon Monoxide	6.36	102	108.4	B
Fossil Carbon Dioxide	2,627	23,005	25,632	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05	7.00	7.0E+00	C
Other Aldehydes	0.47		0.47	C
Other Organics	0.30		0.30	D
Ammonia	0.040		0.040	C
Lead	1.4E-04		0.0001	B
Methane	4.05		4.05	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		0.0000	E
Arsenic	7.9E-05		0.0001	E
Beryllium	5.5E-06		5.5E-06	E
Cadmium	1.2E-04		0.0001	E
Chromium	9.0E-05		0.0001	E
Cobalt	1.1E-04		0.0001	E
Manganese	1.1E-04		0.0001	E
Mercury	2.6E-05		0.0000	E
Nickel	0.0017		0.00	E
Selenium	7.2E-05		0.0001	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028		0.0028	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.6E-06		4.6E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

(continued)

Table A-23 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF DIESEL POWERED INDUSTRIAL EQUIPMENT
(pounds of pollutants per 1,000 gallons of diesel fuel)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	8.4E-06		8.4E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	34.8		34.8	D
Suspended Solids	0.79		0.79	D
BOD	0.13		0.13	D
COD	0.87		0.87	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.81		0.81	E
Sulfuric Acid	0.0069		0.0069	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.5E-04		6.5E-04	E
Chlorides	1.28		1.28	E
Sodium	1.6E-04		1.6E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.03		1.03	E
Manganese	0.0092		0.0092	E
Fluorides	4.1E-04		4.1E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.085		0.085	E
Chromates	9.8E-05		9.8E-05	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.8E-08		9.8E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	133		133	B

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(1) Sum of precombustion process-related emissions from Table A-3b and precombustion fuel-related emissions from Table A-12b.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-24

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF GASOLINE POWERED INDUSTRIAL EQUIPMENT (pounds of pollutants per 1,000 gallons of gasoline)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.42	6.47	7.89	B
Nitrogen Oxides	7.22	102	109	B
Hydrocarbons (other than methane)	42.8	132	175	C
Sulfur Oxides	22.0	5.31	27.3	B
Carbon Monoxide	5.42	3,940	3,945	B
Fossil Carbon Dioxide	2,239	12,844	15,083	A
Non-Fossil Carbon Dioxide	5.20		5.20	B
Formaldehyde	1.8E-05	4.36	4.36	C
Other Aldehydes	0.40		0.40	C
Other Organics	0.26		0.26	D
Ammonia	0.034		0.034	C
Lead	1.2E-04		1.2E-04	B
Methane	3.45		3.45	C
Kerosene	8.9E-05		8.9E-05	D
Chlorine	0.0013		0.0013	D
Hydrochloric Acid	0.021		0.021	C
Hydrogen Fluoride	0.0028		0.0028	C
Metals	0.0021		0.0021	D
Antimony	3.2E-05		3.2E-05	E
Arsenic	6.7E-05		6.7E-05	E
Beryllium	4.7E-06		4.7E-06	E
Cadmium	1.0E-04		1.0E-04	E
Chromium	7.6E-05		7.6E-05	E
Cobalt	9.2E-05		9.2E-05	E
Manganese	9.1E-05		9.1E-05	E
Mercury	2.2E-05		2.2E-05	E
Nickel	0.0014		0.0014	E
Selenium	6.2E-05		6.2E-05	E
Acreolin	4.0E-06		4.0E-06	D
Nitrous Oxide	0.0024		0.0024	D
Benzene	1.3E-05		1.3E-05	D
Perchloroethylene	3.9E-06		3.9E-06	D
Trichloroethylene	3.8E-06		3.8E-06	D
Methylene Chloride	1.8E-05		1.8E-05	D
Carbon Tetrachloride	1.6E-05		1.6E-05	D
Phenols	1.0E-04		1.0E-04	D
Naphthalene	6.0E-06		6.0E-06	D
Dioxins	2.2E-11		2.2E-11	D
n-nitrodimethylamine	8.4E-07		8.4E-07	D
Radionuclides (Ci)	7.4E-05		7.4E-05	D

(continued)

Table A-24 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF GASOLINE POWERED INDUSTRIAL EQUIPMENT

(pounds of pollutants per 1,000 gallons of gasoline)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	7.1E-06		7.1E-06	E
Metal Ion	0.15		0.15	E
Dissolved Solids	29.7		29.7	D
Suspended Solids	0.68		0.68	D
BOD	0.11		0.11	D
COD	0.74		0.74	D
Phenol	4.9E-04		4.9E-04	E
Oil	0.69		0.69	E
Sulfuric Acid	0.0059		0.0059	E
Iron	0.016		0.016	E
Ammonia	0.012		0.012	E
Chromium	0.0011		0.0011	E
Lead	1.3E-05		1.3E-05	E
Zinc	5.5E-04		5.5E-04	E
Chlorides	1.09		1.09	E
Sodium	1.4E-04		1.4E-04	E
Calcium	7.6E-05		7.6E-05	E
Sulfates	0.88		0.88	E
Manganese	0.0078		0.0078	E
Fluorides	3.5E-04		3.5E-04	E
Nitrates	3.3E-05		3.3E-05	E
Phosphates	0.0030		0.0030	E
Boron	0.024		0.024	E
Other Organics	0.072		0.072	E
Chromates	8.3E-05		8.3E-05	E
Cyanide	1.6E-06		1.6E-06	E
Mercury	8.4E-08		8.4E-08	E
Cadmium	0.0011		0.0011	E
Solid Waste	113		113	B

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(1) Sum of precombustion process-related emissions from Table A-3c and precombustion fuel-related emissions from Table A-12c.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-25

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIQUEFIED PETROLEUM GAS IN INDUSTRIAL BOILERS
(pounds of pollutants per 1,000 gallons of LPG)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.0	0.60	1.6	B
Nitrogen Oxides	5.3	20	25	B
Hydrocarbons (other than methane)	31	0.26	32	C
Sulfur Oxides	16.1	0.017	16.2	B
Carbon Monoxide	4.0	3.40	7.37	B
Fossil Carbon Dioxide	1,640	13,600	15,240	A
Non-Fossil Carbon Dioxide	3.8		3.8	B
Formaldehyde	1.3E-05		1.3E-05	C
Other Aldehydes	0.29		0.29	C
Other Organics	0.19		0.19	D
Ammonia	0.025		0.025	C
Lead	8.5E-05	0.28	0.28	B
Methane	2.5		2.5	C
Kerosene	6.5E-05		6.5E-05	D
Chlorine	9.6E-04		9.6E-04	D
Hydrochloric Acid	0.015		0.015	C
Hydrogen Fluoride	0.0020		0.0020	C
Metals	0.0016		0.0016	D
Antimony	2.4E-05		2.4E-05	E
Arsenic	4.9E-05		4.9E-05	E
Beryllium	3.4E-06		3.4E-06	E
Cadmium	7.4E-05		7.4E-05	E
Chromium	5.6E-05		5.6E-05	E
Cobalt	6.7E-05		6.7E-05	E
Manganese	6.7E-05		6.7E-05	E
Mercury	1.6E-05		1.6E-05	E
Nickel	0.0010		0.0010	E
Selenium	4.5E-05		4.5E-05	E
Acreolin	2.9E-06		2.9E-06	D
Nitrous Oxide	0.0018		0.0018	D
Benzene	9.4E-06		9.4E-06	D
Perchloroethylene	2.9E-06		2.9E-06	D
Trichloroethylene	2.8E-06		2.8E-06	D
Methylene Chloride	1.3E-05		1.3E-05	D
Carbon Tetrachloride	1.2E-05		1.2E-05	D
Phenols	7.7E-05		7.7E-05	D
Naphthalene	4.4E-06		4.4E-06	D
Dioxins	1.6E-11		1.6E-11	D
n-nitrodimethylamine	6.2E-07		6.2E-07	D
Radionuclides (Ci)	5.4E-05		5.4E-05	D

(continued)

Table A-25 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF LIQUEFIED PETROLEUM GAS IN INDUSTRIAL BOILERS

(pounds of pollutants per 1,000 gallons of LPG)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	5.2E-06		5.2E-06	E
Metal Ion	0.11		0.11	E
Dissolved Solids	21.8		21.8	D
Suspended Solids	0.50		0.50	D
BOD	0.081		0.081	D
COD	0.55		0.55	D
Phenol	3.6E-04		3.6E-04	E
Oil	0.51		0.51	E
Sulfuric Acid	0.0043		0.0043	E
Iron	0.012		0.012	E
Ammonia	0.0088		0.0088	E
Chromium	8.2E-04		8.2E-04	E
Lead	9.3E-06		9.3E-06	E
Zinc	4.1E-04		4.1E-04	E
Chlorides	0.80		0.80	E
Sodium	1.0E-04		1.0E-04	E
Calcium	5.6E-05		5.6E-05	E
Sulfates	0.65		0.65	E
Manganese	0.0057		0.0057	E
Fluorides	2.6E-04		2.6E-04	E
Nitrates	2.4E-05		2.4E-05	E
Phosphates	0.0022		0.0022	E
Boron	0.017		0.017	E
Other Organics	0.053		0.053	E
Chromates	6.1E-05		6.1E-05	E
Cyanide	1.2E-06		1.2E-06	E
Mercury	6.1E-08		6.1E-08	E
Cadmium	8.0E-04		8.0E-04	E
Solid Waste	83		83	B

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(1) Sum of precombustion process-related emissions from Table A-3d and precombustion fuel-related emissions from Table A-12d.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-26

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF FUEL-GRADE URANIUM
(pounds of pollutants per 1,000 pounds of uranium)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	44,000		44,000	B
Nitrogen Oxides	58,000		58,000	B
Hydrocarbons (other than methane)	6,500		6,500	C
Sulfur Oxides	174,000		174,000	B
Carbon Monoxide	5,700		5,700	B
Fossil Carbon Dioxide	6,800,000		6,800,000	A
Non-Fossil Carbon Dioxide	129,000		129,000	B
Formaldehyde	0.41		0.41	C
Other Aldehydes	18.9		18.9	C
Other Organics	45.8		45.8	D
Ammonia	30.7		30.7	C
Lead	0.36		0.36	B
Methane	15,000		15,000	C
Kerosene	223		223	D
Chlorine	0.50		0.50	D
Hydrochloric Acid	447		447	C
Hydrogen Fluoride	61.8		61.8	C
Metals	52.7		52.7	D
Antimony	0.049		0.049	E
Arsenic	0.21		0.21	E
Beryllium	0.023		0.023	E
Cadmium	0.055		0.055	E
Chromium	0.27		0.27	E
Cobalt	0.13		0.13	E
Manganese	1.16		1.16	E
Mercury	0.17		0.17	E
Nickel	1.38		1.38	E
Selenium	0.64		0.64	E
Acreolin	0.089		0.089	D
Nitrous Oxide	50.4		50.4	D
Benzene	0.30		0.30	D
Perchloroethylene	0.085		0.085	D
Trichloroethylene	0.084		0.084	D
Methylene Chloride	0.37		0.37	D
Carbon Tetrachloride	0.15		0.15	D
Phenols	2.57		2.57	D
Naphthalene	0.15		0.15	D
Dioxins	4.8E-07		4.8E-07	D
n-nitrodimethylamine	0.019		0.019	D
Radionuclides (Ci)	1.65		1.65	D

(continued)

Table A-26 (cont)

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF FUEL-GRADE URANIUM

(pounds of pollutants per 1,000 pounds of uranium)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	1.0E-04		1.0E-04	E
Metal Ion	2.11		2.11	E
Dissolved Solids	27,000		27,000	D
Suspended Solids	4,270		4,270	D
BOD	27.9		27.9	D
COD	385		385	D
Phenol	0.0068		0.0068	E
Oil	484		484	E
Sulfuric Acid	57.5		57.5	E
Iron	4,440		4,440	E
Ammonia	334		334	E
Chromium	1.25		1.25	E
Lead	1.8E-04		1.8E-04	E
Zinc	0.43		0.43	E
Chlorides	2,230		2,230	E
Sodium	353		353	E
Calcium	192		192	E
Sulfates	112,000		112,000	E
Manganese	395		395	E
Fluorides	889		889	E
Nitrates	83.8		83.8	E
Phosphates	28.7		28.7	E
Boron	230		230	E
Other Organics	122		122	E
Chromates	0.079		0.079	E
Cyanide	0.0018		0.0018	E
Mercury	9.6E-05		9.6E-05	E
Cadmium	1.25		1.25	E
Solid Waste	6,750,000		6,750,000	B

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(1) Sum of precombustion process-related emissions from Table A-4 and precombustion fuel-related emissions from Table A-13.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Heating values for this waste range from 4000 to 5000 Btu per pound of fuel on a wet, as-fired basis. The moisture content of as-fired wood is typically near 50 percent, but may vary from 5 to 75 weight percent.

Generally, bark is the major type of waste burned in pulp mills; either a mixture of wood and bark waste or wood waste alone is burned most frequently in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1600 wood-fired boilers operating in the U.S., with a total capacity of over 30 GW (1.0 x 10^{11} Btu per hour).

The emission factors in given in Table A-27 are based on wet, as-fired wood waste with average properties of 50 percent (by weight) moisture and 4500 Btu per pound higher heating value.

Solid wastes from the combustion of wood are proportional to the ash content of the wood. This typically varies between 0.5 and 2.2 percent by weight of dry wood. Some is released as fly ash, and some remains as bottom ash. If there are controls for particulate matter, some of the fly ash is collected before leaving the emissions stack.

The solid residues from the combustion process are boiler ash, clinker and slag, fly ash, and carbon char. The major components of these wastes are silica, alumina, and calcium oxides. Minor constituents include sodium, magnesium, potassium, and trace amounts of heavy metals (Reference A-48). Another source of solid wastes is impurities in wood bark (sand and dirt), which are picked up during transportation as rough logs are dragged to central loading points.

Mobile Sources

Transportation sources such as barges, locomotives, and diesel- and gasoline-powered trucks constitute a major source of air pollution. Some of the emissions, such as carbon monoxide and hydrocarbons, are due to incomplete combustion. Other emissions, such as nitrogen oxides, are normal byproducts of combustion. Lead emissions are directly related to the addition of tetraethyl lead to the fuel as an antiknock compound. Lead emissions in the U.S. have been decreasing significantly due to EPA regulations requiring a phase-out of lead in fuels. The major gaseous pollutants from mobile sources are carbon monoxide, nitrogen oxides, and hydrocarbons.

Trucks. Transportation trucks are classified into two categories. Combination or tractor-trailer trucks are those most commonly used to transport large quantities of material. Single unit trucks are generally used for local delivery. Several assumptions and calculations were made based on these classifications:

1. Single unit delivery trucks have a gross weight of 8,500 to 14,000 pounds. Tractor-trailer trucks include all trucks greater than 14,000 pounds in gross weight.

Table A-27

ENVIRONMENTAL EMISSIONS FOR THE COMBUSTION OF WOOD IN INDUSTRIAL BOILERS

(pounds of pollutant per 1,000 lb of wood—as fired)

Atmospheric Emissions	**Combustion (lb/1000 lb)**	**pounds per MM Btu (1)**	**DQI**
Particulates	0.085	0.019	C
Nitrogen oxides	0.75	0.17	C
Sulfur oxides	0.038	0.0083	C
Carbon monoxide	6.80	1.51	C
Carbon dioxide	1,050	233	C
Lead	6.0E-04	1.3E-04	C
Total organic compounds (unspeciated)	0.11	0.024	D
Speciated organic compounds			
Phenols	0.020	0.0043	E
Formaldehyde	0.0033	7.3E-04	E
Acetaldehyde	0.0015	3.3E-04	E
Benzene	0.0018	4.0E-04	E
Naphthalene	0.0012	2.6E-04	E
Speciated metals			
Potassium	0.39	0.087	E
Zinc	0.0022	4.9E-04	E
Barium	0.0022	4.9E-04	E
Sodium	0.0090	0.0020	E
Iron	0.022	0.0049	E
Chlorine	0.0039	8.7E-04	E
Rubidium	6.0E-04	1.3E-04	E
Manganese	0.0045	0.0010	E
Nickel	2.8E-04	6.2E-05	E
Arsenic	4.4E-05	9.8E-06	E
Chromium	2.3E-05	5.1E-06	E
Solid Wastes	45.0	10.0	C

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(1) Wood "as fired" has a higher heating value of about 4500 Btu/lb.
References A-6 and A-48.

Source: Franklin Associates, Ltd.

2. Average miles per gallon for tractor-trailers = 5.9 miles per gallon. These gallons are distributed based on the following fuel usage split: 19.4 percent gasoline tractor-trailers and 80.6 percent diesel tractor-trailers. Average miles per gallon for single unit trucks = 6.8 miles per gallon. These gallons are distributed based on the following fuel usage split: 19.4 percent gasoline trucks and 80.6 percent diesel trucks (Reference A-4).

Emissions from trucks were determined using the following assumptions:

1. Low and high altitude emissions are averaged.
2. 19.4 percent of material transport trucks use gasoline for fuel, 80.4 percent use diesel, and 0.2 percent use LPG (Reference A-4). The use of LPG was considered insignificant.
3. Emissions obtained for each truck model year transporting material in 1990 are weighted based on the miles traveled per model year.

Tables A-28a, A-28b, A-29a and A-29b show the pre-combustion and combustion emissions for tractor-trailer and single unit delivery trucks in 1992.

Locomotives. Table A-30 lists the emissions resulting from transportation of material by locomotives. Freight locomotives use diesel fuel exclusively (Reference A-4).

Barges and Ocean Freighters. Commercial water transport can be categorized by boundary of travel, fuel used, and type of power source. In an effort to narrow these options, the following assumptions were made:

1. Barges are typically vessels traveling in the Great Lakes, rivers, or along a coast. Ocean freighters encompass longer travel not within the range or capability of a barge.
2. Only two options are available for a power source—diesel fuel and steam produced from residual oil.
3. 77.3 percent of barges use diesel fuel in their engines, and 22.7 percent use residual oil to generate steam for steam turbines (Reference A-4).
4. 90.8 percent of ocean freighters utilize residual fuel in steam turbines, and 9.2 percent have diesel engines (Reference A-4).
5. Power usage of the engines is modeled at 50 percent of full capacity. This adjusts for fuel use and emissions occurring at dockside while the engine is idling, as well as fuel use and emissions during transport.

Tables A-31 and A-32 list the emissions for transport of material by barge and ocean freighter, respectively.

Table A-28a

ENVIRONMENTAL EMISSIONS FOR 1992 TRACTOR-TRAILER GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.42	43.3	44.7	B
Nitrogen Oxides	7.22	58.3	65.5	B
Hydrocarbons (other than methane)	42.8	20.5	63.3	C
Sulfur Oxides	22.0	4.34	26.3	B
Carbon Monoxide	5.42	380	385	B
Fossil Carbon Dioxide	2,239	18,400	20,639	A
Non-Fossil Carbon Dioxide	5.20		5.20	B
Formaldehyde	1.8E-05		1.8E-05	C
Other Aldehydes	0.40		0.40	C
Other Organics	0.26	117	117	D
Ammonia	0.034		0.034	C
Lead	1.2E-04	0.031	0.031	B
Methane	3.45		3.45	C
Kerosene	8.9E-05		8.9E-05	D
Chlorine	0.0013		0.0013	D
Hydrochloric Acid	0.021		0.021	C
Hydrogen Fluoride	0.0028		0.0028	C
Metals	0.0021		0.0021	D
Antimony	3.2E-05		3.2E-05	E
Arsenic	6.7E-05		6.7E-05	E
Beryllium	4.7E-06		4.7E-06	E
Cadmium	1.0E-04		1.0E-04	E
Chromium	7.6E-05		7.6E-05	E
Cobalt	9.2E-05		9.2E-05	E
Manganese	9.1E-05		9.1E-05	E
Mercury	2.2E-05		2.2E-05	E
Nickel	0.0014		0.0014	E
Selenium	6.2E-05		6.2E-05	E
Acreolin	4.0E-06		4.0E-06	D
Nitrous Oxide	0.0024		0.0024	D
Benzene	1.3E-05		1.3E-05	D
Perchloroethylene	3.9E-06		3.9E-06	D
Trichloroethylene	3.8E-06		3.8E-06	D
Methylene Chloride	1.8E-05		1.8E-05	D
Carbon Tetrachloride	1.6E-05		1.6E-05	D
Phenols	1.0E-04		1.0E-04	D
Naphthalene	6.0E-06		6.0E-06	D
Dioxins	2.2E-11		2.2E-11	D
n-nitrodimethylamine	8.4E-07		8.4E-07	D
Radionuclides (Ci)	7.4E-05		7.4E-05	D

(continued)

Table A-28a (cont)

ENVIRONMENTAL EMISSIONS FOR 1992 TRACTOR-TRAILER GASOLINE POWERED TRUCKS

(pounds of pollutants per 1,000 gallons of gasoline)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	7.1E-06		7.1E-06	E
Metal Ion	0.15		0.15	E
Dissolved Solids	29.7		29.7	D
Suspended Solids	0.68		0.68	D
BOD	0.11		0.11	D
COD	0.74		0.74	D
Phenol	4.9E-04		4.9E-04	E
Oil	0.69		0.69	E
Sulfuric Acid	0.0059		0.0059	E
Iron	0.016		0.016	E
Ammonia	0.012		0.012	E
Chromium	0.0011		0.0011	E
Lead	1.3E-05		1.3E-05	E
Zinc	5.5E-04		5.5E-04	E
Chlorides	1.09		1.09	E
Sodium	1.4E-04		1.4E-04	E
Calcium	7.6E-05		7.6E-05	E
Sulfates	0.88		0.88	E
Manganese	0.0078		0.0078	E
Fluorides	3.5E-04		3.5E-04	E
Nitrates	3.3E-05		3.3E-05	E
Phosphates	0.0030		0.0030	E
Boron	0.024		0.024	E
Other Organics	0.072		0.072	E
Chromates	8.3E-05		8.3E-05	E
Cyanide	1.6E-06		1.6E-06	E
Mercury	8.4E-08		8.4E-08	E
Cadmium	0.0011		0.0011	E
Solid Waste	113		113	B

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(1) Sum of precombustion process-related emissions from Table A-3c and precombustion fuel-related emissions from Table A-12c.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-28b

ENVIRONMENTAL EMISSIONS FOR 1992 TRACTOR-TRAILER DIESEL POWERED TRUCKS

(pounds of pollutants per 1,000 gallons of diesel fuel)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.66	29.8	31.5	B
Nitrogen Oxides	8.47	210	218	B
Hydrocarbons (other than methane)	50.2	37.7	87.9	C
Sulfur Oxides	25.8	36.2	62.0	B
Carbon Monoxide	6.36	209	215	B
Fossil Carbon Dioxide	2,627	22,800	25,427	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05		2.1E-05	C
Other Aldehydes	0.47	5.50	5.97	C
Other Organics	0.30	116	116	D
Ammonia	0.040		0.040	C
Lead	1.4E-04		1.4E-04	B
Methane	4.05		4.05	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		3.8E-05	E
Arsenic	7.9E-05		7.9E-05	E
Beryllium	5.5E-06		5.5E-06	E
Cadmium	1.2E-04		1.2E-04	E
Chromium	9.0E-05		9.0E-05	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04		1.1E-04	E
Mercury	2.6E-05		2.6E-05	E
Nickel	0.0017		0.0017	E
Selenium	7.2E-05		7.2E-05	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028		0.0028	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.6E-06		4.6E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

(continued)

Table A-28b (cont)

ENVIRONMENTAL EMISSIONS FOR 1992 TRACTOR-TRAILER DIESEL POWERED TRUCKS

(pounds of pollutants per 1,000 gallons of diesel fuel)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	8.4E-06		8.4E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	34.8		34.8	D
Suspended Solids	0.79		0.79	D
BOD	0.13		0.13	D
COD	0.87		0.87	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.81		0.81	E
Sulfuric Acid	0.0069		0.0069	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.5E-04		6.5E-04	E
Chlorides	1.28		1.28	E
Sodium	1.6E-04		1.6E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.03		1.03	E
Manganese	0.0092		0.0092	E
Fluorides	4.1E-04		4.1E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.085		0.085	E
Chromates	9.8E-05		9.8E-05	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.8E-08		9.8E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	133		133	B

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(1) Sum of precombustion process-related emissions from Table A-3b and precombustion fuel-related emissions from Table A-12b.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-29a

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT GASOLINE POWERED TRUCKS

(pounds of pollutants per 1,000 gallons of gasoline)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.42	63.4	64.8	B
Nitrogen Oxides	7.22	76.5	83.7	B
Hydrocarbons (other than methane)	42.8	26.8	69.6	C
Sulfur Oxides	22.0	4.30	26.3	B
Carbon Monoxide	5.42	528	533	B
Fossil Carbon Dioxide	2,240	18,200	20,440	A
Non-Fossil Carbon Dioxide	5.2		5.2	B
Formaldehyde	1.8E-05		1.8E-05	C
Other Aldehydes	0.40		0.40	C
Other Organics	0.26	171	171	D
Ammonia	0.034		0.034	C
Lead	1.2E-04	0.031	0.031	B
Methane	3.45		3.45	C
Kerosene	8.9E-05		8.9E-05	D
Chlorine	0.0013		0.0013	D
Hydrochloric Acid	0.021		0.021	C
Hydrogen Fluoride	0.0028		0.0028	C
Metals	0.0021		0.0021	D
Antimony	3.2E-05		3.2E-05	E
Arsenic	6.7E-05		6.7E-05	E
Beryllium	4.7E-06		4.7E-06	E
Cadmium	1.0E-04		1.0E-04	E
Chromium	7.6E-05		7.6E-05	E
Cobalt	9.2E-05		9.2E-05	E
Manganese	9.1E-05		9.1E-05	E
Mercury	2.2E-05		2.2E-05	E
Nickel	0.0014		0.0014	E
Selenium	6.2E-05		6.2E-05	E
Acreolin	4.0E-06		4.0E-06	D
Nitrous Oxide	0.0024		0.0024	D
Benzene	1.3E-05		1.3E-05	D
Perchloroethylene	3.9E-06		3.9E-06	D
Trichloroethylene	3.8E-06		3.8E-06	D
Methylene Chloride	1.8E-05		1.8E-05	D
Carbon Tetrachloride	1.6E-05		1.6E-05	D
Phenols	1.0E-04		1.0E-04	D
Naphthalene	6.0E-06		6.0E-06	D
Dioxins	2.2E-11		2.2E-11	D
n-nitrodimethylamine	8.4E-07		8.4E-07	D
Radionuclides (Ci)	7.4E-05		7.4E-05	D

(continued)

Table A-29a (cont)

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT GASOLINE POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of gasoline)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	7.1E-06		7.1E-06	E
Metal Ion	0.15		0.15	E
Dissolved Solids	29.7		29.7	D
Suspended Solids	0.68		0.68	D
BOD	0.11		0.11	D
COD	0.74		0.74	D
Phenol	4.9E-04		4.9E-04	E
Oil	0.69		0.69	E
Sulfuric Acid	0.0059		0.0059	E
Iron	0.016		0.016	E
Ammonia	0.012		0.012	E
Chromium	0.0011		0.0011	E
Lead	1.3E-05		1.3E-05	E
Zinc	5.5E-04		5.5E-04	E
Chlorides	1.09		1.09	E
Sodium	1.4E-04		1.4E-04	E
Calcium	7.6E-05		7.6E-05	E
Sulfates	0.88		0.88	E
Manganese	0.0078		0.0078	E
Fluorides	3.5E-04		3.5E-04	E
Nitrates	3.3E-05		3.3E-05	E
Phosphates	0.0030		0.0030	E
Boron	0.024		0.024	E
Other Organics	0.072		0.072	E
Chromates	8.3E-05		8.3E-05	E
Cyanide	1.6E-06		1.6E-06	E
Mercury	8.4E-08		8.4E-08	E
Cadmium	0.0011		0.0011	E
Solid Waste	113		113	B

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(1) Sum of precombustion process-related emissions from Table A-3c and precombustion fuel-related emissions from Table A-12c.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-29b

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT DIESEL POWERED TRUCKS
(pounds of pollutants per 1,000 gallons of diesel fuel)

Atmospheric Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Particulates	1.66	69.1	70.8	B
Nitrogen Oxides	8.47	312	321	B
Hydrocarbons (other than methane)	50.2	54.2	104	C
Sulfur Oxides	25.8	36.2	62.0	B
Carbon Monoxide	6.36	300	306	B
Fossil Carbon Dioxide	2,630	22,700	25,330	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05		2.1E-05	C
Other Aldehydes	0.47	5.50	5.97	C
Other Organics	0.30	186	187	D
Ammonia	0.040		0.040	C
Lead	1.4E-04		1.4E-04	B
Methane	4.05		4.05	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		3.8E-05	E
Arsenic	7.9E-05		7.9E-05	E
Beryllium	5.5E-06		5.5E-06	E
Cadmium	1.2E-04		1.2E-04	E
Chromium	9.0E-05		9.0E-05	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04		1.1E-04	E
Mercury	2.6E-05		2.6E-05	E
Nickel	0.0017		0.0017	E
Selenium	7.2E-05		7.2E-05	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028		0.0028	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.6E-06		4.6E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

(continued)

Table A-29b (cont)

ENVIRONMENTAL EMISSIONS FOR 1992 SINGLE-UNIT DIESEL POWERED TRUCKS

(pounds of pollutants per 1,000 gallons of diesel fuel)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	8.4E-06		8.4E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	34.8		34.8	D
Suspended Solids	0.79		0.79	D
BOD	0.13		0.13	D
COD	0.87		0.87	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.81		0.81	E
Sulfuric Acid	0.0069		0.0069	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.5E-04		6.5E-04	E
Chlorides	1.28		1.28	E
Sodium	1.6E-04		1.6E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.03		1.03	E
Manganese	0.0092		0.0092	E
Fluorides	4.1E-04		4.1E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.085		0.085	E
Chromates	9.8E-05		9.8E-05	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.8E-08		9.8E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	133		133	B

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(1) Sum of precombustion process-related emissions from Table A-3b and precombustion fuel-related emissions from Table A-12b.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-30

ENVIRONMENTAL EMISSIONS FOR DIESEL POWERED LOCOMOTIVES

(pounds of pollutants per 1,000 gallons of diesel fuel)

Atmospheric Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Particulates	1.66	75.0	76.7	B
Nitrogen Oxides	8.47	266	275	B
Hydrocarbons (other than methane)	50.2	94.0	144	C
Sulfur Oxides	25.8	36.2	62.0	B
Carbon Monoxide	6.36	130	136	B
Fossil Carbon Dioxide	2,630	23,000	25,630	A
Non-Fossil Carbon Dioxide	6.10		6.10	B
Formaldehyde	2.1E-05		2.1E-05	C
Other Aldehydes	0.47	5.50	5.97	C
Other Organics	0.30	7.00	7.30	D
Ammonia	0.040		0.040	C
Lead	1.4E-04		1.4E-04	B
Methane	4.05		4.05	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0015		0.0015	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		3.8E-05	E
Arsenic	7.9E-05		7.9E-05	E
Beryllium	5.5E-06		5.5E-06	E
Cadmium	1.2E-04		1.2E-04	E
Chromium	9.0E-05		9.0E-05	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04		1.1E-04	E
Mercury	2.6E-05		2.6E-05	E
Nickel	0.0017		0.0017	E
Selenium	7.2E-05		7.2E-05	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0028		0.0028	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.6E-06		4.6E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.5E-11		2.5E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.7E-05		8.7E-05	D

(continued)

Table A-30 (cont)

ENVIRONMENTAL EMISSIONS FOR DIESEL POWERED LOCOMOTIVES
(pounds of pollutants per 1,000 gallons of diesel fuel)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	8.4E-06		8.4E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	34.8		34.8	D
Suspended Solids	0.79		0.79	D
BOD	0.13		0.13	D
COD	0.87		0.87	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.81		0.81	E
Sulfuric Acid	0.0069		0.0069	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.5E-04		6.5E-04	E
Chlorides	1.28		1.28	E
Sodium	1.6E-04		1.6E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.03		1.03	E
Manganese	0.0092		0.0092	E
Fluorides	4.1E-04		4.1E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.085		0.085	E
Chromates	9.8E-05		9.8E-05	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.8E-08		9.8E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	133		133	B

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(1) Sum of precombustion process-related emissions from Table A-3b and precombustion fuel-related emissions from Table A-12b.

References: A-5, A-6, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-31

ENVIRONMENTAL EMISSIONS FOR BARGES
(pounds of pollutants per 1,000 gallons of fuel)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.70	16.1	17.8	B
Nitrogen Oxides	8.64	268	277	B
Hydrocarbons (other than methane)	51.3	62.6	114	C
Sulfur Oxides	26.3	36.2	62.5	B
Carbon Monoxide	6.49	68.2	74.7	B
Fossil Carbon Dioxide	2,680	23,100	25,780	A
Non-Fossil Carbon Dioxide	6.22		6.22	B
Formaldehyde	2.2E-05		2.2E-05	C
Other Aldehydes	0.48	5.50	5.98	C
Other Organics	0.31	7.00	7.31	D
Ammonia	0.041		0.041	C
Lead	1.4E-04		1.4E-04	B
Methane	4.13		4.13	C
Kerosene	1.1E-04		1.1E-04	D
Chlorine	0.0016		0.0016	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.9E-05		3.9E-05	E
Arsenic	8.0E-05		8.0E-05	E
Beryllium	5.6E-06		5.6E-06	E
Cadmium	1.2E-04		1.2E-04	E
Chromium	9.2E-05		9.2E-05	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04		1.1E-04	E
Mercury	2.6E-05		2.6E-05	E
Nickel	0.0017		0.0017	E
Selenium	7.4E-05		7.4E-05	E
Acreolin	4.8E-06		4.8E-06	D
Nitrous Oxide	0.0029		0.0029	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.7E-06		4.7E-06	D
Trichloroethylene	4.5E-06		4.5E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.1E-06		7.1E-06	D
Dioxins	2.6E-11		2.6E-11	D
n-nitrodimethylamine	1.0E-06		1.0E-06	D
Radionuclides (Ci)	8.9E-05		8.9E-05	D

(continued)

Table A-31 (cont)

ENVIRONMENTAL EMISSIONS FOR BARGES
(pounds of pollutants per 1,000 gallons of fuel)

Waterborne Emissions	Precombustion (1)	Combustion	Total	DQI
Acid	8.6E-06		8.6E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	35.5		35.5	D
Suspended Solids	0.81		0.81	D
BOD	0.13		0.13	D
COD	0.89		0.89	D
Phenol	5.9E-04		5.9E-04	E
Oil	0.83		0.83	E
Sulfuric Acid	0.0071		0.0071	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.6E-04		6.6E-04	E
Chlorides	1.31		1.31	E
Sodium	1.7E-04		1.7E-04	E
Calcium	9.1E-05		9.1E-05	E
Sulfates	1.05		1.05	E
Manganese	0.0094		0.0094	E
Fluorides	4.2E-04		4.2E-04	E
Nitrates	4.0E-05		4.0E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.087		0.087	E
Chromates	1.0E-04		1.0E-04	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	1.0E-07		1.0E-07	E
Cadmium	0.0013		0.0013	E
Solid Waste	135		135	B

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(1) Sum of precombustion process-related emissions from Tables A-3b and A-3c, and precombustion fuel-related emissions from Tables A-12b and A-12c.

References: A-4, A-5, A-6, A-10, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

Table A-32

ENVIRONMENTAL EMISSIONS FOR OCEAN FREIGHTERS
(pounds of pollutants per 1,000 gallons of fuel)

Atmospheric Emissions	Precombustion (1)	Combustion	Total	DQI
Particulates	1.68	19.5	21.2	B
Nitrogen Oxides	8.54	82.5	91.0	B
Hydrocarbons (other than methane)	50.7	8.80	59.5	C
Sulfur Oxides	26.0	36.2	62.2	B
Carbon Monoxide	6.41	9.02	15.4	B
Fossil Carbon Dioxide	2,650	25,200	27,850	A
Non-Fossil Carbon Dioxide	6.15		6.15	B
Formaldehyde	2.2E-05		2.2E-05	C
Other Aldehydes	0.47	5.50	5.97	C
Other Organics	0.30	7.00	7.30	D
Ammonia	0.041		0.041	C
Lead	1.4E-04		1.4E-04	B
Methane	4.08		4.08	C
Kerosene	1.0E-04		1.0E-04	D
Chlorine	0.0016		0.0016	D
Hydrochloric Acid	0.025		0.025	C
Hydrogen Fluoride	0.0033		0.0033	C
Metals	0.0025		0.0025	D
Antimony	3.8E-05		3.8E-05	E
Arsenic	7.9E-05		7.9E-05	E
Beryllium	5.5E-06		5.5E-06	E
Cadmium	1.2E-04		1.2E-04	E
Chromium	9.1E-05		9.1E-05	E
Cobalt	1.1E-04		1.1E-04	E
Manganese	1.1E-04		1.1E-04	E
Mercury	2.6E-05		2.6E-05	E
Nickel	0.0017		0.0017	E
Selenium	7.3E-05		7.3E-05	E
Acreolin	4.7E-06		4.7E-06	D
Nitrous Oxide	0.0029		0.0029	D
Benzene	1.5E-05		1.5E-05	D
Perchloroethylene	4.7E-06		4.7E-06	D
Trichloroethylene	4.4E-06		4.4E-06	D
Methylene Chloride	2.1E-05		2.1E-05	D
Carbon Tetrachloride	1.9E-05		1.9E-05	D
Phenols	1.2E-04		1.2E-04	D
Naphthalene	7.0E-06		7.0E-06	D
Dioxins	2.6E-11		2.6E-11	D
n-nitrodimethylamine	9.9E-07		9.9E-07	D
Radionuclides (Ci)	8.8E-05		8.8E-05	D

(continued)

Table A-32 (cont)

ENVIRONMENTAL EMISSIONS FOR OCEAN FREIGHTERS
(pounds of pollutants per 1,000 gallons of fuel)

Waterborne Emissions	**Precombustion (1)**	**Combustion**	**Total**	**DQI**
Acid	8.5E-06		8.5E-06	E
Metal Ion	0.18		0.18	E
Dissolved Solids	35		35	D
Suspended Solids	0.80		0.80	D
BOD	0.13		0.13	D
COD	0.88		0.88	D
Phenol	5.8E-04		5.8E-04	E
Oil	0.82		0.82	E
Sulfuric Acid	0.0070		0.0070	E
Iron	0.019		0.019	E
Ammonia	0.014		0.014	E
Chromium	0.0013		0.0013	E
Lead	1.5E-05		1.5E-05	E
Zinc	6.6E-04		6.6E-04	E
Chlorides	1.29		1.29	E
Sodium	1.7E-04		1.7E-04	E
Calcium	9.0E-05		9.0E-05	E
Sulfates	1.04		1.04	E
Manganese	0.0092		0.0092	E
Fluorides	4.2E-04		4.2E-04	E
Nitrates	3.9E-05		3.9E-05	E
Phosphates	0.0035		0.0035	E
Boron	0.028		0.028	E
Other Organics	0.086		0.086	E
Chromates	9.8E-05		9.8E-05	E
Cyanide	1.9E-06		1.9E-06	E
Mercury	9.9E-08		9.9E-08	E
Cadmium	0.0013		0.0013	E
Solid Waste	135		135	B

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(1) Sum of precombustion process-related emissions from Tables A-3b and A-3c, and precombustion fuel-related emissions from Tables A-12b and A-12c.

References: A-4, A-5, A-6, A-10, A-16, A-41, A-47, A-54, A-55, and A-58.

Source: Franklin Associates, Ltd.

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GLOSSARY

Ash. Impurities in coal, consisting of silica, alumina, and other non-combustible matter. Ash increases the weight of coal, adds to the cost of handling, and can affect its burning characteristics.

Barrel (Petroleum). A unit of volume equal to 42 U.S. gallons.

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

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

Bituminous Coal. A dense black coal, often with well-defined bands of bright and dull material, with a moisture content usually less than 20 percent. Often referred to as soft coal. It is the most common coal and is used primarily for generating electricity, making coke, and space heating.

Boiler. A device for generating steam for power, processing, or heating purposes or for producing hot water for heating purposes or hot water supply.

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

Butane. A normally gaseous straight-chained or branched hydrocarbon (C_4H_{10}). It is extracted from natural gas or refinery gas streams. It includes isobutane and normal butane.

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

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

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

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

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

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

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

Fossil Fuel. Any naturally occurring organic fuel, such as petroleum, natural gas, or coal.

Fossil Fuel Steam-Electric Power Plant. An electricity generation plant in which the prime mover is a turbine rotated by high-pressure steam produced in a boiler by heat from burning fossil fuels.

Flue Gas Desulfurization Unit (Scrubber). Equipment used to remove sulfur oxides from the combustion gases of a boiler plant before discharge to the atmosphere. Chemicals, such as lime, are used as the scrubbing media.

Fugitive Emissions. Unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels.

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

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

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

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

Hydroelectric Power Plant. A plant in which the turbine generators are driven by falling water.

Lease Condensate. A natural gas liquid recovered from gas well gas (associated and non-associated) in lease separators or natural gas field facilities. Lease condensate consists primarily of pentanes and heavier hydrocarbons.

Lignite. A brownish-black coal of low rank with a high content of moisture and volatile matter. Often referred to as brown coal.

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

Methane. A hydrocarbon gas (CH_4) that is the principal constituent of natural gas.

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

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

Natural Gas Liquids (NGL). Those hydrocarbons in natural gas that are separated as liquids from the gas. Natural gas liquids include natural gas plant liquids (primarily ethane, propane, butane, and isobutane), and lease condensate (primarily pentanes produced from natural gas at lease separators and field facilities.)

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

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

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

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

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

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

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

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

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

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

Plant Condensate. One of the natural gas liquids (NGLs), mostly pentanes and heavier hydrocarbons, recovered and separated as liquids at gas inlet separators or scrubbers in processing plants.

Processing Plant (natural gas). A surface installation designed to separate and recover natural gas liquids from a stream of produced natural gas through the process of condensation, absorption, refrigeration, or other methods, and to control the quality of natural gas marketed or returned to oil or gas reservoirs for pressure maintenance, repressuring, or cycling.

Refinery (petroleum). An installation that manufactures finished petroleum products from crude oil, unfinished oils, natural gas liquids, other hydrocarbons, and alcohol.

Residual Fuel Oil. The heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Included are No. 5, No. 6, and Navy

Special. It is used for commercial and industrial heating, electricity generation, and to power ships.

Subbituminous Coal. A dull, black coal of rank intermediate between lignite and bituminous coal.

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

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

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

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

Uranium. A heavy naturally radioactive metallic element (atomic number 92). Its two principally occurring isotopes are ^{235}U and ^{238}U. ^{235}U is indispensable to the nuclear industry, because it is the only isotope existing in nature to any appreciable extent that is fissionable by thermal neutrons. ^{238}U is also important, because it absorbs neutrons to produce a radioactive isotope that subsequently decays to ^{239}Pu, an isotope that also is fissionable by thermal neutrons.

Uranium Ore. Rock containing uranium mineralization, typically 0.05 to 0.2 percent U_3O_8.

APPENDIX B

DEFINITION OF PACKAGING SYSTEMS

INTRODUCTION

This Appendix provides the following information:

- Definition of the shipped product
- Definition of packaging options
    - Materials and postconsumer recycled content
    - Sizes and weights

Information on the production of packaging materials and fabrication of packaging products can be found in Appendix C. Transportation steps are described in Appendix D. End of life management of packaging materials is discussed in Appendix E.

The LCI analysis of each packaging configuration will be evaluated on the equivalent use basis of delivery of 10,000 packages of mail-order soft goods to consumers. The representative shipped product and the quantities of materials required to package the shipped product using each packaging configuration are characterized in the following sections.

DEFINITION, WEIGHT AND VOLUME OF THE SHIPPED PRODUCT

The amounts of different packaging materials used are important inputs for the life cycle inventory analysis. Burdens from most process steps are expressed as functions of pounds of packaging material used, so determining the weight of different packaging materials used is of key importance. The amount of packaging material used, in turn, is a function of the size, weight and type of product or products being shipped. Knowing the weight of the product(s) shipped is also important because outbound (retailer to customer) transportation burdens are allocated between the burdens of shipping the product and the burdens of shipping the package.

Franklin Associates required from Oregon Department of Environmental Quality (DEQ) a standard weight and volume for a “unit product” and each packaging material used in order to complete the modeling of burdens. An alternative approach, involving modeling a variety of weights and volumes for each packaging material, was not affordable given DEQ’s budget for this study. As such, the project team set about to define the weight and volume of an “average” unit product and the weight and volume of each packaging material that would be used, on average, to ship that product.

In making these determinations, DEQ established as its most important objective avoiding assumptions regarding weights and volumes that could have the undesired consequence of biasing the results of the study in favor of a certain packaging material or combination of materials. Therefore, DEQ developed the following methodology to define average weights and volumes, in a manner designed to avoid biasing the results. Actual averages for real packaging users may vary from the averages used in this study. Study users interested in tailoring the results for their unique circumstances will be able to work with the assumptions, calculations, and results portrayed in the report (and appendices) to derive their own custom findings.

This study focuses on packaging alternatives for shipping non-breakable items from a retailer or retail distribution center/order fulfillment center to a residential customer. Non-breakable items are defined to include most garments of clothing, linens (towels, sheets, etc.) as well as some other durable products including a variety of paper products that are not likely to be broken or damaged if shipped to residential customers in shipping/mailing bags.

The decision to exclude breakable items from the study allows for the use of some important simplifying assumptions. The first assumption is that the packaging options included in this study are all equally adequate in their ability to protect non-breakable items in the normal shipping environment. Put differently, cardboard boxes with different types of void fill and different types of padded and non-padded shipping bags will be equally protective of non-breakable items during transit. (The widespread use of shipping bags for direct-to-customer sales of soft goods, and the very high costs associated with managing returns, suggests that this assumption is reasonable.) Assuming that the damage rates for non-breakable items in different packaging systems are equal (or close to each other) avoids the need to model different product return rates for different packaging systems. This assumption allows us to avoid calculating the environmental burdens of product damage, a complex undertaking that would require selecting a "typical" consumer product or blend of products and modeling the burdens of product manufacturing and waste. If each packaging system results in the same, small percentage of products damaged in transit, then the environmental burdens of product damage are equal across all packaging systems, and these burdens can be conveniently ignored for the purpose of comparing packaging systems.

A corollary assumption is that items shipped in a corrugated cardboard box require void fill only to stabilize the product in transit, and not to cushion the product against shock. Different void fill systems have different protective qualities. Were breakable items being shipped, different box sizes might be needed to allow for adequate levels of internal cushioning and protective packaging (void fill that is less protective would be needed in greater amounts, thus potentially requiring a larger box). Alternatively, if the same size of box was used to ship breakable items regardless of the type of internal packaging used for cushioning, and this resulted in different damage rates in transit (for different cushioning materials), the study team would need to model the environmental burdens of product damage, which is undesirable for the reasons described above.

In order to identify an "average" shipment of non-breakable items, DEQ worked closely with staff from Norm Thompson Outfitters (NTO), one of the companies partnering with DEQ on packaging waste reduction. NTO provided DEQ with data on its four top-selling "soft goods" (a subset of non-breakable items), including the weight and dimensions (as shipped) of each (see Table B-1). All four of these items arrive at Norm Thompson's Distribution Center in a thin polyethylene bag; three of the items also arrive pre-folded. Norm Thompson will not further fold these items when shipping them out, to avoid wrinkling the products. Thus, the dimensions provided by Norm Thompson and shown in Table B-1 represent the actual dimensions of each item as the customer would receive it.

Table B-1.
Norm Thompson Outfitters' Top-Selling "Soft Goods"

	Length (inches)	Width (inches)	Height (inches)	Weight (pounds)
Miracle Cloth (set of 3) (SKU 62355)	8"	8"	2"	0.3
Med. Microfiber (Healthy Back Bag) (SKU 13140)	19"	12"	2"	1.0
Reg. Fleece Duster (SKU 10161)	21"	16"	1"	1.0
Prima Cotton Tee Faux Wrap 3/4 Sleeve (SKU 24739)	22"	12"	0.5"	0.5
SIMPLE AVERAGE	17.5"	12"	1.375"	0.7

The average represents a simple, non-weighted average of all four items. The use of a simple (non-weighted) average is not expected to bias the results of the study.

While an average item may measure 17.5" x 12" x 1.375", some retail customers purchase more than one item. While Norm Thompson sells both "soft goods" and "hard goods" (breakable items outside of the scope of this study), DEQ estimated, using proprietary data provided by NTO, that among shipments to customers that are exclusively made up of soft goods, the average customer orders 1.83 items. (The actual number of items shipped per package might be slightly less than 1.83 on average, as some items may be on back-order and shipped separately.) This was applied to the height and weight of the average parcel (above) as a scaling factor. As a result, the dimensions of the unit product (also called "shipped product") for the purposes of this study are 17.5" x 12" x 2.5" (1.375" x 1.83) and the unit product's weight is 1.28 pounds (0.7 pounds x 1.83).

It is also worth noting that the heights of each product are uncompressed heights of products within their individual polybags. Because all four of these products are textiles, compressing the products by placing additional items on top of them might reduce the actual as-shipped heights slightly.

DEFINITION OF PACKAGING OPTIONS, COMPOSITION, AND LEVELS OF POSTCONSUMER CONTENT

The study team identified a large number of alternative packaging systems that could be used to ship the unit product to residential customers. Budget constraints forced the study team to limit the number of systems evaluated. Each system is described below, including assumptions regarding material composition and levels of postconsumer content. The basic systems can be categorized into three groups:

- Corrugated box with void fill.
- Unpadded shipping bag.
- Padded shipping bag.

Each of these three groups has several alternative packaging systems, as listed below:

Corrugated Box with Void Fill
Void Fill Options Include:

- Inflated polyethylene air packets.
- Expanded polystyrene loose fill.
- Bio-based (starch) loose fill.
- Molded pulp loose fill.
- Unbleached kraft paper (purchased as rolls or sheets and then crumpled up).
- Newsprint (purchased as rolls or sheets and then crumpled up).
- Shredded corrugated.
- Shredded office paper.

Unpadded Shipping Bag
Options included in this study include:

- Kraft paper shipping bag.
- Polyethylene shipping bag.

Padded Shipping Bag
Options included in this study include:

- All-paper shipping bag (kraft liner, macerated newsprint filler).
- Kraft paper shipping bag with polyethylene bubble padding.
- Polyethylene shipping bag with polyethylene bubble padding.

Each of these systems is described below. Quantities of packaging material used are described in later sections of this Appendix.

Due to budget limitations, minor components of packaging systems are not included in the study. These include tape for sealing boxes, adhesives used in the fabrication of shipping bags, self-adhesive tabs and pull tabs for shipping bags, inks, address labels, and postage. The analysis does include adhesive used in the production of corrugated boxes.

In the following discussions, it is helpful to understand the distinction between postconsumer material and postconsumer content. The term “postconsumer” refers to a material or product that has been used for its intended purpose and has come to the end of its life in that use. Postconsumer content refers to the amount of postconsumer material (e.g., postconsumer fiber or resin) incorporated in a product. Different postconsumer contents are modeled for paper, paperboard, and plastic resins in this study. Molded pulp cushion cubes, macerated newspaper (used in envelope padding), and shredded office paper and corrugated (used for dunnage) are all made from 100% postconsumer material, although the postconsumer fiber content in the postconsumer material may be less than 100%. However, because the postconsumer material used has already completed an original useful life (as newspaper, office paper, or a corrugated box), it comes in free of upstream virgin material production burdens just as postconsumer content does.

Corrugated Box

Corrugated boxes are constructed with a fluted layer of medium sandwiched between two layers of linerboard. Paperboard industry statistics (References B-3 through B-6) indicate that an average corrugated box is about 32% by weight medium and 68% by weight linerboard. Paperboard industry statistics report recovered fiber use in containerboard in the following categories: kraft linerboard, semichemical, and recycled containerboard. (Semichemical is used for medium, while recycled containerboard includes both recycled linerboard and medium.) Overall, recovered fiber use in kraft linerboard is 7.7% industrial scrap such as kraft paper trim scrap and box clippings and 9.6% postconsumer old corrugated containers, or OCC. Industry statistics for recovered paper use in semichemical paperboard are 3.2% industrial scrap and 30.1% OCC. These are overall industry statistics; kraft linerboard or semichemical medium produced by individual mills may contain varying amounts of industrial and postconsumer fiber. The recycled content in recycled containerboard (linerboard and medium) is 100% OCC. More detailed description of the processes and input materials for box production are provided in Appendix C.

The study models two options for postconsumer content in corrugated boxes: 38% and 80%. The 38% represents a U.S. average based on paperboard industry statistics for the market shares of virgin linerboard, recycled linerboard, semichemical medium, and recycled medium and the postconsumer recycled content of each. Eighty percent represents a level of postconsumer content that is considered high yet achievable. It was developed based on conversations between staff from Pack Edge Development (under contract to DEQ) and several Pacific Northwest box makers. Specifically, one box maker (Tharco) told Pack Edge staff that Tharco’s recycled line of stock cartons contain 80% postconsumer content. Another area box maker, Alliance Packaging, informed Pack Edge that it would be possible to make 100% postconsumer content boxes, although this would require special ordering, and quantities might be limited.

Inflated Polyethylene Air Packets

Inflated polyethylene air packets are sold to order fulfillment centers as flat (deflated) tubes of polyethylene. The tubes are fed into a machine, which uses either electricity or a combination of electricity and compressed air to inflate the tubes and seal them at regular intervals. The resulting "air packets" are used as void fill and cushioning by many retail mail-order companies. Different systems allow for different levels of inflation and packet sizes. DEQ and Pack Edge Development identified four different manufacturers of these types of materials:

- FP International (brand name: "flo-pak Cell-O")
- Pactiv (brand name: "Pactiv Air 3000 System")
- Sealed Air Corporation (brand name: "Fill-Air")
- Storopack (brand name: "AIRplus")

Samples of all four brands were obtained. The FP International brand was labeled as being HDPE. All three other brands were labeled as LDPE. Pack Edge staff was informed that at one time, one of the LDPE products was co-extruded with nylon as a vapor barrier; however, that company told Pack Edge that nylon was no longer used. DEQ learned from talking with another one of the air packet manufacturers that their product is actually a blend of LDPE and LLDPE. Because the burdens of these materials are fairly similar (see Appendix C), and the manufacturers were unwilling to divulge the exact composition of their products, the study assumes that the inflated polyethylene air packs are 100% LDPE.

None of the manufacturers interviewed by Pack Edge and DEQ indicated that their materials contain recycled content, and their marketing literature was equally silent on this issue. For purposes of the study, we assume that this material contains 0% postconsumer recycled content, although a 30% postconsumer option is also modeled.

Expanded Polystyrene (EPS) Loose Fill

This is one of the most commonly used void fill materials in the U.S. It is often referred to as "packing peanuts" or "foam peanuts". Technically, it is expanded polystyrene composed of polystyrene resin beads impregnated with blowing agent during polymerization. The blowing agent represents about 5% by weight of the material inputs of EPS foam production. More detail on the production of EPS foam loose fill is provided in Appendix C.

Staff from Pack Edge Development spoke with four manufacturers of EPS loose fill: American Excelsior, Inter-Pac, Space-Pak, and Storopack. Inter-Pac both manufactures loose fill and sells resin to other companies such as Space-Pak. The apparent standard in the EPS loose fill industry is that loose fill made from virgin or preconsumer resin only is colored white, while loose fill that contains some level of postconsumer content is colored green. All manufacturers sell a virgin (0% postconsumer) option; some also sell an option containing some postconsumer material. The levels of postconsumer content used by these four manufacturers in their postconsumer option (as reported to Pack Edge Development) are:

- American Excelsior: 15 – 25% postconsumer content.
- Inter-Pac: guarantees minimum 15% postconsumer content, can get as high as 40% if desired.
- Space-Pak: doesn’t sell the green loose fill.
- Storopack: 10% postconsumer content.

This study models two different levels of postconsumer EPS content: 0% and 30%, representing a relatively high but commercially available level of recycled content.

Bio-Based (Starch) Loose Fill

Similar in size, shape, and use to the expanded polystyrene loose fill, this product is made from starch and is typically marketed as “bio-degradable”.

Pack Edge Development spoke with representatives of two companies: National Starch and American Excelsior. American Excelsior manufactures starch loose fill. National Starch, in contrast, does not manufacture the loose fill material but licenses independent manufacturers throughout the United States. National Starch also sells base starch to independent manufacturers. Licensees are not required to purchase their starch from National Starch; they can buy it on the open market but still have to pay a royalty to National Starch.

According to National Starch, their product is 85 – 87% corn starch. The remainder is “biodegradable but proprietary in makeup”.

The American Excelsior plant manufacturing starch peanuts that is closest to Oregon is located in Yakima, WA. According to staff there, their product is 92 – 94% wheat starch, 1 – 2% talc, and 4 – 7% a “natural, biodegradable plasticizer made by Dow Chemical”. The actual percentages are adjusted for manufacturing reasons depending on the weather. Although American Excelsior in Yakima uses wheat starch, they say that the different starches (corn, wheat, potato, rice, etc.) are “more or less interchangeable,” and they buy primarily based on price.

Neither National Starch nor American Excelsior was willing to provide additional information about the non-starch components of their product, or the steps (including energy inputs, wastes, emissions etc.) involved in fabricating this product. Franklin Associates was, however, able to estimate energy requirements for fabrication based on the operating specifications for process equipment used in the production of starch loose fill, as described in conversations with starch loose fill producers. Because of the lack of information about the proprietary non-starch components of the loose fill, and because

Franklin Associates only has available data on corn starch, the study makes the simplifying assumption that this packaging material is 100% corn starch by weight.

Molded Pulp Loose Fill

A relatively new product is a flowable loose fill made from molded pulp. Staff from Norm Thompson Outfitters identified UFP Technologies as one company that manufactures a molded pulp loose fill. Marketed under the brand name "Cushion Cubes", UFP's product is a paper-based alternative to other loose fills (such as expanded polystyrene and starch-based).

According to a representative from UFP Technologies, Cushion Cubes are made from 100% postconsumer newspaper and water.

Unbleached Kraft Paper

Some companies purchase rolls of unbleached kraft paper for use as void fill. The paper is torn off in sheets, and then crumpled up to fill void spaces in the box. According to discussions between Pack Edge Development and Longview Fiber, the maximum practical postconsumer content for this type of kraft sheet is 50%. This study models a 0% postconsumer and 50% postconsumer unbleached kraft paper.

Newsprint (Unprinted)

Other companies purchase rolls or sheets of unprinted newsprint for use as void fill. Like the kraft paper (above), the paper is crumpled up to fill void spaces in the box. According to staff at an Oregon newsprint mill, this newsprint is typically off-spec product that is not suitable for printing applications (newspapers). It is typically sold in jumbo rolls to converters who then cut it into sheets or re-roll it into smaller rolls.

As users typically purchase from a converter or a converter's sales representative (wholesaler), and the converter may have purchased paper from multiple mills, it can be difficult for a retailer to specify minimum levels of postconsumer content for this packaging material. Regardless, the study models two different levels of postconsumer content: 10% and 50%. These percentages are considered to be below average and above-average yet still attainable. Franklin Associates' "industry average" model, based on paperboard industry statistics for use of recycled paper (Reference B-4) for newsprint represents 38% postconsumer newspaper and 62% virgin pulp. More detail on newsprint production is provided in Appendix C.

Norm Thompson Outfitters uses sheets of newsprint as dunnage/void fill at both of its order fulfillment centers in Portland, OR and Kearneysville, WV. According to suppliers, the dunnage used in Oregon averages 30% postconsumer content, while the supplier to the West Virginia site states that postconsumer content isn't clear due to the large number of supplying mills, but "should be 20% on average". Similarly, a local (Portland area) supplier of packaging materials (U-Line) interviewed by Pack Edge Development stated that their newsprint dunnage contains 25% postconsumer content.

The State of Oregon surveys Oregon users of newsprint (newspaper publishers) on an annual basis. Combining survey responses from 2000, 2001, and 2002, only 12% of responses (N = 92) were for average postconsumer content higher than 50%. 15% of responses reported average postconsumer content lower than 10%.

Shredded Corrugated

A number of companies sell an on-site shredding machine that produces a void fill material out of “waste” corrugated boxes. This allows order fulfillment centers to reduce their purchase of new materials by utilizing a material that otherwise requires recycling or disposal. Some of these machines produce strips of corrugated that are 1/8” wide and 3 – 12 inches long. The strips can be used to fill void space in outbound boxes. Other machines perforate pieces of corrugated into larger, accordion-like mats that can be rolled around a product similar to bubble wrap. For the purposes of this study, we assume the use of the first type of machine.

The feedstock for these machines are “waste” corrugated received by the distribution center or retailer. Normally, retailers exert little influence over the postconsumer content of packaging used by their product suppliers. As such, the study assumes that the shredded corrugated contains 38% postconsumer content, which is the weighted average postconsumer recycled content for corrugated box components as described in the section on corrugated containers.

Shredded Office Paper

This is office paper that might be generated on-site (for example, in the retailer’s administrative or sales office) and then run through a strip-cut (not cross-cut) office paper shredder. Some companies (generally smaller companies) choose to use this material as a void fill, thus reducing their recycling need while also reducing the purchase of new void fill materials.

The composition of shredded paper will vary depending on the unique circumstances of the office and what types of papers are fed into the shredder. For the purposes of this study, we assume that it is 83.6% printing-writing and 16.4% newspaper (Reference B-7).

Non-Padded Kraft Paper Shipping Bag

This packaging material is akin to a manila envelope, but is made of thicker material and is more strongly reinforced than standard manila envelopes. Several major bag manufacturers offer this type of shipping bag with or without reinforcing filaments. The filaments are typically made of fiberglass or some type of plastic. Pack Edge Development destructed a Pactiv “Tuff Kraft” brand mailer with fiberglass filaments and found that the filaments were less than 2% of the mass of the mailer. Due to the availability of bags both with and without filaments, the low relative weight of the filaments, and budget limitations, the study defines this shipping bag to be an all-kraft product without reinforcing filaments.

DEQ and Pack Edge Development staff reviewed literature or spoke with representatives of two of the largest shipping bag manufacturers: Sealed Air Corporation (product: Jiffy Utility Mailers) and Pactiv (product: Tuff-Kraft). According to a Tharco Distributor Price List, the Jiffy Utility Mailers contain 8% postconsumer content. (A sample stock bag obtained from Sealed Air Corporation confirms this as the bag is printed “8% postconsumer”.) Pactiv’s web site claims that the Tuff-Kraft shipping bag contains 50% postconsumer content, although a representative of Pactiv states that Pactiv is moving away from certifying postconsumer content of its products, because their experience is that higher levels of postconsumer content degrades the tear- and puncture-resistance of the kraft, and also because they outsource their kraft from several suppliers and the postconsumer content will vary. For the sake of this study, we model two different levels of postconsumer content: 0% and 30%.

Non-Padded Polyethylene Shipping Bag

This product is a generic polyethylene non-padded shipping bag. There are a variety of different single- and multi-resin (blend) options for this type of bag.

According to the American Plastics Council “Plastic Film Recovery Guide”, “There are a variety of niche film products where (multiple) resins are combined to yield a film product with enhanced properties for a specific application. Most often, this involves the combination of LDPE and HDPE. In such applications, HDPE contributes strength, while LDPE provides a smooth flexible surface with high printability. Common applications include . . . mailing pouches.” The same document also states: “Linear low-density polyethylene (LLDPE) was developed in 1978. Its production process is less costly than high-pressure processes used to produce standard low-density resins, making it attractive to manufacturers. Additionally, its improved stretch and strength characteristics relative to LDPE have led to an increased market share in a variety of film applications, especially for stretch wrap and bags.”

DEQ and Pack Edge Development staff also attempted to find out the resins used in these types of bags sold by two major suppliers, Sealed Air Corporation and Pactiv, as well as the resins used in the stock bags used by Norm Thompson Outfitters. One of the two suppliers would not divulge their resin information, while the other stated that their all-plastic, non-padded shipping bags contain blends of LDPEs and LLDPEs, but no HDPE. The bag currently used by Norm Thompson Outfitters is an all-LLDPE bag.

Because the burdens of LDPE and LLDPE are similar (see Appendix C), and the manufacturers were unwilling to divulge the exact composition of their products, the study assumes that these shipping bags are 100% LLDPE.

Neither of the manufacturers interviewed by Pack Edge and DEQ indicated that their materials contain recycled content, and their marketing literature was equally silent on this issue. For purposes of the study, we assume that this bag contains 0% postconsumer recycled content, although a 30% postconsumer option is also modeled.

Kraft Paper Shipping Bag with Newsprint Padding

This padded shipping bag consists of an outer surface layer and inner liner made from kraft paper, and an inner layer of padding that is made from macerated newsprint/newspapers. Typically, the outer paper is bleached kraft (goldenrod or some other color) while the inner liner is unbleached kraft (dark brown in color).

DEQ and Pack Edge Development staff reviewed literature or spoke with representatives of two of the largest shipping bag manufacturers: Sealed Air Corporation (product: Jiffy Padded Mailers) and Pactiv (product: Pad-Kraft). A representative of Pactiv stated that postconsumer content degrades the tear- and puncture-resistance of the kraft. Pactiv outsources their kraft from several suppliers, and the postconsumer content will vary. Pactiv has discontinued Green Cross certification of this product, and the company would not release the level of recycled content in the kraft paper. However, the Pactiv representative did state that the filler is “100% postconsumer macerated newspaper”.

Pack Edge Development fully deconstructed a Pactiv #7 Pad-Kraft mailer and found it to be 50.0% newspaper/filling, 24.4% brown kraft inner liner, and 25.6% goldenrod outer liner by weight. On the comparable Sealed Air mailer, Pack Edge was not able to separate the inner and outer liner, but otherwise found comparable results: newspaper/filling was 51.7% and liners (combined) were 48.3%.

According to Tharco’s 9/2/2002 Distributor Price List, the Sealed Air Corporation “Jiffy Padded Mailers” contain 62% postconsumer recycled paper fibers. If the macerated newspaper is similar to Pactiv’s and is made from 100% postconsumer newsprint, then the kraft liner(s) averages about 21% postconsumer content (100% of 52% + 21% of 48% = 62%). Although the proportion of inner to outer liner on the Sealed Air Jiffy Padded Mailer is not known, if it is comparable to the Pactiv product (roughly 50/50) then the 21% postconsumer content for the liner could be achieved through having both liners at 21%, one liner as high as 42% and the second liner at 0%, or something in-between.

For the purpose of analysis, this report evaluates two generic bags:

1. Filler: 100% postconsumer newsprint; outer liner: 30% postconsumer content, bleached kraft; inner liner: 30% postconsumer content unbleached kraft.

2. Filler: 100% postconsumer newsprint; outer liner: 0% postconsumer content, bleached kraft; inner liner: 0% postconsumer content unbleached kraft.

Kraft Paper Shipping Bag with Polyethylene Bubble Padding

This padded shipping bag consists of an outer liner made from kraft paper, and an inner layer of padding that is made from a bubble wrap-like material. Typically, the outer liner is bleached kraft (goldenrod or some other color).

As with other shipping bags, DEQ and Pack Edge Development staff reviewed literature or spoke with representatives of two of the largest shipping bag manufacturers: Sealed Air Corporation (product: Jiffylite R Bubble Gold Kraft Mailers) and Pactiv (product: Air-Kraft).

A representative from Pactiv stated that the bubble used in the Air-Kraft mailer is a proprietary blend that contains LDPE, LLDPE, and nylon. Nylon is added to enhance the barrier properties of the other resins, allowing for "significant" source reduction. While Pactiv would not divulge the exact composition of the bubble material, a representative did state that the nylon represents less than 5% of the material, by weight. Preliminary comparisons by Franklin Associates using composition-weighted averages of the burdens of nylon and polyethylene showed that modeling the bubble material as 5% nylon and 95% PE (50% LDPE/50% LLDPE) would not yield significantly different results than modeling the bubble material as a 50%LDPE/50%LLDPE blend without the nylon, but would increase study costs. As the relative burdens of LDPE and LLDPE are similar to each other (see Appendix C), and the exact composition may vary between suppliers, the study makes the simplifying assumption that the bubble material is 50% LDPE and 50% LLDPE, by weight.

As noted in other package descriptions, Pactiv no longer certifies postconsumer recycled content of its mailers. In contrast, the Tharco 9/2/2002 Distributor Price List states that the Sealed Air Corporation "Jiffylite R Bubble Gold Kraft Mailers" contain 15% postconsumer recycled paper fibers and 15% postconsumer recycled plastic.

For the sake of analysis, this study assumes two different options for postconsumer content:

1. 0% postconsumer content bleached kraft, 0% postconsumer content LDPE/LLDPE blend.

2. 30% postconsumer content bleached kraft, 30% postconsumer content LDPE/LLDPE blend.

Polyethylene Shipping Bag with Polyethylene Bubble Padding

This padded shipping bag consists of an outer liner made from polyethylene, and an inner layer of padding that is made from a bubble wrap-like material.

Consistent with this study's approach with the polyethylene unpadded bag and the kraft/bubble padded bag, the study assumes that the outer liner is 100% LLDPE and that the inner bubble material is a 50% LDPE/50% LLDPE blend. For the sake of simplicity, two recycled-content options are modeled:

1. All materials 0% postconsumer content.

2. All materials 30% postconsumer content.

Weight and Volume of Packaging Materials

Drawing on the weight and volume of the shipped product and the different packaging options defined above, this section describes the methodologies used to define the weight and volume of different packaging materials used to transport the shipped product to the final customer. This description has three parts:

- Weight and volume of the shipping bags.
- Weight and volume of the corrugated box.
- Weight and volume of the void-fill materials.

In determining the box and bag sizes that this average product would be shipped in, DEQ’s goals were to identify sizes that are reasonable, unbiased, and reflect a likely outcome for companies that are shipping a variety of products. The distinction between companies that ship a limited variety of items vs. a larger variety of items is an important one. Companies that sell and ship a small number of products of a uniform size are better able to optimize the sizes of packaging; if there is no or little variability in the size of products sold, then packaging can be chosen that is “just right” in size. However, many companies which sell mail-order goods to residential customers sell not one but many different sizes of products. Customers may order one or more than one product, and so the number of possible permutations is very large. Order fulfillment (packing) staff are typically provided with a selection of box and/or bag sizes to choose from. Greater variety among box and bag sizes provides greater opportunity to use a shipping package that is optimized: just large enough to provide adequate protection to the product, but not overly large. In fact, a whole industry has sprung up in recent years to help distribution and order fulfillment centers optimize the selection of shipping cartons.

In a perfect world, the average product would be shipped in a bag or box that is optimized in volume (is “just right”). This would minimize the cost of packaging materials, reduce the “cube” of the package and associated expenses, and reduce the environmental burdens associated with several stages of the packaging material’s life cycle (“cube” is packaging industry parlance for the effective volume of the package while in shipment). However, most companies that sell a variety of products (typically in combination with each other) are not able to optimize packaging all of the time because doing so would require stocking each packing station with an unrealistically large number of different sizes of bags and/or boxes.

Significant variation exists within companies in this regard. For example, in 2002, the direct-to-customer order fulfillment center for Norm Thompson Outfitters provided each packing station with 15 different sizes of stock boxes. A 2002 study of box utilization at a direct-to-customer order fulfillment center for the larger Williams Sonoma family of companies (which includes Williams Sonoma, Pottery Barn, and Hold Everything) found nine different sizes of stock boxes in use. Also in 2002, seven different sizes of boxes were made available to Pottery Barn retail stores, and six different sizes of boxes were made available to Williams-Sonoma retail stores. Clearly, not all products can be shipped in a box that is sized “just right”. The same is true of stock shipping bags.

For example, when Norm Thompson first began using shipping bags, four different sizes of stock bags were purchased. Over the years, this was reduced to just two different sizes, and at times, only one size is actually kept in stock.

One challenge is to determine the sizes of shipping bags and corrugated box that would be used to ship this “average product” for the purposes of modeling life cycle environmental burdens. For starters, it is assumed that the average product is shipped “flat”, that is, without additional folding. (This reflects standard practice among many clothing retailers, as they don’t want to introduce additional wrinkles or creases into the product. It also reflects reality for shipments of other non-breakable items that are not textiles, such as books, that cannot be folded or rolled.)

For the purposes of this study, it is assumed that the average order fulfillment/ packing station will be stocked with a reasonable selection of stock bags and boxes. It is further assumed that packing staff will, on average, optimize the selection of boxes and bags to provide the “best fit” for the outbound product, given the boxes and/or bags provided for their use.

Weight and Volume of Shipping Bags. U.S. industry standards for stock shipping bags are as follows:

Stock #	Size (when flat)
000	4” x 8”
00	5” x 10”
0	6” x 10”
1	7.25” x 12”
2	8.5”x 12”
3	8.5” x 14.5”
4	9.5” x 14.5”
5	10.5” x 16”
6	12.5” x 19”
7	14.25” x 20”

While some order fulfillment centers might choose to carry all of these sizes of stock bags, inventory management limitations, space limitations at individual packing stations, and higher per-bag prices resulting from spreading bag purchases over a larger variety of sizes, make this scenario unlikely. Given the variety in product sizes that might be shipped, it is reasonable to assume that most order fulfillment centers would stock at least the largest stock size available, and then some variety of smaller sizes.

The “shipped product” defined earlier in this appendix measures 17.5” x 12” x 2.5”, which allows it to lie flat within the largest stock size available (bag #7: interior dimensions of 20” x 14.25”, when flat). The average product will not fit into any of the other stock bag sizes. Therefore, the study assumes that the shipped product will be sent to customers inside a #7 stock bag.

It is worth noting that all of the different bag types included in this study can also be purchased in custom sizes (including larger sizes), and that some companies provide different stock sizes than listed above.

Bag weights used in this study are derived primarily through weighing actual #7 stock bags provided by Sealed Air Corporation and Pactiv. Weighing and destructive analysis of multi-material bags was conducted by Scott Kopacek of Pack Edge Development, on behalf of DEQ.

<u>Kraft Paper Shipping Bag.</u> Pack Edge weighed a Sealed Air #7 “Jiffy Utility Mailer” as 0.168 pounds. A Pactiv #7 “TuffKraft” weighed 0.114 pounds after fiberglass filaments were removed. This study uses a simple average of these two results, or 0.141 pounds per bag.

<u>Polyethylene Shipping Bag.</u> Pack Edge weighed a Sealed Air #7 “Shurtuff Durable Mailer” as 0.058 pounds. A Pactiv #7 “Polylite Mailer” weighed 0.076 pounds. This study uses a simple average of these two results, or 0.067 pounds per bag.

<u>Kraft Paper Shipping Bag with Newsprint Padding.</u> Pack Edge destructed and weighed the components of a Sealed Air #7 “Jiffy Padded Mailer” and a Pactiv #7 “Pad-Kraft Mailer”. The Pactiv mailer was separated into three components: outer liner (0.090 pounds), inner liner (0.086 pounds), and newsprint filler (0.176 pounds). The Sealed Air mailer was only separated into two components: liners (0.194 pounds) and newsprint filler (0.208 pounds).

This study assumes filler of 0.192 pounds per bag, or a simple average of the two weighed bags. We assume that the total weight of the inner and outer liner (combined) is the average of the two bags (0.185 pounds, an average of 0.194 [Sealed Air] and 0.176 [Pactiv]), and that the weight of each liner equals the assumed total weight of the liner multiplied by the percentage weight in the Pactiv product. Thus, the assumed outer liner weighs 0.095 pounds and the assumed inner liner weighs 0.090 pounds per bag.

<u>Kraft Paper Shipping Bag with Polyethylene Bubble Padding.</u> Pack Edge destructed and weighed the components of a Sealed Air #7 “Jiffylite Mailer” and a Pactiv #7 “Air-Kraft Mailer”. The bag modeled in this study is based on an average weight of 0.086 pounds kraft per bag (0.090 for Jiffylite and 0.082 for Air-Kraft) and an average weight of 0.047 pounds of bubble per bag (0.050 for Jiffylite and 0.044 for Air-Kraft).

<u>Polyethylene Shipping Bag with Polyethylene Bubble Padding.</u> Pack Edge weighed a Sealed Air #7 “Jiffy Tuffguard Mailer” (0.160 pounds) and a Pactiv #7 “Armor-Lite Mailer” (0.1056 pounds). This study assumes the bag’s weight is 0.1328 pounds, a simple average of the two weighed bags. Pack Edge attempted to destruct and weigh the components of the two bags but was only able to destruct the Sealed Air bag, where the outer layer was found to be 47.5% of the total weight and the bubble was 52.5% of the total weight. These percentages are applied against the assumed bag weight of 0.1328 pounds, resulting in assumed weights of 0.063 pounds of liner and 0.070 pounds of bubble per bag.

Bag volumes of unpadded bags (when filled with a shipped product) are assumed to be 14.25” x 20” x 2.5” (width and length of the stock bag, thickness of the shipped product). Bag volumes of padded bags are assumed to be 14.25” x 20” x 2.9” due to the extra thickness of the padding.

Weight and Volume of the Corrugated Box. A much larger number of stock box sizes are available than sizes of stock shipping bags. By one estimate, at least 200 different sizes of stock boxes are readily and commercially available in the Pacific Northwest. Despite having all these different sizes (plus custom sizes) to choose from, the average order fulfillment center will not stock its packing stations with this many different sizes of boxes. As noted earlier, in 2002, Norm Thompson’s direct-to-customer order fulfillment center supplied its packing stations with a portfolio of 15 different sizes of stock boxes; a Williams-Sonoma direct-to-customer order fulfillment center used nine different sizes, and Williams-Sonoma and Pottery Barn retail stores were provided six and seven different sizes to choose from, respectively.

This being the case, what size corrugated shipping carton is the average order fulfillment center likely to use to ship the average product that is defined earlier in this appendix? For the purposes of estimating environmental burdens of the life cycle of the corrugated box, this is an important question. The size of shipping carton used not only determines the amount of linerboard and medium used, but also the cube of the box and the amount of void space in the box, which in turn impacts the amount of void-fill material (loose-fill “peanuts”, crinkled newsprint, shredded paper, etc.).

The method of box selection used in this study uses a combination of two approaches: first, a review of one retail mail-order company’s actual portfolio of boxes, and second, a review of average void spaces in corrugated boxes among several order fulfillment operations.

The portfolio of box sizes used by Norm Thompson Outfitters forms the basis of the first element of this selection process. Norm Thompson Outfitters is the largest of the Oregon-based companies working with DEQ on packaging waste reduction and also is the company that provided that data used to define the dimensions of the average unit product being shipped. The choice to use an actual portfolio of box sizes from an actual company, rather than defining our own portfolio of “likely box sizes” removes a potential element of bias from the process of box selection.

All 15 of the stock boxes currently used by Norm Thompson at its order fulfillment center were reviewed against the dimensions of the average unit product. Of the 15 boxes in stock, six of the boxes are too small to allow the product to be placed in the box without additional folding. Of the remaining nine box sizes, four are most likely to be selected by packing staff when deciding which box to use to ship this unit product, based on their size and how packing staff might select boxes based on the principle of “best fit” (assumed above). These four box sizes are also the most commonly used of the nine available boxes, collectively representing 82% of the projected number of boxes actually used by Norm Thompson in FY 2003 from among the nine possible boxes.

These four boxes are shown in Table B-2. A packer might select Box #07 because it allows for the product to fit into the box while minimizing void volume. However, there would only be a ½” vertical gap (head space) between the top of the product and the top of the box. Box #26 or Box #08 might be selected if the packer wanted to increase the headspace; the product would barely fit length-wise into Box #26. Finally, Box #18 would get chosen by a packer who wanted to minimize the box’s footprint (length times width), although due to its height, this box has the greatest total volume. The other five boxes (not shown) all have significantly larger footprints and/or volumes.

Table B-2.
Possible “Best Fitting” Box Sizes at Norm Thompson Outfitters.

Box #	Interior Length	Interior Width	Interior Height	Total Volume	Product Volume	Void Volume	% Void Volume
#07	21.25”	17.25”	3”	1,100 in^3	530 in^3	570 in^3	52%
#26	17.5”	15”	5.75”	1,510 in^3	530 in^3	980 in^3	65%
#08	22.5”	16.75”	5.25”	1,979 in^3	530 in^3	1,449 in^3	73%
#18	17.75”	13.75”	11.5”	2,807 in^3	530 in^3	2,277 in^3	81%
Unit Product	17.5”	12”	2.5”		530 in^3		

For reference, it is useful to know the average percentage of box cube which is empty space (void) for companies doing order fulfillment in corrugated boxes. We define this as “% Void Space” (also called “% Void Volume” in Table B-2). For example, if a box has interior dimensions of 10” x 10” x 10”, its total volume would be 1,000 in^3. If the box is used to ship a product 250 in^3 in volume, then the remaining 750 in^3 of the box would be empty space, or void, resulting in a % void space of 75%.

DEQ has not been able to obtain data for average percentage void space for companies shipping non-breakable soft goods in corrugated boxes. However, DEQ does have limited data sets for two companies shipping a combination of hard and soft goods in corrugated boxes.

The first company, Williams-Sonoma, is also working with DEQ on packaging waste reduction. While most Williams-Sonoma direct-to-customer shipments originate from an order fulfillment center in the Memphis area, retail stores also conduct a limited amount of direct-to-customer shipments in corrugated boxes. DEQ staff conducted an assessment of outbound packaging (including void space) at the Portland Williams-Sonoma store in October 2002. Sixteen actual orders had been packed into shipping cartons by store associates, who were instructed to pack boxes as normal, but not to seal the boxes with tape. After all 16 orders were packed, DEQ staff then measured the interior dimensions of these shipping cartons and measured (or estimated) the volume of the products being shipped.

Of the 16 boxes, all but one had been "scored" in order to reduce the height of the box as shipped. Scoring boxes involves cutting down the four vertical seams of a box, then folding the top (cut) portions of the box sides into the box, as if the box's top flaps had been extended. The advantage of scoring boxes is that it reduces the need for void fill. (In fact, on this day, scoring of boxes reduced the amount of void fill used by 40%.) DEQ measured both the height of boxes scored and the height had the boxes not been scored. Anecdotally, even when opportunities exist to reduce box void by scoring, more boxes used for direct-to-customer shipments appear to be unscored, rather than scored.

The average % void space for the 16 boxes as shipped (scored volumes) was 65%, with a standard deviation of 17%. Had none of the boxes been scored, the average % void space would have been 74%, with a standard deviation of 16%. (These are simple averages that do not take into account differences in box sizes.)

The second company for which DEQ has data on void space is the Portland order fulfillment center for an office products company that sells office products to State agencies as well as many of the local governments that DEQ works with on waste reduction. In a related effort, DEQ and the City of Beaverton, OR, conducted a study in 2002 in which inbound boxes received from this company were evaluated for void space. The DEQ/Beaverton study only looked at boxes that contained "repacked" items that had been packed through an order-fulfillment process. Product boxes with their original product in place (such as a case of paper containing 10 reams of paper) were not evaluated. Over a two-month period starting in May, staff measured the product and box dimensions of 59 boxes (50 received at Beaverton) packed at this company's Portland order fulfillment center. The average % void space for these boxes was 57%, with a standard deviation of 30%.

For reference, it is worth noting that both FedEx and United Parcel Service recommend, when shipping items in a corrugated shipping box, to provide for at least two inches of void space between the product and each side of the shipping box. Greater void spaces are encouraged for fragile items. Were this study's average unit product shipped in a box that met this minimum guidance, the 17.5" x 12" x 2.5" product would be packed into a box with interior dimensions of 21.5" x 16" x 6.5", and the % void space would be 76%.

Only a limited amount of void space data were available for this study. The average void percentages observed for boxed items originating at the office supply company's and Williams-Sonoma's Portland locations were 57% and 65%, respectively. Had Williams-Sonoma not scored its boxes, the void percentage there would have been 74%. Were this study's average unit product packed following minimal UPS and FedEx guidance, the void percentage would be 76%.

Interestingly, this range of real-life data (57% - 74%) is neatly overlapped by the range of possible void percentages contained in Table B-2 (52% - 81%). Of the four boxes shown in Table B-2, which one is most likely to be used? It is reasonable to assume that, on average, breakable items will be shipped with greater cushioning, and thus greater void space, than soft goods. Conversely, non-breakable items (the subject of this study) will be shipped on average with less cushioning, and thus less void space, than hard goods. Box #07, with a void percentage of 52%, is the only box for which: a) the average unit product can be placed in the box without being further folded; and b) the box results in a void percentage lower than that observed for hard goods and mixed soft & hard goods shipments from DEQ's limited data set. In theory, an even smaller box (resulting in less void space) might be used, but this would require using a different list of available stock boxes, and no such list is available to DEQ at this time. Now that the dimensions of the average unit product are known, introducing a different list of stock boxes would potentially introduce bias into the study. Further, since the dimensions of the average unit product were derived using data from Norm Thompson, it seems appropriate to use the same company's portfolio of stock boxes for determining the box size. Therefore, this study assumes that the corrugated box used to ship the average unit product will have the same interior dimensions as Norm Thompson's stock box #07: 21.25" x 17.25" x 3".

According to Pack Edge Development, a box of this size constructed from 200# B-Flute, or an equivalent ECT corrugated paperboard will have exterior dimensions of 21.5" x 17.5" x 3.5" and will weigh 1.39 pounds. (The carton contains 11.37 square feet of corrugated at 122 pounds per 1,000 square feet.)

Weight and Volume of Void Fill Materials. The volume of void fill materials used per unit shipment is roughly equal to (or slightly less than) the void space of the average box with the shipped product inside it. Some retail companies add other items into the box, such as a receipt, catalog, or other materials; rather than modeling or accounting for these types of materials, this study assumes that the box contains only the shipped product and void fill.

Pack Edge Development conducted a void fill study in order to estimate the average amount of void fill material that would be used to ship each package configuration. A "mock product" was created out of a medium density polyurethane foam cut to the unit product dimensions of 17.5" x 12" x 2.5". A "mock carton" with the interior dimensions of 21.25" x 17.25" x 3" was fabricated from 200#, B-flute corrugated fiberboard.

Samples of each void fill material were obtained either directly from the manufacturer or through an authorized local distributor. In either case no reference to this study was made in order to obtain average general inventory samples. It should be noted that there were variations in inflated polyethylene air packets obtained from differing vendors, both in size and inflation level. Several vendors' systems allow for inflation levels to be set by the user. For the purposes of this study we assume that the inflation levels for the samples provided represent what the manufacturer considers to be an average level.

In order to minimize error in the study, data was recorded using five different packers. Each packer completed the study at the same loading center while following the same verbal instructions. Packers were told to load the "mock product" into the "mock carton" and use enough dunnage material to void fill the package so the product would be held in position for shipment. They were told that the added dunnage did not need to cushion the product, but only to hold the product in its relative position. After each packaging configuration was loaded the dunnage was removed, weighed, and recorded.

Results of this study are shown in Table B-3. For all void fill materials except for the inflated polyethylene air packets, the simple average of the five packers is what this study uses as the assumed weight of void fill used per package. For the inflated polyethylene air packets, where two different brands of 8" x 4" packets were provided, the study assumes a simple average of the results for both brands. One brand of 8" x 8" air packets were also evaluated but are not included in the study due to anecdotal observations by study team members that the 8" x 4" packets appear to be more commonly used.

The weights and postconsumer recycled contents of all packaging options analyzed for the defined soft goods shipment are summarized in Table B-4.

Table B-3.
Results of Void Fill Study (Pack Edge Development)

	Loader #1	Loader #2	Loader #3	Loader #4	Loader #5	**Average**	**Standard Deviation**
Cushion Cubes (Molded Pulp)	0.352	0.420	0.382	0.364	0.378	**0.379**	**0.026**
Kraft Paper: 24" x 18", 50#	0.200	0.160	0.158	0.200	0.202	**0.184**	**0.023**
	(5 Sheets)	(4 Sheets)	(4 Sheets)	(5 Sheets)	(5 Sheets)		
Inflated PE Packs: Pactiv (8"x4")	0.090	0.090	0.114	0.086	0.090	**0.094**	**0.011**
	(15 Packs)	(15 Packs)	(19 Packs)	(15 Packs)	(15 Packs)	**(15.8 Packs)**	
Inflated PE Packs: Storopak (8"x4")	0.068	0.070	0.094	0.068	0.072	**0.074**	**0.011**
	(11 Packs)	(11 Packs)	(15 Packs)	(11 Packs)	(11 Packs)	**(11.8 Packs)**	
Average, Pactiv/Storopack (8" x 4")						**0.084**	
Pillow Pack: Storopak (8"x8")	0.040	0.052	0.054	0.052	0.047	**0.049**	**0.006**
	(4 Packs)	(5 Packs)	(5 Packs)	(5 Packs)	(5 Packs)	**(4.8 Packs)**	
EPS Peanuts	0.044	0.042	0.050	0.052	0.050	**0.048**	**0.004**
Cornstarch Peanuts	0.078	0.084	0.094	0.094	0.082	**0.086**	**0.007**
Newsprint (25" x 22.5")	0.118	0.120	0.200	0.204	0.197	**0.168**	**0.045**
	(3 Sheets)	(3 Sheets)	(3 Sheets)	(5 Sheets)	(5 Sheets)		
Loose Fill Shredded OCC	0.284	0.310	0.448	0.234	0.315	**0.318**	**0.079**
Loose Fill Shredded Office Paper	0.132	0.150	0.174	0.140	0.142	**0.148**	**0.016**

All results are pounds of packaging material.
Unit Product: 17.5" x 12" x 2.5"
Unit Product Weight: 1.28 pounds
Shipping Carton: 21.25" x 17.25" x 3"

Table B-4

DEFINITION OF PACKAGING OPTIONS

		Postconsumer Recycled Content	Pounds/ Package	Thou Lb/ 10,000 Packages
CORRUGATED BOX				
Option 1	industry average linerboard	28%	0.95	9.49
	industry average medium	59%	0.44	4.41
	overall box	38%	1.39	13.90
Option 2	recycled linerboard	71%	0.95	9.49
	recycled medium	100%	0.44	4.41
	overall box	80%	1.39	13.90
DUNNAGE (used with corrugated box)				
Inflated Polyethylene Air Packets				
Option 1	LDPE	0%	0.084	0.84
Option 2	LDPE	30%	0.084	0.84
Polystyrene Foam Loose Fill				
Option 1	EPS	0%	0.048	0.48
Option 2	EPS	30%	0.048	0.48
Starch-based Loose Fill				
	cornstarch	0%	0.086	0.86
Molded Pulp Loose Fill				
	newspaper	100% (1)	0.38	3.79
Kraft Paper (Crumpled)				
Option 1	unbleached kraft	0%	0.18	1.84
Option 2	unbleached kraft	50%	0.18	1.84
Newsprint (Crumpled)				
Option 1	newsprint	10%	0.17	1.68
Option 2	newsprint	50%	0.17	1.68
Shredded Postconsumer Paper(board)				
Option 1	corrugated	100% (1)	0.32	3.18
Option 2	office paper (2)	100% (1)	0.15	1.48

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(1) 100% postconsumer material; postconsumer content of postconsumer material may be less than 100%.

(2) 83.6% printing-writing, 16.4% newspaper

Table B-4 (cont.)

DEFINITION OF PACKAGING OPTIONS

SHIPPING BAGS		Postconsumer Recycled Content	Pounds/ Package	Thou Lb/ 10,000 Packages
Unlined Kraft				
Option 1	bleached kraft	0%	0.14	1.41
Option 2	bleached kraft	30%	0.14	1.41
Kraft with Paper Padding				
Option 1	bleached kraft outer	0%	0.10	0.95
	unbleached kraft inner	0%	0.090	0.90
	shredded newspaper pad	100% (1)	0.19	1.92
			0.38	3.77
Option 2	bleached kraft outer	30%	0.10	0.95
	unbleached kraft inner	30%	0.090	0.90
	shredded newspaper pad	100% (1)	0.19	1.92
			0.38	3.77
Kraft with Bubble Wrap				
Option 1	bleached kraft bag	0%	0.086	0.86
	LDPE film (50% of bubble)	0%	0.024	0.24
	LLDPE film (50% of bubble)	0%	0.024	0.24
			0.13	1.33
Option 2	bleached kraft bag	30%	0.086	0.86
	LDPE film (50% of bubble)	30%	0.024	0.24
	LLDPE film (50% of bubble)	30%	0.024	0.24
			0.13	1.33
Unlined Film Bag				
Option 1	LLDPE	0%	0.067	0.67
Option 2	LLDPE	30%	0.067	0.67
Film Bag with Bubble Wrap				
Option 1	LLDPE bag	0%	0.063	0.63
	LDPE film (50% of bubble)	0%	0.035	0.35
	LLDPE film (50% of bubble)	0%	0.035	0.35
			0.13	1.33
Option 2	LLDPE bag	30%	0.063	0.63
	LDPE film (50% of bubble)	30%	0.035	0.35
	LLDPE film (50% of bubble)	30%	0.035	0.35
			0.13	1.33

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(1) 100% postconsumer material; postconsumer content of postconsumer material may be less than 100%.

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B-4 "Capacity and Fiber Consumption: Paper, Paperboard, Pulp" 42nd Annual Survey 2000-2004 American Forest & Paper Association, December 2001 Page 24 Recovered Paper Consumed in Paper and Paperboard Manufacture.

B-5 "2001 Annual Statistical Summary Recovered Paper Utilization" Fifteenth Edition Paper Recycling Group, American Forest & Paper Association, April 2001. Page 85.

B-6 Fibre Box Association "Annual Report 2001" Table "Consumption By Corrugator Plants" Table "Containerboard Production and Consumption".

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APPENDIX C

MANUFACTURE OF PACKAGING FOR MAIL-ORDER SOFT GOODS

INTRODUCTION

The energy requirements, raw material requirements, and environmental emissions for the major processes in the manufacture of alternative packaging configurations for mail-order soft goods are presented in this appendix. The analysis begins with raw materials extraction and proceeds through the manufacture of the packaging materials. The tables in this appendix present aggregated data for all steps from raw material extraction through fabrication of packaging material. For shipping bag materials, the tables also include transportation of component materials to the bag manufacturer. Transportation of packaging materials to the order fulfillment center is described in Appendix D.

The steps in the production of the following packaging materials are described in the Material Production section of this appendix:

- Polyethylene Resin
  - Virgin LDPE Resin Production
  - Virgin LLDPE Resin Production
  - Postconsumer Polyethylene Resin Production
- EPS Resin
  - Virgin EPS Resin Production
  - Postconsumer EPS Resin Production
- Cornstarch
- Bleached Kraft Paper (Virgin)
- Unbleached Kraft Paper (Virgin)
- Postconsumer Recycled Paper Production
- Newsprint Production
  - Virgin Newsprint Production
  - Recycled Newsprint Production
- Corrugated Paperboard
  - Kraft Linerboard Production
  - Semichemical Medium Production
  - Recycled Linerboard and Medium Production

Manufacture of the following packaging components are described in the Product Fabrication section of this appendix:

- Polyethylene Film Fabrication
- Polyethylene Inflatable Air Pack Fabrication
- EPS Foam Product Fabrication
- Cornstarch Foam Fabrication

- Molded Pulp Cushion Cubes Fabrication
- Corrugated Box Fabrication
- OCC Shredding
- Paper Shredding

MATERIAL PRODUCTION

This section discusses the processes for manufacturing materials commonly used in mail-order soft packaging. These materials include polyethylene resins, expandable polystyrene (EPS), cornstarch, bleached and unbleached kraft paper, newsprint, and corrugated paperboard. The collection of postconsumer materials is also discussed in this section.

Polyethylene Resin

Polyethylene film is used for manufacturing inflatable air packs, bubble wrap, and shipping bags. Low-density polyethylene (LDPE) is used in the manufacture of bag film linings, bubble wrap, and inflatable air packs. Linear low-density polyethylene (LLDPE) is used in the manufacture of bags, bag film linings, and bubble wrap. The production of polyethylene film includes the following steps:

- Crude Oil Production
- Crude Oil Processing (Desalting, Distillation, and Hydrotreating)
- Natural Gas Production
- Natural Gas Processing
- Ethylene Production
- Virgin LDPE Resin Production
- Virgin LLDPE Resin Production
- Postconsumer Polyethylene Resin Collection and Recycling

Figure C-1 shows the material flows and steps in the production of polyethylene film. These steps are discussed below.

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

The American Petroleum Institute identifies three categories of oil extraction wastes: produced water, drilling waste, and associated waste.

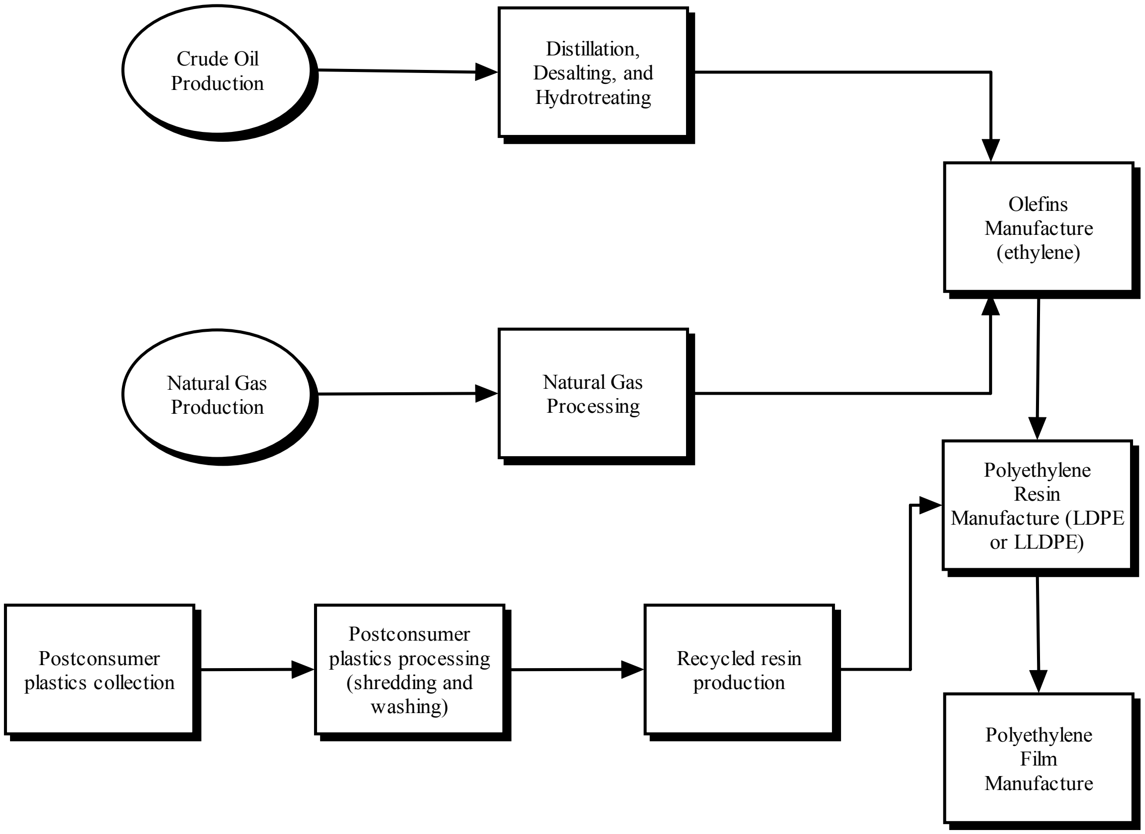

Figure C-1. Flow diagram for the manufacture of polyethylene film.

The water that is extracted with crude oil is called the "oil field brine". The brine goes through a separator at or near the wellhead in order to remove the oil from the water. According to the American Petroleum Institute (API), it is estimated that 17.9 billion barrels of brine water were produced from crude oil production in 1995. This quantity of water equates to a ratio of 3.3 barrels of water for each barrel of oil. The majority of this water (85 percent) is injected into separate wells specifically designed to accept production-related waters. This represents all waters produced by onshore oil production facilities, which are not permitted to discharge "oil field brine" to surface waters (Reference A-29). The remainder of the produced water is from offshore oil production facilities and is assumed to be discharged to the ocean. Therefore, the waterborne wastes represent the brine wastes present in this 15 percent of brine water (Reference A-50). Because crude oil is frequently produced along with natural gas, a portion of the waterborne waste is allocated to natural gas production (Reference A-20).

The second type of oil extraction waste is drilling waste. Drilling waste includes the rock cuttings and fluids produced from drilling a wellbore. Drilling mud, a viscous fluid, is a particular kind of drilling fluid that is commonly used for drilling wellbores.

The third source of waste is associated waste, which is a broad category of small volume wastes. Associated wastes include atmospheric emissions, which are primarily hydrocarbons. These atmospheric emissions originate from the natural gas produced from combination wells and result in line losses and unflared venting.

The transportation data are based on a mix of foreign and domestically produced crude oil. According to the **Petroleum Supply Annual, June 1994,** 49 percent of the crude oil used in the United States is imported.

Crude Oil Processing (Desalting, Distillation, and Hydrotreating). A petroleum refinery is a complex combination of processes that serve to separate and physically and chemically transform the mixture of hydrocarbons found in crude oil into a number of products. Modern refineries are able to vary the different processing steps through which a charge of crude oil passes in order to maximize the output of higher value products. This variation of processing steps can change according to the make-up of the crude oil as well as the economic value of the products. Because of this variation, it is necessary to make certain assumptions about the refinery steps to which crude oil is subjected in order to produce petrochemical feedstocks.

For this analysis, it is assumed that crude oil used to produce feedstocks for olefins production goes through the following refinery operations: desalting, atmospheric and vacuum distillation, and hydrotreating. Due to a lack of facility-specific data, literature sources were used to estimate the energy requirements for these refining steps. A number of literature references were used, most of which showed similar energy inputs (References C-13 through C-17).

Crude desalting is the water-washing of crude oil to remove water-soluble minerals and entrained solids (Reference C-18). For this analysis it is assumed that all of the crude that enters a refinery passes through the desalting step (References C-16 and C-18).

Crude oil distillation separates the desalted crude oil into fractions with differing boiling ranges. Atmospheric distillation is used to separate the fractions with a boiling point less than 650° Fahrenheit (References C-16, C-17, and C-18). At temperatures greater than 650° Fahrenheit thermal cracking of the hydrocarbons starts. Fuel gas or still gas that is liberated from the crude during distillation is further processed into liquefied petroleum gas or natural gas, depending on the carbon chain length. This gas is sold or used in the refinery to generate heat. About 52 percent of the non-electrical energy used in a refinery for direct heating or steam production comes from fuel gas (Reference C-19). Coproduct credit is given on a mass basis for the gas fractions not used for energy in the refinery. Fuel gas or still gas used as an energy source in refining is assumed to have the same composition as natural gas and is shown as process energy, not as raw material.

The residue from the atmospheric distillation unit passes to a vacuum distillation unit where separation of the various fractions can be accomplished at lower temperatures than would be required at atmospheric pressure. The residue or bottoms of the vacuum distillation unit is a valuable coproduct that is further processed to make usable products. Coproduct credit is given on a weight basis for this residue. It is assumed that all of the crude used to produce olefins feedstock passes through atmospheric distillation, while only 46 percent of the initial crude oil charge passes through vacuum distillation (References C-13, C-14, and C-18).

Hydrotreating is a catalytic hydrogenation process that reduces the concentration of sulfur, nitrogen, oxygen, metals, and other contaminants in a hydrocarbon feed. These contaminants can poison or foul catalysts used in catalytic crackers and contribute to air emissions if the hydrocarbon is used as a fuel. It is assumed that all of the feedstock for olefin cracking passes through hydrotreatment. Sulfur and metals removed from crude are separated and sold as coproducts (References C-13 and C-16). Coproduct credit is given for these materials on a mass basis.

Energy requirements for petroleum refineries are usually listed in literature sources as Btu of fuel, pounds of steam, and electricity per 42-gallon barrel of crude processed. For this analysis, a conversion of 3.385 barrels of crude per 1,000 pounds was used. Steam inputs were converted to Btu requirements using a conversion of 1,200 Btu per pound. Btu inputs for steam were added to the Btu inputs listed as fuels, and the total was converted to quantities of fuels using the combustion energy values listed in Appendix A and the following refinery fuel mix: residual oil and residues (coke), 22 percent; purchased natural gas, 24 percent; LPG, 2 percent; and fuel gas or still gas, 52 percent (Reference C-20). Negligible quantities of coal and distillate oil are also used in the “average” refinery.

Desalting, distillation (atmospheric and vacuum), and hydrotreating of crude oil consume the majority of energy required for the refining of petroleum fuels. Still gas, an energy source produced in refineries as a byproduct, is included in the natural gas process energy category in this analysis. Raw material inputs are calculated from the average loss due to atmospheric, waterborne, and solid waste emissions per unit of processed crude oil (Reference C-20). The data in this analysis are representative of petroleum refineries in 1992.

Refined oil products such as ethane, propane, and other linear (paraffinic) and aromatic hydrocarbons used in the production of packaging materials undergo further processing at the refinery (into materials such as ethylene, propylene, butylenes, butadiene, benzene, toluene, and xylenes), so no transportation is necessary between petroleum refining and the production of feedstock petroleum products.

Natural Gas Production. Natural gas is extracted from deep underground wells and is frequently co-produced with crude oil. Because of its gaseous nature, it flows quite freely from wells which produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. Atmospheric emissions from natural gas production are primarily due to line or transmission losses and unflared venting. The waterborne waste pertains to the portion of natural gas that is produced in combination with oil. These combination wells account for approximately 25 percent of all natural gas production. Natural gas is typically processed at or very near the extraction site, so transportation is not required between natural gas extraction and processing.

Natural Gas Processing. Light straight-chain hydrocarbons are normal products of a natural gas liquids processing plant. The plants typically use compression, refrigeration and oil adsorption to extract these products. Heavy hydrocarbons are removed first. The remaining components are extracted and kept under controlled conditions until transported in high-pressure pipelines, insulated rail cars or barges.

If the natural gas has a hydrogen sulfide content of greater than 0.25 grain per 100 standard cubic feet, it is considered "sour." Before it can be used, the gas must undergo removal of the hydrogen sulfide by adsorption in an amine solution, a process known as "sweetening."

The primary pollutants from the natural gas stream are volatile hydrocarbons that leak into the atmosphere. Additional sources of pollutants are natural gas-fired compressor engines. Emissions will also result from the gas sweetening plants if the acid waste gas from the amine process is flared or incinerated. When flaring or incineration is practiced, sulfur dioxide is the major pollutant of concern.

Ethylene Production. The primary process used for manufacturing olefins (ethylene and propylene) is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils. Cracking converts heavier gas oils into more valuable products by breaking down the complex molecule chains which make up the heavier hydrocarbon compounds into simpler, lighter ones. Currently the feedstocks for the production of propylene, ethylene, and other olefins in the United States are approximately 75 percent ethane/propane and 25 percent naphtha.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high-pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

When ethane is the principal feedstock, the final production distribution shows approximately 80 percent ethylene and 20 percent other coproducts. For propane and naphtha feeds, ethylene production represents only 45 percent and 35 percent of the total reaction products, respectively. Therefore, with the present feedstock mix (75 percent ethane/propane, 25 percent heavier fuels), ethylene represents about 60 percent of the total reaction products (assuming the light feed represents 68 percent ethane and 32 percent propane, and assuming the heavier feed to be all naphtha).

Virgin LDPE Resin Production. LDPE is used for the manufacture of inflated air packets and bubble wrap padding. Low-density polyethylene (LDPE) is produced by the polymerization of ethylene in high-pressure reactors (above 3,000 psi). The two reactor types used are autoclaves and tubular reactors. Generally, tubular reactors operate at a higher average ethylene conversion than autoclave reactors. The polymerization mechanism is either free-radical, using peroxide initiators, or ionic polymerization, using Ziegler catalyst.

Reactor effluent consists of unreacted ethylene and polymer. The pressure of the effluent mixture is reduced and the ethylene is purified and recycled back to the reactor. The polyethylene is fed to an extruder and pelletized.

Virgin LLDPE Resin Production. Linear low-density polyethylene (LLDPE) is used for the manufacture of shipping bags and bubble wrap padding. LLDPE is produced through the polymerization of ethylene. Polyethylene is most commonly manufactured by either a slurry process or a gas phase process. Ethylene and small amounts of comonomers are continuously fed with a catalyst into a reactor.

In the slurry process, ethylene and comonomers come into contact with the catalyst, which is suspended in a diluent. Particulates of polyethylene are then formed. After the diluent is removed, the reactor fluff is dried and pelletized (Reference C-28).

In the gas phase process, a transition metal catalyst is introduced into a reactor containing ethylene gas, comonomer, and a molecular control agent. The ethylene and comonomer react to produce a polyethylene powder. The ethylene gas is separated from the powder, which is then pelletized (Reference C-28).

Franklin Associates has a limited number of industry data sets for the production of plastic resins. Because there were not enough LLDPE data sets to combine to protect the confidentiality of the data in an aggregated LLDPE data set, energy and emissions data for producing 1,000 pounds of LLDPE resin were estimated based on proprietary data sets for the production of LLDPE and HDPE (which, like LLDPE, is produced by low pressure gas phase or slurry polymerization), as well as a published data source (Reference C-120).

Postconsumer Polyethylene Resin Production. For this analysis, postconsumer polyethylene products are assumed to be collected by curbside collection techniques using single unit diesel trucks. In the United States, curbside collection of plastics is performed in one of four material mixes: single resins (such as HDPE milk jugs) collected separately; mixed resins (such as HDPE and PET bottles) collected together; an “all containers” mix (such as plastic bottles, glass bottles, and aluminum and steel cans mixed together); and a “single stream” mix (where all recyclables, including containers and fibers, are collected together, although some “single stream” programs continue to collect glass separately). How the plastics are collected, and whether they are compacted on-route, impacts the quantity of fuel used during collection, and it also impacts the amount of energy required to process and sort mixed recyclables after they have been collected. Generally speaking, mixing or commingling of materials on-route reduces collection energy requirements and increases processing energy requirements.

The trend in the United States is a move away from source separation and towards partial commingling and "single stream" collections. Modeling the energy requirements for collection and post-collection processing of each of these approaches is outside of the scope of this study and a simplifying assumption is made that the plastics are kept separate from other curbside recyclables during collection and thus require no intermediate processing to sort them from glass, metal, paper, etc. Although this assumption leads to an underestimation of processing (sorting) energy requirements, this will be offset by an overestimation of collection energy requirements. Relative to the energy required to produce virgin polyethylene resin, the differences in total energy requirements for different post-consumer collection and processing approaches will be small.

Using this approach, curbside collection is assumed to use approximately three gallons of diesel per 1,000 pounds of recyclables that are collected and transported to a processing facility (Reference C-124).

Collected plastics are assumed to be baled without further sorting. Baling is done using a double ram horizontal baler that produces a 30-inch by 44-inch by 46-inch bale (References C-109 and C-115). Bales of postconsumer plastics have an average density of 25 pounds per cubic foot (Reference C-116). The baler uses a 100 horsepower motor and has a throughput of five tons per hour (Reference C-116). An LPG-fueled front-end loader is used to move the material from the collection truck unloading area to the baler.

Once baled, the plastics are transported to a facility where they are granulated, washed, and palletized. The postconsumer plastic is received at the plant, typically in bales of recyclable plastic. The bales are sent through a debaler and then sorted if they contain mixed plastics. Sorting may be done by hand, mechanically, or through a combination of manual and mechanical means. The selected plastics are then sent by conveyor belt to a granulator. The granulated plastic flakes are blown into a washer. They are washed in water of approximately 200 degrees Fahrenheit and then spun dry. The flakes must be completely dry before going into the extruder; therefore, they may be stored to dry for an extended period of time (Reference C-109).

The dried plastic flakes are then sent through an extruder. In the extrusion process, the granules of plastic are fed into a hopper, which feeds into the heated barrel of the extruder. In this barrel, the screw rotates and sends the resin to a melt reservoir. When a sufficient amount of resin is in the reservoir, the screw pushes the plastic through an exit port. The resin is then immersed in a water-filled cooling tank. It is air dried and enters the pelletizer, which cuts the rod of dried resin into small pellets (Reference C-117). The final pellets are packed and sent to plastic product manufacturers.

Energy data for mechanical recycling of plastics is based on a survey of six different recycling plants from across the United States. As very few of the plants could tell how many kilowatt-hours of electricity they use, a survey of motor sizes for each piece of machinery and their throughput was taken. From the motor sizes, an efficiency for each size motor was found (References C-118 and C-119). The motors were assumed to be a 3-phase, 60 Hz, 1750 RPM, wound-rotor type. No energy data are included for mechanical sorting of debaled mixed plastics.

EPS Resin

Expandable polystyrene (EPS) is used in the production of foam packaging products, including loose fill. The production of virgin and recycled EPS are discussed below.

Virgin EPS Resin Production. Foam loose fill, used to fill the void space in packages, is made of expandable polystyrene (EPS). The steps of EPS manufacture are as follows:

- Crude Oil Production
- Crude Oil Processing (Desalting, Distillation, and Hydrotreating)
- Natural Gas Production
- Natural Gas Processing
- Ethylene Production
- Mixed Xylenes Production
- Benzene Production
- Styrene Production
- Blowing Agent Production
- Expandable Polystyrene (EPS) Resin Production

The material flows and steps in EPS production are shown in Figure C-2. Crude oil production, crude oil processing, natural gas production, natural gas processing, and ethylene production are discussed previously in this appendix and are not repeated here. The remaining steps of EPS production (mixed xylenes production, benzene production, styrene production, blowing agent production, and EPS production) are discussed below.

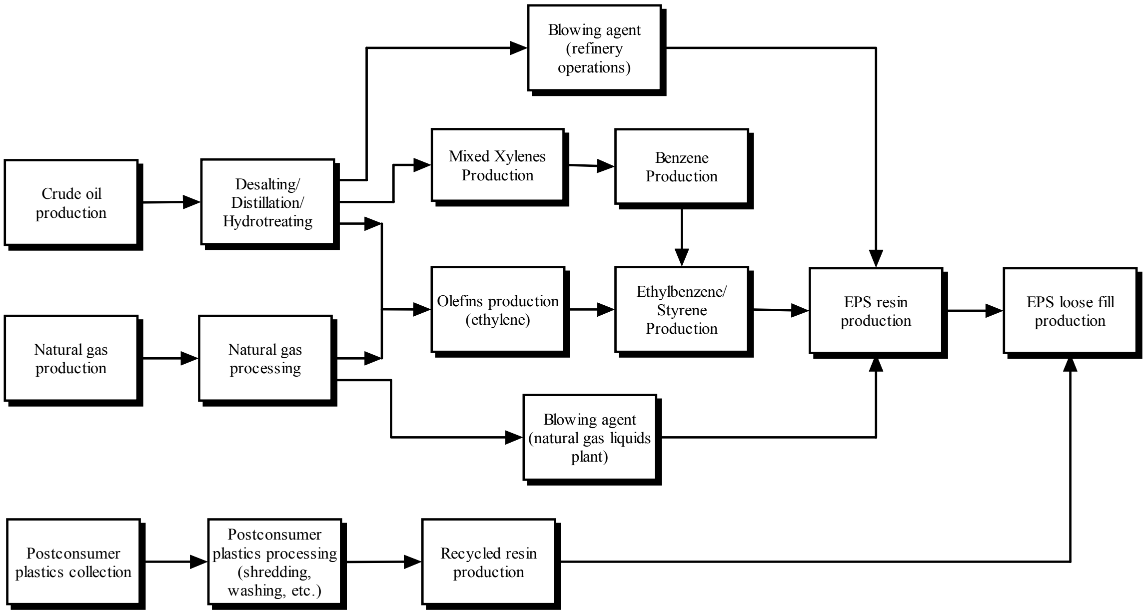

Figure C-2: Flow diagram for the production of EPS loose fill production.

Mixed Xylenes. Reforming processes are used at the refinery to convert paraffinic hydrocarbon streams into aromatic compounds such as benzene, toluene, and xylene. Catalytic reforming has virtually replaced thermal reforming operations. Catalytic reforming has many advantages over thermal reforming including the following:

1. Greater production of aromatics.
2. More olefin isomerization.
3. More selective reforming and fewer end products.
4. Operated at a low pressure, hence comparatively lower cost.

Catalysts such as platinum, alumina, or silica-alumina and chromium on alumina are used (Reference C-17).

Benzene Production. Benzene is naturally produced from crude oil as it is distilled in the refinery process. Also, a large portion of benzene is produced by the catalytic reforming of light petroleum distillate. In the reforming process, refined crude oil is fed through a catalyst bed at elevated temperatures and pressures. The most common type of reforming process is platforming, in which a platinum-containing catalyst is used. Products obtained from the platforming process include aromatic compounds (benzene, toluene, xylene), hydrogen, light gas, and liquefied petroleum gas. The aromatics content of the reformate varies and is normally less than 45 percent (References C-21 and C-22).

The reformate from the platforming process undergoes solvent extraction and fractional distillation to produce pure benzene, toluene, and other coproducts. Additional benzene is often produced by the dealkylation of the toluene.

Styrene Production. The production of styrene monomer is accomplished through a series of processes. The first is the production of ethylbenzene by the alkylation of benzene with ethylene. In this process, benzene initially passes through a drying column. From the drying column, the benzene and ethylene are mixed in a reactor with a suitable catalyst. This reaction is exothermic and occurs at relatively low pressures and temperatures. Unreacted benzene is removed and recycled back to the process. The ethylbenzene is then separated from the solution. The heavy bottoms, tars, and vent gases are burned while the solution is recycled back to the reactor.

Styrene is produced by dehydrogenation of ethylbenzene. The ethylbenzene is mixed with steam, and then allowed to come in contact with a catalyst in a reactor. This reaction is carried out at high temperature under vacuum. The heat is recovered from this reaction, and the hydrocarbon solution is sent to a series of fractionation units. The first separation removes the small amount (4 to 6 percent) of toluene and benzene produced by cracking. This toluene/benzene stream is typically sent back to the benzene plant. The second separation removes unreacted ethylbenzene and recycles it back into the system. Purified styrene monomer is recovered in the third and final phase. Bottoms or tar residue is removed from this third phase (Reference C-23).

Blowing Agent Production. There are a number of blowing agents available for use in foam polystyrene production including n-pentane, isopentane, isobutane, and n-butane. Some manufacturers use carbon dioxide, recovered from other industrial processes, as a blowing agent for polystyrene (Reference C-92). However, n-pentane is the most common blowing agent used for polystyrene foam.

The blowing agent is introduced into the polystyrene polymer during the polymerization step. The vaporization of the blowing agent is responsible for the foam character of the final product.

In this analysis, n-pentane is considered a generic product from either a refinery or a natural gas liquids plant. The n-pentane data in this analysis are based on a 60/40 percent weighted average of the data for natural gas processing and oil refining data discussed previously in this appendix.

Expanded Polystyrene (EPS) Resin Production. Expanded Polystyrene Resin (EPS) resin is typically produced by either a one-step or two-step process. These two processes are discussed below.

One Step EPS Production. Styrene is dispersed in water in a reactor and polymerized in the presence of initiators and suspending agents. Prior to the completion of the polymerization, blowing agent is added to the reactor. The blowing agent is incorporated into the polystyrene beads and the temperature of the reactants is increased to finish off the polymerization. After the reactor and contents are cooled, the beads are dewatered and dried. The waste water is sent to an effluent treatment facility. The dried beads are screened into different sizes and the final EPS products are packed into containers for shipment to molders.

Two Step EPS Production. Styrene is dispersed in water in a reactor and polymerized in the presence of initiators and suspending agents. The reaction is taken essentially to completion by raising the temperature of the reactants to finish off the polymerization. After the reactor and contents are cooled, the beads are dewatered and dried. The waste water is sent to a waste water treatment facility. The dried beads are screened into different fractions and sent to storage.

Each separate polystyrene bead fraction produced in the first step is in turn recharged to a reactor, re-suspended in water and blowing agent is added. The reactor and contents are heated and held at elevated temperatures for a predetermined time while the blowing agent is impregnated into the polystyrene beads. The reactor and contents are cooled and the final EPS product is dewatered and dried a second time. The dried beads are screened into different sizes and the final EPS products are packed into containers for shipment to molders.

The emissions from the one- and two-step processes are similar. The vent streams consist mainly of varying concentrations of blowing agent in air. Typical wastewater effluents include BOD, COD, and suspended solids in varying degrees depending on the treatment processes employed. BOD and COD emissions can be reduced to very low levels by a combination of flocculation, sedimentation, aeration, and biological digestion operations. Solid waste generation includes EPS particulates and dust as well as suspending agent residuals.

Postconsumer EPS Resin Production. EPS loose fill can contain a portion of postconsumer EPS. The recycling of postconsumer EPS includes the following processes:

- Postconsumer Expanded Polystyrene (EPS) Collection
- Recycled Expanded Polystyrene (EPS) Resin Production

Postconsumer Expanded Polystyrene (EPS) Collection. Postconsumer EPS is collected from assemblers of durable goods or from established retail collection programs.

Recycled Expanded Polystyrene (EPS) Resin Production. The recycling process for postconsumer EPS includes shredding the material and passing it through an extruder system. This increases the density of the EPS from 2 pounds per cubic foot to 9-12 pounds per cubic foot. No washing operations are necessary during the recycling process because postconsumer EPS is usually clean (Reference C-114).

Cornstarch Production

Cornstarch is used to make starch-based foam, which can be used as a loose fill alternative to expanded polystyrene (EPS). The production of corn starch requires the growing and harvesting of corn, which includes the production of fertilizers and pesticides. The material flows and steps of cornstarch production are shown in Figure C-3. The steps of cornstarch production are listed below.

- Corn Growing and Harvesting
    - Fertilizer Manufacture
        - Nitrogen Fertilizer
        - Phosphate Fertilizer
        - Potash Fertilizer
    - Pesticide Manufacture
- Corn Starch Production

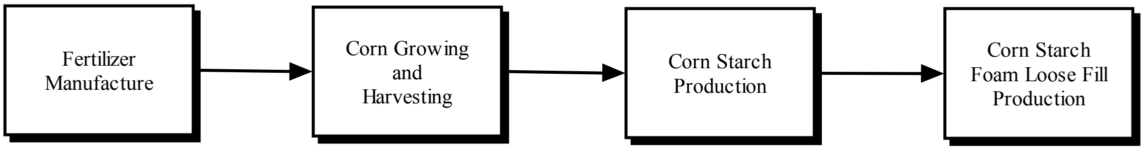

Figure C-3. Flow diagram for the production of corn starch loose fill.

Corn Growing and Harvesting. To produce high corn yields, many factors must be considered. The most important of these factors include temperature, climate, and nutrients. Corn needs nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur from the soil. Soil fertility is easily depleted, especially when the entire plant is harvested for silage. Therefore, these nutrients are added to the soil as fertilizer.

Fertilizer Manufacture. Most corn land receives applications of fertilizer, typically nitrogen, phosphate, and/or potash. Over half of all fertilizers are applied as single nutrient materials. USDA literature reports applications of nitrogen, phosphate, and potash fertilizers in terms of pounds of N, P_2O5, and K_2O (Reference C-29). Figure C-4 shows the steps required to produce each of these fertilizers.

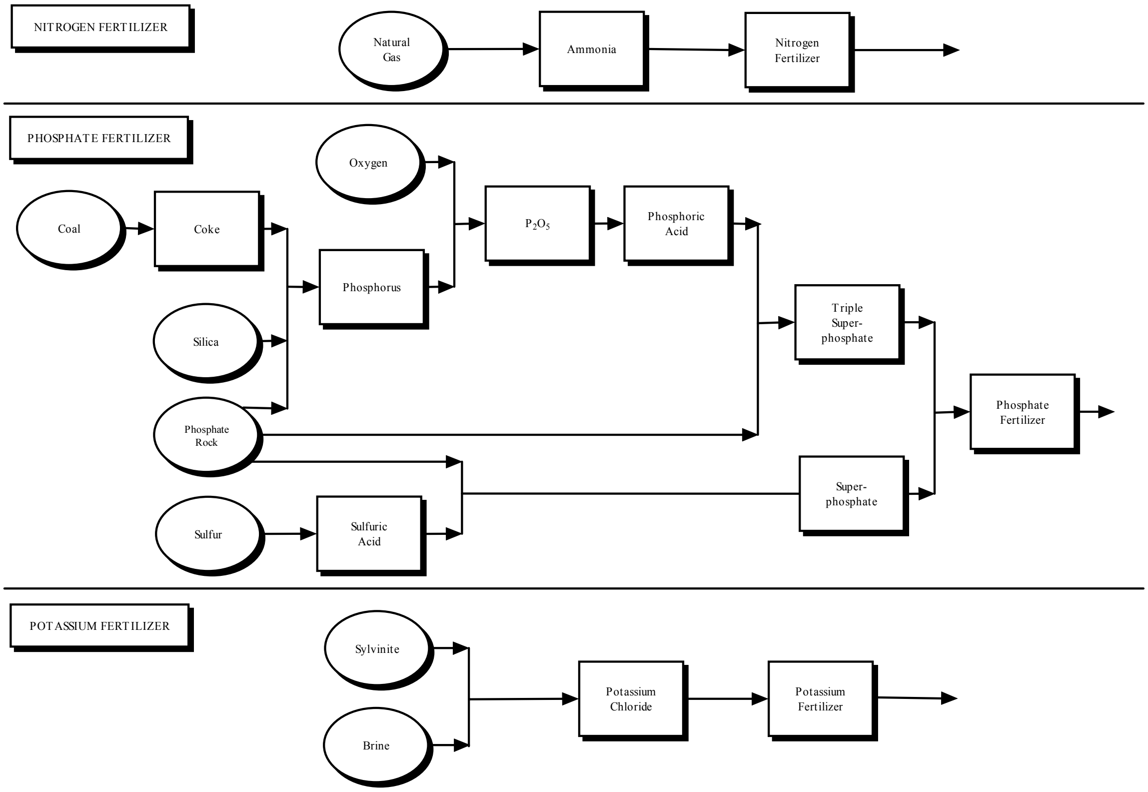

Figure C-4. Flow Diagram for the production of fertilizer.

Nitrogen Fertilizer. Nitrogen as a single nutrient is commonly applied in the form of anhydrous ammonia. The steps in the production of nitrogen fertilizer are listed below.

- Natural gas production
- Ammonia production
- Nitrogen fertilizer production

Natural gas production is discussed previously in this appendix. The remaining steps of nitrogen fertilizer production are discussed below.

Ammonia Production. Ammonia is produced primarily by steam reformation of natural gas. Natural gas and steam are fed into a tubular furnace where the reaction over a nickel reforming catalyst produces hydrogen and carbon oxides. The primary reformer products are then mixed with preheated air and reacted in a secondary reformer to produce the nitrogen needed in ammonia synthesis.

The gas is cooled to a lower temperature and subjected to a water shift reaction in which carbon monoxide and steam are reacted to form carbon dioxide and hydrogen. The carbon dioxide is removed from the shifted gas in an absorbent solution. Hydrogen and nitrogen are reacted in a synthesis converter to form ammonia (References C-30 and C-31).

Nitrogen Fertilizer Production. Nitrogen fertilizer is applied in the form of anhydrous ammonia that is 82 percent by weight N.

Phosphate Fertilizer. Phosphate fertilizer applied as a single nutrient is most commonly in the form of superphosphate, with 16 to 20 percent available P_2O_5, or triple superphosphate, with 44 to 51 percent available P_2O_5. Superphosphates are produced by the action of sulfuric acid on phosphate rock, while triple superphosphates are made by adding phosphoric acid to phosphate rock (References C-32 and C-33). The data are based on half of the phosphate applied as superphosphate and half as triple superphosphate. The following process steps are required for the manufacture of the phosphate fertilizers:

- Superphosphate
    - Phosphate rock mining
    - Crude oil production
    - Crude oil refining
    - Natural gas production
    - Natural gas processing
    - Sulfur production
    - Sulfuric acid production
    - Superphosphate production
- Triple superphosphate
    - Phosphate rock mining
    - Silica mining and processing
    - Coal mining
    - Metallurgical coke production
    - Elemental phosphorus production
    - Oxygen production
    - Phosphorus pentoxide production
    - Phosphoric acid production
    - Triple superphosphate production
- Phosphate fertilizer production

Crude oil production and refining, natural gas production, and natural gas processing are discussed previously in this appendix. Oxygen production is discussed later in this appendix. Coal mining is discussed in Appendix A. The remaining steps in the manufacture of phosphate fertilizers are discussed below:

Phosphate Rock Mining. Phosphate is mined as a natural rock containing mostly calcium phosphate. Large deposits are contained in the United States, North Africa, and the former Soviet Union (Reference C-33).

Sulfur Production. Sulfur exists in nature as elemental sulfur and is also found in ores such as pyrite (FeS_2). Sulfur is also recovered from hydrogen sulfide (H_2S), a component of petroleum and natural gas. Approximately, 10 percent of U.S. sulfur is obtained from limestone during the Frasch process, while the remaining 90 percent is obtained from natural gas and petroleum via the Claus process.

Descriptions of the two sulfur production processes follow.

Frasch Process. Sulfur is obtained from sulfur-bearing porous limestone primarily by the Frasch process. In this process, a set of three concentric pipes are inserted into a well drilled into an underground sulfur dome. Injecting superheated water into the well raises the temperature of the sulfur-bearing rock above the melting point of sulfur.

Compressed air is then injected into the well. This forces the molten sulfur to the surface. As all Frasch mines in the U.S. are near waterways, the sulfur is shipped by insulated barge or boat, or allowed to solidify and shipped as a solid (Reference C-25).

Claus Process. Recovery of sulfur from sour natural gas and crude oil via the Claus process accounts for about 90 percent of the sulfur produced in the United States. Approximately 76 percent of the sulfur produced via Claus recovery is obtained from hydrogen sulfide recovered from petroleum refining, and the remaining 24 percent is recovered from natural gas sweetening (Reference C-25). The following data include the production of sulfur from petroleum refining only.

Hydrogen sulfide is recovered from refinery gases by absorption in a solvent or by regenerative chemical absorption (Reference C-18). Hydrogen sulfide concentrations in the gas from the absorption unit vary. For this analysis, an industry average H_2S gas concentration of 85 percent is used (References C-18 and C-26). This concentrated hydrogen sulfide stream is treated by the Claus process to recover the sulfur. The Claus process is based upon the reaction of hydrogen sulfide with sulfur dioxide according to the exothermic reaction (Reference C-18):

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \qquad \text{(Reaction 1)}$$

Sulfur dioxide for the reaction is prepared by oxidation of hydrogen sulfide with air or oxygen in a furnace using either the partial combustion process (once-through process) or the split-stream process. The partial combustion method is used when the H_2S concentration is greater than 50 percent and the hydrocarbon concentration is less than 2 percent. The split stream process is used when there is an H_2S concentration of 20 to 50 percent and a hydrocarbon concentration of less than 5 percent.

In the partial combustion method, the hydrogen sulfide-rich gas stream is burned with a fuel gas in an oxygen-limited environment to oxidize one-third of the H_2S to SO_2 according to the reaction (Reference C-16):

$$2H_2S + 2O_2 \rightarrow SO_2 + S + 2H_2O \qquad \text{(Reaction 2)}$$

Sulfur is removed from the burner and the H_2S/SO_2 mixture moves to the catalytic converter chambers.

In the split stream process, one-third of the hydrogen sulfide is split off and completely oxidized to SO_2 according to the reaction:

$$2H_2S + 1.5O_2 \rightarrow SO_2 + H_2O \qquad \text{(Reaction 3)}$$

The remaining two-thirds of the H_2S is mixed with the combustion product and enters the catalytic converter chambers.

The H_2S and SO_2 mixture from either process is passed through one or more catalyst beds and is converted to sulfur, which is removed by condensers between each bed (Reference C-18). For this analysis, an H_2S concentration of 85 percent has been assumed; therefore, it is also assumed that the partial combustion process is used.

Although efficiencies of 96 to 99 percent sulfur recovery have been demonstrated for the Claus process, recovery is usually not over 96 percent and is limited by thermodynamic considerations (References C-16 and C-18). For this analysis, a sulfur recovery efficiency of 95 percent is assumed.

The energy generated from burning hydrogen sulfide to produce SO_2 is usually recovered and used directly to reheat the process stream in secondary and tertiary condensers, or recovered as steam for use in other processes (Reference C-16). Heat released from cooling the exothermic reaction to form sulfur is also recovered. The fuel value of H_2S is not included in the total energy for the system because H_2S is not used as a commercial fuel. The system is also not given an energy credit for any steam exported from the system.

Sulfuric Acid Production. Sulfur is burned with air to produce sulfur dioxide and heat. The heat is used to generate steam that is usually used in adjacent processing plants and to supply energy to the sulfuric acid plant. The energy import (as the calorific value) of sulfur and the energy export of steam cancel in the energy balance for this process. The sulfur dioxide gas is converted to sulfur trioxide and combined with dilute sulfuric acid to form the concentrated product.

Superphosphate Production. Superphosphate is produced by the addition of sulfuric acid to phosphate rock. Superphosphate is a mixture of gypsum and calcium phosphate.

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

Mining operations vary depending on the nature of the deposit at each location. Open pit excavation and dredging are the two basic mining methods, each requiring a combination of many types of equipment including crushers, screens, washers, classifiers, and grinding mills.

Metallurgical Coke. The two proven processes for manufacturing metallurgical coke are known as the beehive process and the byproduct process. The primary method for manufacturing coke is the byproduct method, which accounts for more than 98 percent of U.S. coke production. In the byproduct method, air is excluded from the coking chambers, and the necessary heat for distillation is supplied from external combustion of some of the gas recovered from the coking process.

Elemental Phosphorus Production. Elemental phosphorus is produced from phosphate rock by a reaction with coke and silica in an electric furnace. Elemental phosphorus is one of several materials resulting from this process.

Phosphorus Pentoxide Production. Oxidation of elemental phosphorus produces phosphorus pentoxide.

Phosphoric Acid Manufacture. Hydration of phosphorus pentoxide produces phosphoric acid.

Triple Superphosphate Production. Triple superphosphate is produced by the addition of phosphoric acid to phosphate rock. It has three times the amount of available phosphate as in superphosphate and contains no gypsum.

Phosphate Fertilizer Production. Phosphate fertilizer is applied in the form P_2O_5. This study assumes that the superphosphate is applied with 20 percent available P_2O_5 and the triple superphosphate with 50 percent available P_2O_5.

Potash. Potash fertilizer is generally applied in the form of potassium chloride (KCl), which is sold in various agricultural grades, containing 60 to 62 percent K_2O, 48 to 52 percent K_2O, or 22 percent K_2O. The following steps are required for the production of potash fertilizer:

- Sylvinite Mining and Processing
- KCl Production
- Potash fertilizer production

Sylvinite Mining and Processing. Most of the U.S. supply of KCl produced from sylvinite ore is mined from deep deposits in the Carlsbad, New Mexico region. Sylvinite mining and processing is assumed to be similar to soda ash mining and processing.

KCl Production. KCl is obtained from sylvinite ore and purified by fractional crystallization or flotation. It is also extracted from salt lake brines and purified by recrystallization (References C-32 and C-33).

KCl is prepared from sylvinite ore by passing hot liquor through a series of steam-heated turbomixer dissolvers countercurrent to a flow of crushed ore. KCl and a small amount of NaCl go into solution. When the solution is cooled from its boiling point, KCl separates out. Waste tailings from the process, largely NaCl, are carried out of the plant to waste storage. A large part of the process liquor is decanted to be used again (Reference C-32). The solid portion of the tailings, including the NaCl, is included in the reporting of process solid waste.

KCl is also produced by extraction from the brines of Searles Lake, California. This brine, containing various salts, is carbonated with flue gas from the boiler plant. Sodium bicarbonate separated by this reaction is calcined and converted to dense soda ash. Crude borax is crystallized from the carbonated end liquor by cooling under vacuum. The filtrate is returned to the lake. Soda ash, KCl, borax/boric acid, and salt cake are produced by brine extraction (Reference C-32).

Potash Fertilizer. The potash fertilizer analyzed in this study is based on application as KCl containing 50 percent K_2O. Seventy-five percent of the KCl is assumed to be produced from sylvinite and 25 percent from brine extraction.

Pesticide Manufacture. Pesticides applied to corn include a variety of herbicides, insecticides, defoliants, and desiccants. Fungicides, miticides, and growth regulators may be applied as well. A wide variety of pesticides have been formulated to address the varying needs and conditions of each region; thus, the types and quantities of pesticide applied to corn acreage vary widely. As a result, the effects of individual pesticides on the environment also vary. Due to the complexity and variability of pesticide manufacture and use, and the budget limitations for this study, data on pesticide manufacture is not included in this analysis.

Corn Growing and Harvesting. Whole grain corn is composed of 71.7 percent starch (Reference C-34). Corn is a warm weather plant requiring a growing season of about 140 days with an average daytime temperature of 75°F with nighttime temperatures exceeding 58°F. High yields also require 16 to 26 inches of rainfall. Irrigation is used on most corn-growing farms to supplement inadequate rainfall. Fertilizer and limes are added to bring necessary nutrients to the soil. Pesticides are added to destroy insects, fungus, and any other pests that would hurt the plant.

Pesticide use in corn production can lead to significant environmental burdens. For example, atrizine used in corn production is a major contaminant of groundwater and surface water. However, pesticide emissions are difficult to quantify since there are many pesticides used, each varying in application rate and degradability. Emission rates also vary widely depending on the soil type and topography, pesticide application process, weather factors such as wind and rain, etc. Because pesticide manufacture is not included in this study and because of the wide variability in pesticide emissions in agricultural runoff, pesticide emissions are not included in this study.

Today, corn harvesting is mostly done by multi-row combines. The corn is removed from the cobs in the field, then stored for drying. The cobs and husks are left in the field to decompose. Agricultural wastes that are returned to the land for natural decomposition without waste treatment are not reported as solid waste.

After drying, the corn is transported to customers. Corn used in the production of corn starch must be transported to a wet milling plant.

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

Bleached Kraft Paper

Bleached kraft paper is used for the fabrication of shipping bags. Figure C-5 shows the flow diagram for the production of 1,000 pounds of bleached kraft fiber incorporating both virgin and postconsumer fiber. The production of virgin bleached kraft paper includes the following steps:

- Roundwood Harvesting
- Wood Residues (Chips)
- Salt (Sodium Chloride) Mining
- Sodium Chlorate Production
- Production of Caustic Soda (Sodium Hydroxide) and Chlorine

- Hydrogen Production
- Hydrogen Peroxide Production
- Oxygen Production
- Limestone Mining
- Lime Production
- Cornstarch Production
- Kraft Bleached Paper Manufacture

Cornstarch production is discussed previously in this appendix and is not repeated in this section. The remaining steps of bleached kraft paper production are discussed below.

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

Trees harvested specifically for wood pulp production account for approximately 53 percent of the wood delivered to the average U.S. paper mill. The remainder comes from wood residues (sawdust and chips) generated by lumber production or other wood processing operations (Reference C-51).

An unknown amount of water pollution in the form of suspended solids results from runoff from road building into the harvested forests as well as erosion from cut-over lands. The extent to which these solids actually reach streams depends on many factors, including the grade, amount of surface disturbance, soil type, and rainfall. In some areas, significant quantities of these solids could end up in streams. Although perhaps as much as seven pounds of suspended solids are generated, their final deposition is divided between streams and other locations within the forest. Therefore, suspended solids emissions from roundwood harvesting were not included in this analysis since the amount of stream pollution from this source is highly variable and a reasonable average could not be determined from published or unpublished source within the budget constraints for this project.

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

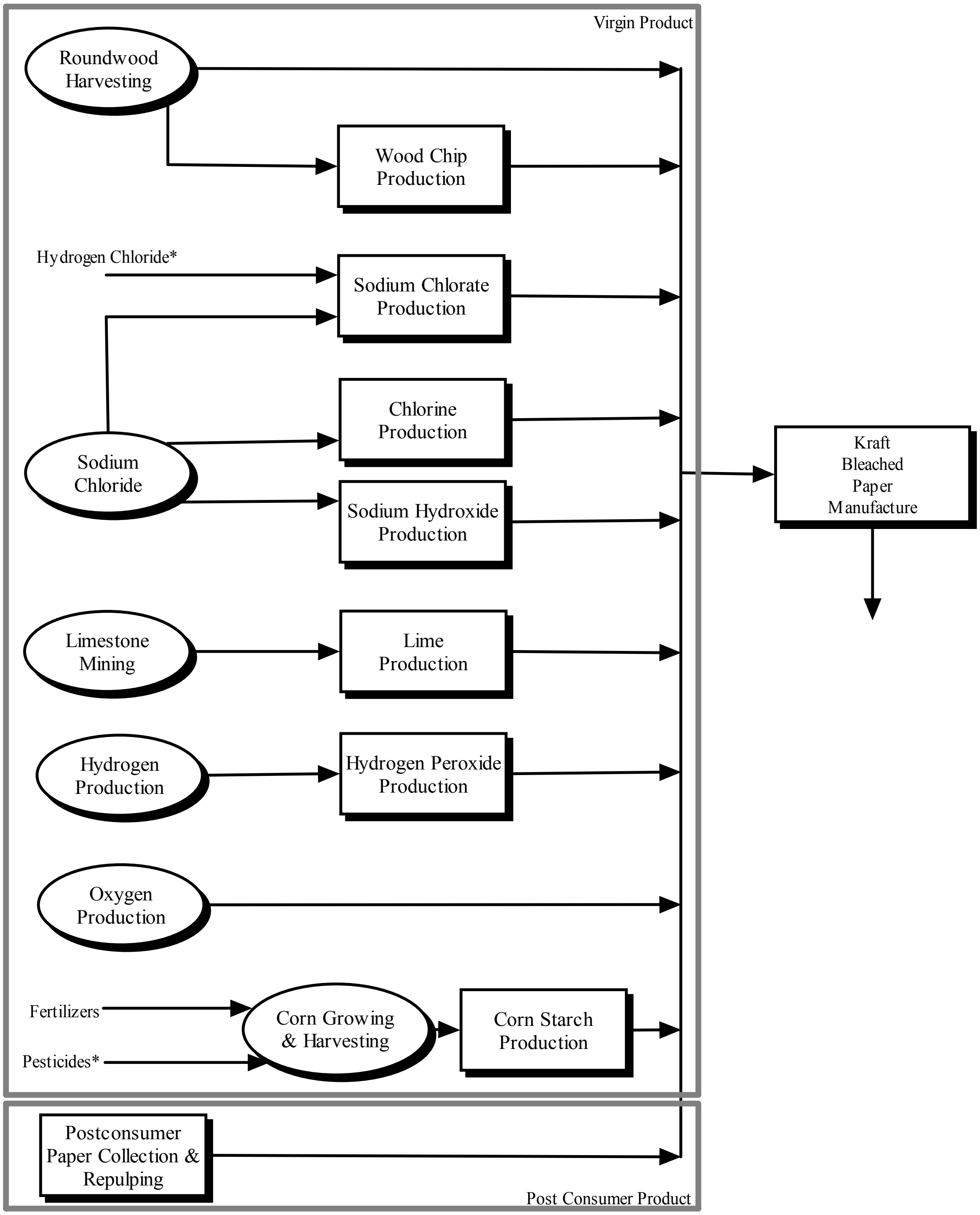

Figure C-5. Flow diagram for the production of 1,000 pounds of kraft bleached paper with virgin and post consumer product.

* These materials are considered negligible in the model.

Typically the wood that a sawmill receives will already be delimbed and cut to manageable lengths. The roundwood is sorted by diameter and then sent to a debarker. After debarking, the logs are conveyed through a series of cutting and planing operations. Roughly 75 to 80 weight percent of the tree as received is converted to lumber, with the remaining 20 to 25 percent becoming wood chips and fines. The chips are sold to pulp mills, and the fines are either burned as an energy source or burned for waste disposal.

Forest residues are small diameter trees, limbs, and cuttings that are turned into chips in the forest. In general, wood residues are generated on site or quite close to the mills. This study assumes that 90 percent of wood residues result from mill operations and 10 percent result from forest operations.

Salt (Sodium Chloride) Mining. For the most part, salt-based chlorine and caustic (sodium hydroxide) facilities use captive salt from another process or salt recovered from underground deposits. According to the U.S. Geological Survey, 48% of domestically-produced salt comes from the brine process and 35% comes from halite mining. Evaporation of seawater is a smaller source of salt.

In the brine process, an injection well is drilled and pressurized fresh water is introduced to the bedded salt (Reference C-27). The brine is then pumped to the surface for treatment. Salt mines are widely distributed throughout the United States. Rock salt is recovered from the mining of halite, a mineral rich in sodium chloride.

Sodium Chlorate Production. Sodium chlorate is used to produce chlorine dioxide at the pulp mill site. The chlorine dioxide is used for bleaching. Sodium chlorate is produced from electrolysis of salt brine similar to the production of caustic and chlorine, except that the chlorine and caustic are not separated, but are instead allowed to mix (Reference C-35). Hypochlorite forms first, followed by the formation of sodium chlorate.

Production of Caustic Soda (Sodium Hydroxide) and Chlorine. Caustic soda (sodium hydroxide) and chlorine are produced from salt by an electrolytic process. The aqueous sodium chloride solution is electrolyzed to produce caustic soda, chlorine, and hydrogen gas. For this analysis, resource requirement and environmental emission coproduct credit is allocated on a weight basis to each of the materials produced in the cell. Thus, the burdens per 1,000 pounds are the same for all coproducts. The reason for giving coproduct credit on a weight basis is that it is not possible, using the electrolytic cell, to get chlorine from salt without also producing sodium hydroxide and hydrogen, both of which have commercial value as useful coproducts. Likewise, sodium hydroxide cannot be obtained without producing the valuable coproducts of chlorine and hydrogen.

Furthermore, it is not possible to control the cell to increase or decrease the amount of chlorine or caustic soda resulting from a given input of salt. This is determined by the stoichiometry of the reaction. The electrolytic cell is perceived as a “black box” with an input of salt and electricity, and an output of chlorine, sodium hydroxide, and hydrogen.

The electrolysis of sodium chloride is performed by one of two processes: the mercury cathode cell process, or the diaphragm cell process. About 83 percent of electrolyzed chlorine and caustic soda production comes from the diaphragm process, with the remainder coming from the mercury cell process (Reference C-36).

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

The mercury cathode cell process is described by:

$$NaCl + x\ Hg \rightarrow 1/2\ Cl_2 + Na(Hg)_x \text{ and}$$
$$Na(Hg)_x + H_2O \rightarrow NaOH + 1/2\ H_2 + x\ Hg$$

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

Hydrogen Production. Hydrogen and carbon dioxide are coproducts in the production of synthesis gas. Synthesis gas is primarily produced from natural gas by steam-methane reforming. Natural gases, or other light hydrocarbons, and steam are fed into a primary reformer over a nickel catalyst to produce hydrogen and carbon oxides, generally referred to as synthesis gas. About 70 percent of the hydrocarbon feed is converted to synthesis gas in the primary reformer (Reference C-18).

The effluent from the reformers is fed into carbon monoxide shift converters where the carbon monoxide reacts with water to form carbon dioxide and hydrogen. The effluent from the shift converters is cooled, and condensed water is removed. The carbon dioxide and some excess hydrogen are also removed from the synthesis gas as coproducts.

The ratio of carbon monoxide to hydrogen in the synthesis gas differs depending on the specifications for the synthesis gas, and therefore the amounts of hydrogen and carbon dioxide coproducts differ also. Synthesis gas is a raw material for many different processes, each with specific requirements. Because of this difference in requirements, it is difficult to show an accurate average material balance for this process. The data for hydrogen production are estimates of the synthesis gas production. Raw material inputs for hydrogen are based on the conversion of methane to carbon monoxide and hydrogen.

Hydrogen Peroxide Production. Hydrogen peroxide can be produced by several electrochemical or organic routes. This study characterizes hydrogen peroxide from the oxidation/reduction of an anthraquinone--the predominant commercial route to hydrogen peroxide.

An anthraquinone in an organic solvent is first catalytically hydrogenated. This material is then oxidized with oxygen taken from air back to anthraquinone, with hydrogen peroxide being produced as a byproduct. The hydrogen peroxide is water-extracted from the reaction medium and the solvent and anthraquinone are recycled.

No energy consumption or environmental emissions data are available for the production of hydrogen peroxide. A very conservative estimate of the energy consumption is made based on other industrial processes.

Oxygen Production. Oxygen is manufactured by cryogenic separation of air, a technique by which air is liquefied, and the oxygen is collected by fractionation. The oxygen is produced in the form of a liquid that boils at 300°F below zero at normal atmospheric pressure. Therefore, it must be kept under stringent conditions of temperature and pressure for handling. Most oxygen plants are located near their point of consumption to minimize transportation difficulties, although there is a small amount of long-distance hauling in insulated rail cars.

Limestone Mining. Limestone is quarried primarily from open pits, but underground mining is becoming more common in the central and eastern United States. The percentage of limestone mining that is open pit and the percentage of limestone mining that is underground are unknown. The energy data (and fuel-related pollutants) used in this analysis represent a combination of open pit and underground mining. The process emission data is based solely on open pit techniques. The most economical method of recovering the limestone has been through blasting, followed by mechanical crushing and screening (References C-27 and C-37). Airborne particulates are generated in the form of limestone dust during many of the operations.

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

The data in this section are for the production of quicklime (References C-38 and C-39).

Solid wastes generated during the manufacture of lime include impurities removed from limestone, tailings collected in the lime production process, and lime kiln dust collected from particulate control devices on the lime kilns. Based on lengthy discussions with a representative of the National Lime Association and a confidential lime industry expert, it was assumed that all collected lime dust and tailings from lime production are either sold for various useful purposes, injected back into mines, replaced in quarries, or land applied on-site (Reference C-40 and C-41). This may not be true of a few smaller companies, which are not close to their source of limestone. The solid waste in the data table is an estimate from a representative of the lime industry and includes packaging and other industrial wastes that may be disposed of in a municipal landfill (Reference C-41).

Kraft Bleached Fiber Production. Kraft pulp is the most widely used type of wood pulp in the United States today, accounting for 80 percent of the total wood pulp produced. It is used in either an unbleached or bleached form. The data in this section are for bleached paperboard.

The kraft pulping process is based on chemical digestion of wood, which has been previously debarked and chipped. The digester is a closed container that holds the wood chips and digestion liquors. The liquor is mainly an aqueous solution of chemicals including sodium sulfide and sodium hydroxide.

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

At this point the pulp is bleached using one or a combination of the following: chlorine, caustic, oxygen, ozone, chlorine dioxide, hydrogen peroxide, and others (Reference C-42). Chlorine dioxide, generated on-site from sodium chlorate, is most commonly used. A mixture of the bleaching agents based on an average of the mill data collected has been used.

One of the features of the kraft process is that the used digestion liquor, called black liquor, is burned for energy. Combustion of black liquor and the bark removed from logs entering the mill often provides a significant portion of the energy to operate a pulp mill. Because the black liquor contains a high percentage of flammable wood components, it burns readily. The digestion liquor remaining after the black liquor is burned is known as green liquor. Lime is added to the green liquor to produce white liquor, which is then returned to the digester.

The airborne emissions of organic halogens for kraft paper were reported by a private industry source and so are confidential. Cradle-to-gate data for the production of bleached virgin kraft paper are shown in Table C-1.

Unbleached Kraft Paper

Unbleached kraft paper is used as dunnage material that fills void spaces in a package, as well as for the inner layer of padded, all-paper shipping bags. The material flows for the production of unbleached kraft paper with both virgin and postconsumer fiber content are shown in Figure C-6. The production of virgin unbleached kraft paper includes the following steps:

- Roundwood Harvesting
- Wood Residues (Chips)
- Salt Mining
- Sodium Hydroxide Production
- Sodium Sulfate Mining
- Limestone Mining
- Lime Production
- Cornstarch Production
- Unbleached Kraft Paper Production

Material inputs that account for less than 1% of the weight of the output product are not included. Roundwood harvesting, wood residues production, salt mining, sodium hydroxide production, limestone mining, lime production, and cornstarch production are discussed previously in this appendix and are not repeated here. The remaining steps of unbleached kraft paper production are discussed below.

Sodium Sulfate Mining. Sodium sulfate is consumed in the Kraft pulping process. The upper levels of Searles Lake, California, the Great Salt Lake in Utah, and the brines of west Texas all contain sodium sulfate. Typically, sodium sulfate crystals are removed from cooled brine. The crystals are then dissolved again and precipitated to achieve the desired purity. No industry data sets were available for sodium sulfate production; the sodium sulfate data in this analysis are based on Census of Mineral Industries data for SIC Code 1474, which covers potash, soda, and borate minerals.

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

Table C-1

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF BLEACHED VIRGIN KRAFT PAPER FOR SHIPPING BAGS (includes all steps from raw material extraction through production of virgin kraft paper and shipment to bag manufacturer)

Raw Materials

Roundwood Harvesting	4,070	lb
Salt Mining	3.79	lb
Hydrogen Production	0.53	lb
Oxygen Production	1.70	lb
Limestone Mining	27.7	lb
Nitrogen Fertilizer	0.48	lb
Phosphate Fertilizer	0.19	lb
Potash Fertilizer	0.21	lb
Corn Growing & Harvesting	32.8	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			7.03
Total Resource			7.03
Process Energy			
Electricity	433	kwh	4,847
Natural gas	1,976	cu ft	2,292
LPG	6.4E-05	gal	0.0068
Coal	252	lb	2,890
Distillate oil	0.47	gal	72.8
Residual oil	18.0	gal	3,046
Gasoline	3.0E-04	gal	0.042
Diesel	1.31	gal	205
Wood	10,533	thou Btu	10,533
Total Process			23,885
Transportation Energy			
Combination truck	295	ton-miles	
Diesel	2.77	gal	433
Rail	7.74	ton-miles	
Diesel	0.019	gal	2.90
Barge	0.40	ton-miles	
Diesel	8.0E-04	gal	0.12
Residual oil	3.2E-04	gal	0.054
Ocean freighter	0.18	ton-miles	
Diesel	1.8E-05	gal	0.0027
Residual	3.2E-04	gal	0.053
Pipeline-natural gas	0.024	ton-miles	
Natural gas	0.055	cu ft	0.064
Pipeline-petroleum products	0.010	ton-miles	
Electricity	2.3E-04	kwh	0.0026
Total Transportation			436

Table C-1 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF BLEACHED VIRGIN KRAFT PAPER FOR SHIPPING BAGS

Environmental Emissions*

Atmospheric Emissions		
Particulates	1.67	lb
Nitrogen Oxides	5.83	lb
Hydrocarbons	0.011	lb
Sulfur Oxides	5.38	lb
Carbon Monoxide	0.98	lb
Aldehydes	3.7E-06	lb
Other Organics	0.094	lb
Odorous Sulfur	0.020	lb
Ammonia	0.040	lb
Mercury	1.9E-05	lb
Chlorine	0.015	lb
Carbon Dioxide (fossil)	11.6	lb
Carbon Dioxide (non-fossil)	0.010	lb
Total Reduced Sulfur	0.40	lb
Solid Wastes	118	lb
Waterborne Emissions		
Acid	0.0030	lb
Dissolved Solids	0.28	lb
SuspendedSolids	6.17	lb
BOD	2.83	lb
COD	4.36	lb
Phenol	5.6E-08	lb
Sulfides	5.2E-06	lb
Oil	5.2E-05	lb
Iron	2.0E-05	lb
Cyanide	1.1E-07	lb
Chromium	1.4E-08	lb
Nickel	3.8E-08	lb
Mercury	5.4E-08	lb
Lead	3.8E-08	lb
Phosphates	0.059	lb
Phosphorus	0.10	lb
Nitrogen	0.039	lb
Zinc	3.8E-08	lb
Ammonia	0.28	lb
Sodium Dichromate	3.4E-06	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

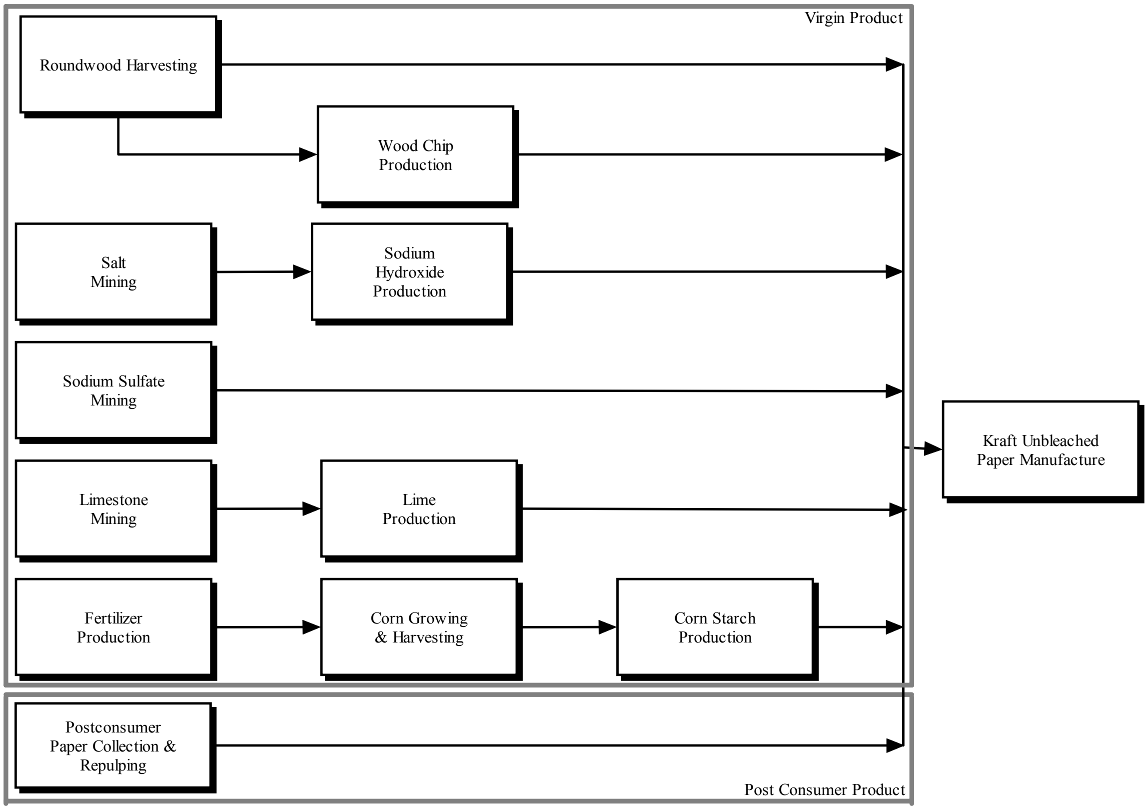

Figure C-6. Flow diagram for the production of kraft unbleached paper with virgin and post consumer product.

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

One of the features of the kraft process is that the used digestion liquor, called black liquor, is burned for energy. Combustion of black liquor and the bark removed from logs entering the mill often provides a significant portion of the energy to operate a pulp mill. Because the black liquor contains a high percentage of flammable wood components, it burns readily. The digestion liquor remaining after the black liquor is burned is known as green liquor. Lime is added to the green liquor to produce white liquor, which is then returned to the digester.

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

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

Cradle-to-gate data for the production of unbleached virgin kraft paper for shipping bags are shown in Table C-2. Cradle-to-gate data for the production of unbleached virgin kraft paper for dunnage are shown in Table C-3.

Postconsumer Recycled Paper(board)

Because a bright white appearance is not necessary for the recycled paper packaging products in this analysis, it is assumed that the recycled fiber is not deinked or bleached. The collection, repulping, and papermaking processes are thus the same for bleached and unbleached recycled paper, except for the sources of postconsumer fiber. The steps in postconsumer paper recycling are discussed below.

- Postconsumer Paper Collection
- Recycled Paper Production

Postconsumer Paper Collection. The majority of postconsumer fiber used in recycled unbleached kraft paper is recovered from old corrugated containers (OCC). Recovered office paper and magazines contribute a small amount to the postconsumer content in recycled kraft paper. The infrastructure for recycling postconsumer corrugated shipping containers in the United States is well established, particularly for warehouses and supermarkets. Typically, the used boxes are loaded onto a conveyer that takes them to a baler. The bales of boxes are then fork-lifted into a diesel truck that ships them to the recycled paperboard mill, where they are repulped. For recycled bleached kraft paper, the main source of recycled content is postconsumer office paper.

Data for the collection of postconsumer paper(board) include the transportation requirements for collecting the material and shipping it to a recycled paper(board) mill. The majority of both postconsumer OCC and postconsumer office paper are generated by commercial or industrial sites. This analysis thus uses commercial and industrial recycling data to represent collection of all grades of postconsumer paper(board).

Table C-2

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF UNBLEACHED VIRGIN KRAFT PAPER FOR SHIPPING BAGS

(includes all steps from raw material extraction through production of unbleached virgin kraft paper and shipment to bag manufacturer)

Raw Materials		
Roundwood Harvesting	5,469	lb
Limestone Mining	19.3	lb
Sulfur Production	1.09	lb
Salt Mining	2.02	lb
Nitrogen Fertilizer	0.29	lb
Phosphate Fertilizer	0.11	lb
Potash Fertilizer	0.14	lb
Corn Growing	19.7	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			4.22
Total Resource			4.22
Process Energy			
Electricity	98.4	kwh	1,102
Natural gas	1,205	cu ft	1,398
LPG	0.0014	gal	0.15
Coal	275	lb	3,155
Distillate oil	0.015	gal	2.31
Residual oil	0.57	gal	95.9
Gasoline	0.0011	gal	0.16
Diesel	1.79	gal	279
Wood	9,388	thou Btu	9,388
Total Process			15,421
Transportation Energy			
Combination truck	305	ton-miles	
Diesel	2.87	gal	448
Rail	15.9	ton-miles	
Diesel	0.038	gal	5.95
Barge	0.39	ton-miles	
Diesel	7.9E-04	gal	0.12
Residual oil	3.1E-04	gal	0.053
Ocean freighter	1.20	ton-miles	
Diesel	1.2E-04	gal	0.019
Residual	0.0022	gal	0.36
Pipeline-natural gas	0.049	ton-miles	
Natural gas	0.11	cu ft	0.13
Pipeline-petroleum products	0.083	ton-miles	
Electricity	0.0018	kwh	0.020
Total Transportation (for shipping bags)			455

Table C-2 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF UNBLEACHED VIRGIN KRAFT PAPER FOR SHIPPING BAGS

Environmental Emissions*

Atmospheric Emissions		
Particulates	1.81	lb
Nitrogen Oxides	7.05	lb
Hydrocarbons	0.024	lb
Sulfur Oxides	12.0	lb
Carbon Monoxide	8.22	lb
Aldehydes	0.012	lb
Ammonia	0.091	lb
Lead	7.7E-10	lb
Mercury	1.0E-04	lb
Chlorine	4.3E-07	lb
Hydrogen Chloride	8.3E-08	lb
Carbon Dioxide (fossil)	8.25	lb
Carbon Dioxide (non-fossil)	0.0059	lb
Total Reduced Sulfur	0.058	lb
Solid Wastes	75.6	lb
Waterborne Emissions		
Acid	0.025	lb
Metal Ion	1.3E-05	lb
Dissolved Solids	0.066	lb
SuspendedSolids	1.96	lb
BOD	1.31	lb
COD	13.0	lb
Phenol	7.5E-08	lb
Sulfides	1.6E-07	lb
Oil	6.4E-05	lb
Iron	1.2E-05	lb
Cyanide	6.8E-08	lb
Chromium	1.1E-08	lb
Aluminum	0.11	lb
Nickel	1.2E-09	lb
Mercury	1.6E-09	lb
Lead	2.2E-09	lb
Phosphates	0.095	lb
Phosphorus	0.065	lb
Nitrogen	0.023	lb
Zinc	1.7E-08	lb
Ammonia	0.043	lb
Nitrates	0.0024	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-3

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF UNBLEACHED VIRGIN KRAFT PAPER FOR DUNNAGE

(includes all steps from raw material extraction through fabrication of packaging material)

Raw Materials		
Roundwood Harvesting	5,469	lb
Limestone Mining	19.3	lb
Sulfur Production	1.09	lb
Salt Mining	2.02	lb
Nitrogen Fertilizer	0.29	lb
Phosphate Fertilizer	0.11	lb
Potash Fertilizer	0.14	lb
Corn Growing	19.7	lb

Energy Usage			Total Energy Thousand Btu
Energy of Material Resource			
Natural Gas			4.22
Total Resource			4.22
Process Energy			
Electricity	98.4	kwh	1,102
Natural gas	1,205	cu ft	1,398
LPG	0.0014	gal	0.15
Coal	275	lb	3,155
Distillate oil	0.015	gal	2.31
Residual oil	0.57	gal	95.9
Gasoline	0.0011	gal	0.16
Diesel	1.79	gal	279
Wood	9,388	thou Btu	9,388
Total Process			15,421
Transportation Energy			
Combination truck	295	ton-miles	
Diesel	2.77	gal	433
Rail	7.74	ton-miles	
Diesel	0.019	gal	2.90
Barge	0.40	ton-miles	
Diesel	8.0E-04	gal	0.12
Residual oil	3.2E-04	gal	0.054
Ocean freighter	0.18	ton-miles	
Diesel	1.8E-05	gal	0.0027
Residual	3.2E-04	gal	0.053
Pipeline-natural gas	0.024	ton-miles	
Natural gas	0.055	cu ft	0.064
Pipeline-petroleum products	0.010	ton-miles	
Electricity	2.3E-04	kwh	0.0026
Total Transportation (for dunnage)			436

Table C-3 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF UNBLEACHED VIRGIN KRAFT PAPER FOR DUNNAGE

Environmental Emissions*

Atmospheric Emissions		
Particulates	1.81	lb
Nitrogen Oxides	7.05	lb
Hydrocarbons	0.024	lb
Sulfur Oxides	12.0	lb
Carbon Monoxide	8.22	lb
Aldehydes	0.012	lb
Ammonia	0.091	lb
Lead	7.7E-10	lb
Mercury	1.0E-04	lb
Chlorine	4.3E-07	lb
Hydrogen Chloride	8.3E-08	lb
Carbon Dioxide (fossil)	8.25	lb
Carbon Dioxide (non-fossil)	0.0059	lb
Total Reduced Sulfur	0.058	lb
Solid Wastes	75.6	lb
Waterborne Emissions		
Acid	0.025	lb
Metal Ion	1.3E-05	lb
Dissolved Solids	0.066	lb
SuspendedSolids	1.96	lb
BOD	1.31	lb
COD	13.0	lb
Phenol	7.5E-08	lb
Sulfides	1.6E-07	lb
Oil	6.4E-05	lb
Iron	1.2E-05	lb
Cyanide	6.8E-08	lb
Chromium	1.1E-08	lb
Aluminum	0.11	lb
Nickel	1.2E-09	lb
Mercury	1.6E-09	lb
Lead	2.2E-09	lb
Phosphates	0.095	lb
Phosphorus	0.065	lb
Nitrogen	0.023	lb
Zinc	1.7E-08	lb
Ammonia	0.043	lb
Nitrates	0.0024	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Recycled Paper Production. Postconsumer paper is recycled by repulping shredded material. In the repulping process, the collected paper is mixed with water in a huge blender-like vat, called a repulper. Blades at the bottom of the vat churn the water and beat the paper fiber away from any coatings. As the repulper is drained, filters allow the paper fibers to pass through. Any coatings are screened off and disposed. Much of the short fibers are also screened off of the pulp. The sludge can be collected from the repulper for beneficial uses, such as animal bedding or ground cover at landfills, or can be thrown away as solid waste. Additional chemicals are used if recycled pulp must be deinked for use in applications such as office paper, but recycled pulp used in packaging applications such as dunnage paper and shipping bags would not be deinked. In this analysis, data for the recycling of postconsumer paper include the repulping and papermaking steps.

Cradle-to-gate data for the production of unbleached recycled kraft paper for shipping bags are shown in Table C-4. Cradle-to-gate data for the production of bleached recycled kraft paper for shipping bags are shown in Table C-5.

Newsprint

The steps in the production of newsprint containing virgin and postconsumer content are shown in Figure C-7. The details for the production of virgin newsprint and 100 percent postconsumer newsprint are discussed below.

Virgin Newsprint. The production of virgin newsprint includes the following processes:

- Roundwood Harvesting
- Wood Residues Generation
- Salt Mining
- Sodium Chlorate Production
- Production of Caustic Soda (Sodium Hydroxide) and Chlorine
- Mechanical Pulp Manufacture
- Thermomechanical Pulp Manufacture
- Bleached Kraft Pulp Manufacture
- Newsprint Production

Roundwood harvesting, wood residues, salt mining, sodium chlorate production, caustic soda production, and bleached kraft manufacture are discussed previously in this appendix and are not repeated here. Mechanical pulp manufacture, thermomechanical pulp manufacture, and newsprint production are discussed below.

Table C-4

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF UNBLEACHED RECYCLED KRAFT PAPER FOR SHIPPING BAGS (100% POSTCONSUMER CONTENT)

(includes all steps from postconsumer material collection through production of unbleached recycled kraft paper and shipment to bag manufacturer)

			Total Energy Thousand Btu
Raw Materials			
OCC/Wastepaper Collection	1,056	lb	
Energy Usage			
Process Energy			
Electricity	292	kwh	3,271
Natural gas	531	cu ft	616
LPG	0.029	gal	3.08
Coal	220	lb	2,528
Distillate oil	0.014	gal	2.19
Residual oil	0.24	gal	40.5
Diesel	0.28	gal	43.4
Total Process			6,504
Transportation Energy			
Combination truck	184	ton-miles	
Diesel	1.73	gal	271
Single unit truck	10.6	ton-miles	
Diesel	0.28	gal	43.7
Total Transportation			315
Environmental Emissions*			
Solid Wastes	62.2	lb	
Waterborne Emissions			
Dissolved Solids	0.30	lb	
SuspendedSolids	3.01	lb	
BOD	3.03	lb	
COD	4.76	lb	
Phenol	0.0024	lb	
Sulfides	0.20	lb	
Oil	0.20	lb	
Iron	0.20	lb	
Aluminum	0.10	lb	
Phosphates	0.065	lb	
Zinc	0.0028	lb	
Ammonia	0.0050	lb	

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-5

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF BLEACHED RECYCLED KRAFT PAPER FOR SHIPPING BAGS (100% POSTCONSUMER CONTENT)

(includes all steps from postconsumer material collection through production of bleached recycled kraft paper and shipment to bag manufacturer)

			Total Energy Thousand Btu
Raw Materials			
OCC/Wastepaper Collection	1,056	lb	
Energy Usage			
Process Energy			
Electricity	292	kwh	3,271
Natural gas	531	cu ft	616
LPG	0.029	gal	3.08
Coal	220	lb	2,528
Distillate oil	0.014	gal	2.19
Residual oil	0.24	gal	40.5
Diesel	0.28	gal	43.4
Total Process			6,504
Transportation Energy			
Combination truck	184	ton-miles	
Diesel	1.73	gal	271
Single unit truck	10.6	ton-miles	
Diesel	0.28	gal	43.7
Total Transportation			315
Environmental Emissions*			
Solid Wastes	62.2	lb	
Waterborne Emissions			
Dissolved Solids	0.30	lb	
SuspendedSolids	3.01	lb	
BOD	3.03	lb	
COD	4.76	lb	
Phenol	0.0024	lb	
Sulfides	0.20	lb	
Oil	0.20	lb	
Iron	0.20	lb	
Aluminum	0.10	lb	
Phosphates	0.065	lb	
Zinc	0.0028	lb	
Ammonia	0.0050	lb	

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

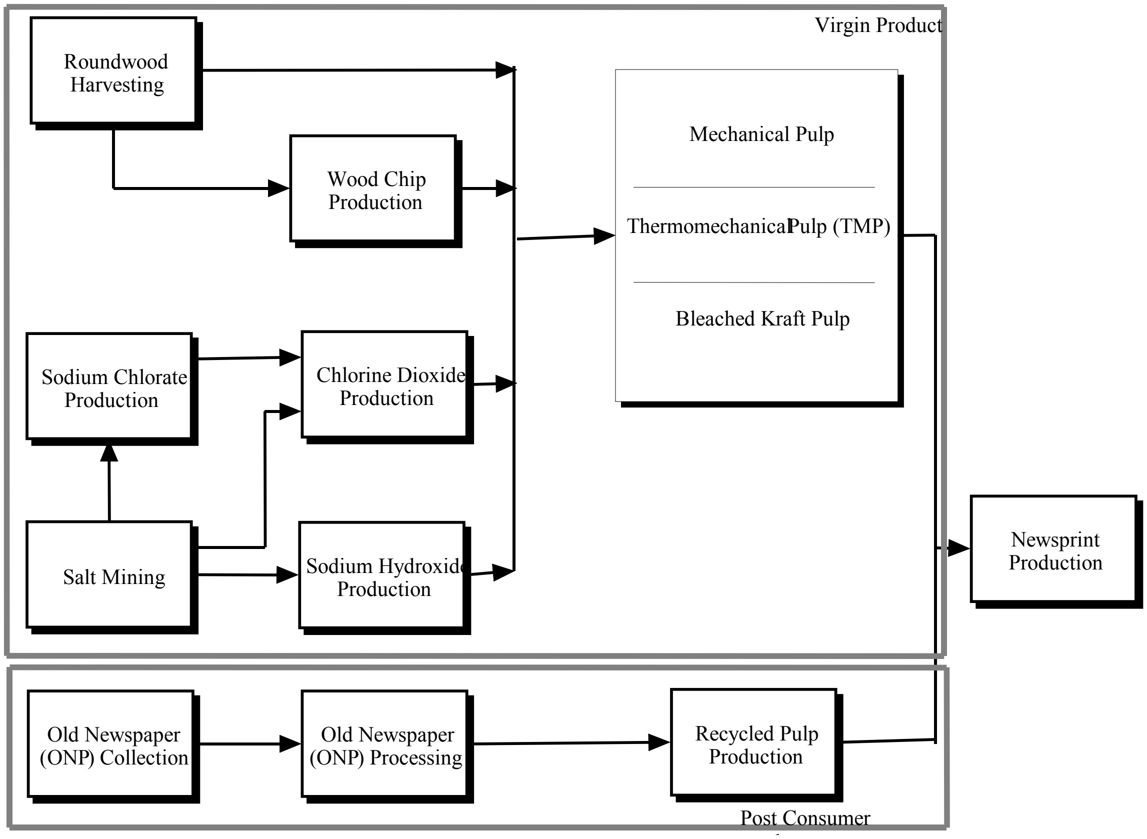

Figure C-7 Flow diagram for the production of newsprint with virgin and postconsumer content.

Mechanical Pulp Manufacture. Mechanical pulp, which is commonly either stone groundwood pulp (SGP) or refiner mechanical pulp (RMP), is one of the types of pulp used for manufacturing newsprint (Reference C-35). Data on refiner mechanical pulp production, which employs a disc refiner to break down wood chips, are now available. The data for mechanical pulp in this analysis represent only the stone groundwood process. The SGP process produces pulp by pressing blocks of wood against an abrasive rotating stone surface. Very little, if any, chemicals are used in this process (Reference C-35). No chemicals are assumed to be used in the production of groundwood pulp. (Usually bleached kraft pulp is blended with groundwood to make newsprint.)

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

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

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

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

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

Cradle-to-gate data for the production of virgin newsprint dunnage are shown in Table C-6.

Recycled Newsprint (100% Postconsumer). The postconsumer inputs to recycled newsprint production are predominantly old newspapers. Production of newsprint containing 100 percent postconsumer fiber includes the following steps:

- Old Newspaper (ONP) Collection
- Recycled Newsprint Production

Old Newspaper (ONP) Collection. The energy and emissions associated with the collection of old newspaper are based on data for similar processes.

Recycled Newsprint Production. The first step in recycled newsprint production is repulping, as described earlier in this appendix in the section **Recycled Paper Production**. Recycled pulp used to produce newsprint used for dunnage paper would not be deinked.

Table C-6

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN NEWSPRINT DUNNAGE PAPER (includes all steps from raw material extraction through fabrication of packaging material)

Raw Materials

Roundwood Harvest	2,703	lb
Salt mining	35.9	lb

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	1,047	kwh	11,726
Natural gas	5,509	cu ft	6,390
LPG	1.9E-05	gal	0.0021
Coal	19.3	lb	222
Residual oil	0.61	gal	103
Gasoline	5.9E-04	gal	0.083
Diesel	0.97	gal	151
Wood	1,757	thou Btu	1,757
Total Process			20,350
Transportation Energy			
Combination truck	146	ton-miles	
Diesel	1.37	gal	214
Rail	80.7	ton-miles	
Diesel	0.19	gal	30.2
Barge	0.31	ton-miles	
Diesel	6.2E-04	gal	0.097
Residual oil	2.5E-04	gal	0.042
Total Transportation			245

Table C-6 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN NEWSPRINT DUNNAGE PAPER

Environmental Emissions*

Atmospheric Emissions		
Particulates	1.55	lb
Nitrogen Oxides	0.34	lb
Hydrocarbons	0.094	lb
Sulfur Oxides	0.66	lb
Aldehydes	0.0097	lb
Other Organics	1.00	lb
Odorous Sulfur	0.11	lb
Mercury	9.8E-06	lb
Chlorine	5.5E-06	lb
ChlorineDioxide	0.0041	lb
Solid Wastes	138	lb
Waterborne Emissions		
Dissolved Solids	0.091	lb
SuspendedSolids	5.57	lb
BOD	5.64	lb
COD	4.04	lb
Phenol	3.1E-07	lb
Sulfides	2.7E-06	lb
Nickel	2.0E-08	lb
Mercury	2.8E-08	lb
Lead	1.4E-06	lb
Zinc	1.7E-04	lb
Methanol	0.014	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

The recycled pulp is then sent to the newsprint (papermaking) section of the mill, where it substitutes for the mechanical pulp, TMP, and bleached kraft pulp used to produce virgin newsprint. The recycled pulp goes through the same papermaking process as described for virgin newsprint.

Cradle-to-gate data for the production of recycled newsprint dunnage are shown in Table C-7.

Table C-7

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED NEWSPRINT DUNNAGE PAPER MADE FROM 100% POSTCONSUMER MATERIAL

(includes all steps from postconsumer material collection through fabrication of packaging material)

			Total Energy Thousand Btu
Raw Materials			
ONP Collection For Recycled Newsprint	1,265	lb	
Energy Usage			
Process Energy			
Electricity	117	kwh	1,313
Natural gas	2,855	cu ft	3,312
Diesel	0.18	gal	27.7
Total Process			4,652
Transportation Energy			
Combination truck	101	ton-miles	
Diesel	0.95	gal	149
Single unit truck	12.7	ton-miles	
Diesel	0.34	gal	52.4
Total Transportation			201
Environmental Emissions*			
Atmospheric Emissions			
Particulates	1.00	lb	
Other Organics	1.00	lb	
Solid Wastes	190	lb	
Waterborne Emissions			
SuspendedSolids	5.03	lb	
BOD	3.02	lb	

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Corrugated Paperboard

The material flows and steps in the production of corrugated containers are shown in Figure C-8. The production of corrugated products includes:

- Unbleached Kraft Linerboard Production
- Semichemical Medium Production
- Old Corrugated Container (OCC) Collection
- Recycled Paperboard (Linerboard and Medium) Production

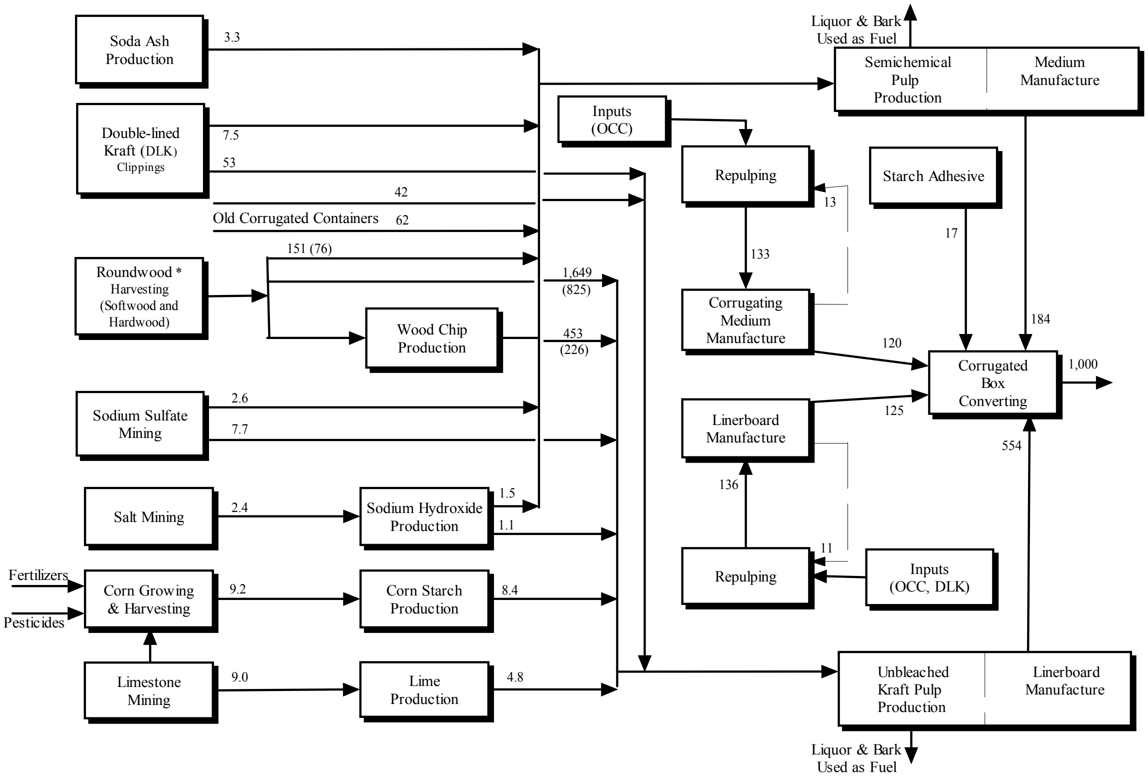

Figure C-8. Process Flow Diagram for the Production of 1,000 Pounds of Corrugated Containers.
All weights shown in pounds. Numbers in parentheses represent bone-dry weight of wood.
*Managed and/or unmanaged forest.

The production of unbleached kraft paper and old corrugated container collection are already discussed in this appendix and are not repeated here. The production of semichemical medium and recycled paperboard is discussed below. The only input material to any of these paper grades that has not already been discussed in this appendix is soda ash, used in the production of semichemical pulp.

Soda Ash Production. Soda ash (sodium carbonate) produced in the U.S. comes from natural soda ash obtained from trona or from alkaline brines. Almost all domestic soda ash comes from either the Green River Basin in Wyoming or Searles Lake in California, although a small amount is produced in Colorado. Underground trona mining is similar to coal mining. The most common methods are the room and pillar method and the long wall method.

In both of these processes the material is undercut, drilled, blasted, crushed, and then transported to the surface. Solution mining is presently being developed as a more efficient technique. In the refining process, the predominant energy use is in the calcining of bicarbonate to produce carbonate (Reference C-27). This analysis uses current percentages of production by each method to apportion energy and emissions data for soda ash production.

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

- Neutral Sulfite (NSSC) process, which uses sodium carbonate and sulfur or, in some cases, sodium sulfite purchased as a byproduct from a nearby chemical operation as the cooking chemical.
- Green Liquor process, which uses green liquor for the kraft recovery process as the cooking chemical.
- Non-sulfur process, which uses a combination of sodium carbonate, sodium hydroxide, and traces of other proprietary chemicals to enhance the properties of the pulp.

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

The data presented is based on two different process – the non-sulfur process and the NSSC process. A market share average of 60 percent non-sulfur and 40 percent NSSC was used in combining the data sets (Reference C-96).

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

Recycled Paperboard (Linerboard and Medium) Production. The collected wastepaper includes primarily old corrugated containers (OCC) and double-lined kraft (DLK). Also, small amounts of postconsumer office wastepaper and old newspapers can be used. Typically, these products are recycled by repulping shredded material.

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

The proportion of postconsumer fiber and industrial scrap consumed varies for specific recycled paperboard mills. The fibrous raw materials used in this data set reflect the national averages.

PRODUCT FABRICATION

This section discusses the fabrication of mail-order packaging for soft goods. This includes polyethylene film and inflated air packets, expanded polystyrene foam, cornstarch foam, molded pulp cushion cubes, corrugated boxes, and shredded materials used as dunnage. This report does not include assembly of these materials into composite packages such as paper shipping bags with bubble wrap lining. No data were available on the fabrication of bubble wrap from polyethylene resin.

Polyethylene Film Fabrication

Extrusion is a process that forms a film by using mechanical and thermal energy to melt a thermoplastic resin and force it through a die (Reference C-99). An extrusion system includes a hopper, a screw barrel, a screen pack, a breaker plate, an adapter valve, and a die. The hopper ensures a constant, sufficient feed of pelletized resin to the extruder. The screw barrel consists of a long, rotating screw that melts the resin through mechanical energy provided by the screw and thermal energy provided by heaters that surround the barrel. The screen pack consists of a series of mesh screens that filter impurities from the resin. The breaker plate creates a smooth, laminar flow of the resin. The adapter valve adjusts the back pressure on the screw barrel, ensuring that the extruder is always filled with resin as well as aiding in the mechanical shearing of the resin. The die forces the resin into its final form (Reference C-98).

Extrusion relies on electrical energy to drive the screw in the extruder barrel and to power the ceramic heaters that heat the extruder barrel. Energy data are available for turning the extruder screw, but no data are available for the ceramic heaters. The extrusion screw is constantly shearing and mixing the resin mixture. The ceramic heaters, on the other hand, are necessary during the startup of the extruder, but are used intermittently during continuous operation (Reference C-98). It is thus assumed that the electrical energy to drive the extrusion screw accounts for the majority of the energy for the extrusion process. In fact, one reference (Reference C-99) asserts that the friction produced by the extruder screw producers enough heat to melt the resin mixture without the assistance of ceramic heaters.

A small amount of smoke is produced at the extruder die. This smoke is captured by a fume collection system that prevents it from being released to the atmosphere (Reference C-98). It is assumed in this study that negligible amounts of airborne emissions are released from extrusion.

In this analysis, the energy and emissions data for polyethylene film fabrication are based on published power requirements for extrusion equipment and the assumptions discussed above.

Table C-8 shows the cradle-to-gate data for the production of virgin LDPE film, while data for the production of recycled LDPE film are shown in Table C-9. Cradle-to-gate data for the production of virgin LLDPE film are shown in Table C-10 and for recycled LLDPE film in Table C-11.

Fabrication of Polyethylene Inflated Air Packets

Inflated polyethylene air packets are typically sold to order fulfillment centers as flat (deflated) tubes of polyethylene film. (Companies can purchase the air packets pre-inflated although this is not cost effective unless very small quantities are needed.) The tube stock is fed into a machine that uses either electricity or a combination of electricity and compressed air (for higher volume machines) to inflate the tubes and seal them at regular intervals.

In this analysis, the energy data for the fabrication of inflated air packets are based on the use of a mid-range machine marketed by Storopack that produces 48 feet of inflated air packets per minute and draws an estimated 220 – 230 Watts of electric power. Data were converted to pounds of inflated air packets based on the packing study described in Appendix B.

Cradle-to-gate data for the production of virgin LDPE sealed air packets are shown in Table C-12. Cradle-to-gate data for the production of recycled LDPE sealed air packets are shown in Table C-13.

EPS Foam Product Fabrication

There are several steps for expanding polystyrene into foam. Polystyrene, in the form of small beads, is first expanded with heat and dry steam. This vaporizes the blowing agent and expands the softened beads. The polystyrene is then conveyed through a cool air stream to a storage container. The storage phase allows the blowing agent content to drop below three percent (Reference C-49). The final product is then produced by molding or extrusion.

Table C-8

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN LDPE FILM (includes all steps from raw material extraction through production of virgin LDPE film and shipment to bag manufacturer)

Raw Materials

Crude Oil Production	255	lb
Natural Gas Production	781	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			18,200
Petroleum			5,103
Total Resource			23,304
Process Energy			
Electricity	659	kwh	7,377
Natural gas	7,144	cu ft	8,287
LPG	0.043	gal	4.58
Distillate oil	0.24	gal	37.6
Residual oil	0.64	gal	109
Gasoline	0.81	gal	112
Total Process			15,927
Transportation Energy			
Combination truck	518	ton-miles	
Diesel	4.87	gal	761
Rail	563	ton-miles	
Diesel	1.35	gal	211
Barge	10.7	ton-miles	
Diesel	0.021	gal	3.34
Residual oil	0.0086	gal	1.44
Ocean freighter	517	ton-miles	
Diesel	0.052	gal	8.07
Residual	0.93	gal	157
Pipeline-natural gas	53.5	ton-miles	
Natural gas	123	cu ft	143
Pipeline-petroleum products	114	ton-miles	
Electricity	2.50	kwh	28.0
Total Transportation			1,312

Table C-8 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN LDPE FILM

Environmental Emissions*		
Atmospheric Emissions		
Particulates	0.19	lb
Nitrogen Oxides	1.11	lb
Hydrocarbons	12.5	lb
Sulfur Oxides	30.6	lb
Carbon Monoxide	0.23	lb
Aldehydes	0.010	lb
Methane	5.98	lb
Ammonia	0.0013	lb
Lead	3.5E-07	lb
Chlorine	5.3E-05	lb
Hydrogen Chloride	4.1E-05	lb
Solid Wastes	100	lb
Waterborne Emissions		
Acid	0.13	lb
Metal Ion	0.0061	lb
Dissolved Solids	47.8	lb
SuspendedSolids	0.35	lb
BOD	0.29	lb
COD	1.11	lb
Phenol	2.0E-05	lb
Sulfides	0.060	lb
Oil	0.87	lb
Iron	1.1E-04	lb
Cyanide	3.2E-06	lb
Chromium	0.0022	lb
Mercury	1.7E-07	lb
Lead	5.1E-07	lb
Phosphates	0.0067	lb
Zinc	0.0019	lb
Ammonia	4.6E-04	lb
Chlorides	2.21	lb
Cadmium	0.0022	lb
Organic Carbon	0.14	lb
Sulfates	1.70	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-9

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED LDPE FILM (100% POSTCONSUMER CONTENT)
(includes all steps from postconsumer material collection through production of recycled LDPE film and shipment to bag manufacturer)

Raw Materials

Postconsumer LDPE resin (collection and recycling)	1,010	lb

Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	486	kwh	5,443
Natural gas	36.4	cu ft	42.2
LPG	0.11	gal	11.8
Total Process			5,497
Transportation Energy			
Combination truck	194	ton-miles	
Diesel	1.82	gal	285
Single unit truck	125	ton-miles	
Diesel	3.32	gal	518
Total Transportation			803

Environmental Emissions*

Solid Wastes	121	lb

---

* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-10

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN LLDPE FILM (includes all steps from raw material extraction through production of virgin LLDPE film and shipment to bag manufacturer)

Raw Materials

Crude Oil Production	256	lb
Natural Gas Production	785	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			18,291
Petroleum			5,129
Total Resource			23,420
Process Energy			
Electricity	499	kwh	5,595
Natural gas	6,885	cu ft	7,986
LPG	0.043	gal	4.60
Distillate oil	0.24	gal	37.8
Residual oil	0.65	gal	109
Gasoline	0.81	gal	113
Total Process			13,846
Transportation Energy			
Combination truck	518	ton-miles	
Diesel	4.87	gal	761
Rail	554	ton-miles	
Diesel	1.33	gal	208
Barge	10.7	ton-miles	
Diesel	0.021	gal	3.36
Residual oil	0.0086	gal	1.45
Ocean freighter	519	ton-miles	
Diesel	0.052	gal	8.11
Residual	0.93	gal	158
Pipeline-natural gas	53.7	ton-miles	
Natural gas	124	cu ft	143
Pipeline-petroleum products	87.9	ton-miles	
Electricity	1.93	kwh	21.7
Total Transportation			1,305

Table C-10 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN LLDPE FILM

Environmental Emissions*

Atmospheric Emissions		
Particulates	0.25	lb
Nitrogen Oxides	1.11	lb
Hydrocarbons	10.4	lb
Sulfur Oxides	30.7	lb
Carbon Monoxide	0.23	lb
Aldehydes	0.010	lb
Methane	6.01	lb
Ammonia	0.0014	lb
Lead	3.6E-07	lb
Chlorine	5.4E-05	lb
Hydrogen Chloride	4.1E-05	lb
Solid Wastes	102	lb
Waterborne Emissions		
Acid	0.13	lb
Metal Ion	0.0061	lb
Dissolved Solids	48.0	lb
SuspendedSolids	0.12	lb
BOD	0.095	lb
COD	0.58	lb
Phenol	2.0E-05	lb
Sulfides	0.060	lb
Oil	0.88	lb
Iron	1.1E-04	lb
Cyanide	3.2E-06	lb
Chromium	0.0022	lb
Mercury	1.7E-07	lb
Lead	5.1E-07	lb
Phosphates	0.0067	lb
Zinc	0.0019	lb
Ammonia	4.6E-04	lb
Chlorides	2.22	lb
Cadmium	0.0022	lb
Organic Carbon	0.14	lb
Sulfates	1.70	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-11

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED LLDPE FILM (100% POSTCONSUMER CONTENT) (includes all steps from postconsumer material collection through production of recycled LLDPE film and shipment to bag manufacturer)

			Total Energy Thousand Btu
Raw Materials			
Postconsumer LLDPE resin (collection and recycling)	1,010	lb	
Energy Usage			
Process Energy			
Electricity	486	kwh	5,443
Natural gas	36.4	cu ft	42.2
LPG	0.11	gal	11.8
Total Process			5,497
Transportation Energy			
Combination truck	194	ton-miles	
Diesel	1.82	gal	285
Single unit truck	125	ton-miles	
Diesel	3.32	gal	518
Total Transportation			803
Environmental Emissions*			
Solid Wastes	121	lb	

---

* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-12

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN LDPE SEALED AIR PACKETS

(includes all steps from raw material extraction through production of LDPE tube stock, plus inflating and sealing at the order fulfillment center)

Raw Materials

Crude Oil Production	255	lb
Natural Gas Production	781	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			18,200
Petroleum			5,103
Total Resource			23,304
Process Energy			
Electricity	663	kwh	7,425
Natural gas	7,144	cu ft	8,287
LPG	0.043	gal	4.58
Distillate oil	0.24	gal	37.6
Residual oil	0.64	gal	109
Gasoline	0.81	gal	112
Total Process			15,975
Transportation Energy			
Combination truck	498	ton-miles	
Diesel	4.68	gal	731
Rail	542	ton-miles	
Diesel	1.30	gal	203
Barge	10.7	ton-miles	
Diesel	0.021	gal	3.34
Residual oil	0.0086	gal	1.44
Ocean freighter	517	ton-miles	
Diesel	0.052	gal	8.07
Residual	0.93	gal	157
Pipeline-natural gas	53.5	ton-miles	
Natural gas	123	cu ft	143
Pipeline-petroleum products	114	ton-miles	
Electricity	2.50	kwh	28.0
Total Transportation			1,274

Table C-12 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN LDPE SEALED AIR PACKETS

Environmental Emissions*

Atmospheric Emissions		
Particulates	0.19	lb
Nitrogen Oxides	1.11	lb
Hydrocarbons	12.5	lb
Sulfur Oxides	30.6	lb
Carbon Monoxide	0.23	lb
Aldehydes	0.010	lb
Methane	5.98	lb
Ammonia	0.0013	lb
Lead	3.5E-07	lb
Chlorine	5.3E-05	lb
Hydrogen Chloride	4.1E-05	lb
Solid Wastes	110	lb
Waterborne Emissions		
Acid	0.13	lb
Metal Ion	0.0061	lb
Dissolved Solids	47.8	lb
SuspendedSolids	0.35	lb
BOD	0.29	lb
COD	1.11	lb
Phenol	2.0E-05	lb
Sulfides	0.060	lb
Oil	0.87	lb
Iron	1.1E-04	lb
Cyanide	3.2E-06	lb
Chromium	0.0022	lb
Mercury	1.7E-07	lb
Lead	5.1E-07	lb
Phosphates	0.0067	lb
Zinc	0.0019	lb
Ammonia	4.6E-04	lb
Chlorides	2.21	lb
Cadmium	0.0022	lb
Organic Carbon	0.14	lb
Sulfates	1.70	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-13

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED LDPE SEALED AIR PACKETS (100% POSTCONSUMER MATERIAL)
(includes all steps from postconsumer material collection through production of recycled LDPE tube stock, plus inflating and sealing at the order fulfillment center)

Raw Materials			
Postconsumer LDPE resin (collection and recycling)	1,010	lb	
Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Process Energy			
Electricity	490	kwh	5,491
Natural gas	36.4	cu ft	42.2
LPG	0.11	gal	11.8
Total Process			5,545
Transportation Energy			
Combination truck	194	ton-miles	
Diesel	1.82	gal	285
Single unit truck	125	ton-miles	
Diesel	3.32	gal	518
Total Transportation			803
Environmental Emissions*			
Solid Wastes	131	lb	

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Cradle-to-gate data for the production of virgin EPS loose fill are shown in Table C-14. Cradle-to-gate data for the production of recycled EPS loose fill are shown in Table C-15.

Table C-14

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN EPS LOOSE FILL (includes all steps from raw material extraction through fabrication of packaging material)

Raw Materials

Crude Oil Production	978	lb
Natural Gas Production	254	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			5,907
Petroleum			19,586
Total Resource			25,492
Process Energy			
Electricity	1,051	kwh	11,777
Natural gas	17,599	cu ft	20,415
LPG	0.17	gal	17.6
Distillate oil	0.75	gal	117
Residual oil	6.16	gal	1,039
Gasoline	0.35	gal	48.3
Total Process			33,414
Transportation Energy			
Combination truck	619	ton-miles	
Diesel	5.82	gal	909
Rail	717	ton-miles	
Diesel	1.72	gal	269
Barge	128	ton-miles	
Diesel	0.26	gal	40.0
Residual oil	0.10	gal	17.3
Ocean freighter	1,983	ton-miles	
Diesel	0.20	gal	31.0
Residual	3.57	gal	603
Pipeline-natural gas	17.3	ton-miles	
Natural gas	39.9	cu ft	46.3
Pipeline-petroleum products	342	ton-miles	
Electricity	7.53	kwh	84.3
Total Transportation			1,999

Table C-14 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF VIRGIN EPS LOOSE FILL

Environmental Emissions*

Atmospheric Emissions		
Particulates	0.12	lb
Nitrogen Oxides	0.36	lb
Hydrocarbons	9.51	lb
Sulfur Oxides	10.4	lb
Carbon Monoxide	0.070	lb
Aldehydes	0.039	lb
Methane	1.94	lb
Ammonia	0.0052	lb
Lead	1.4E-06	lb
Chlorine	2.0E-04	lb
Hydrogen Chloride	1.6E-04	lb
Carbon Dioxide (fossil)	36.3	lb
Solid Wastes	50.3	lb
Waterborne Emissions		
Acid	0.037	lb
Metal Ion	0.023	lb
Dissolved Solids	16.4	lb
SuspendedSolids	0.34	lb
BOD	0.60	lb
COD	1.08	lb
Phenol	7.6E-05	lb
Sulfides	0.020	lb
Oil	0.34	lb
Iron	4.1E-04	lb
Cyanide	1.0E-06	lb
Chromium	7.1E-04	lb
Mercury	5.6E-08	lb
Lead	1.9E-06	lb
Phosphates	0.0019	lb
Zinc	5.9E-04	lb
Ammonia	0.0018	lb
Chlorides	0.72	lb
Cadmium	7.1E-04	lb
Organic Carbon	0.046	lb
Sulfates	0.55	lb
Hydrocarbons	0.10	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-15

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF RECYCLED EPS LOOSE FILL (100% POSTCONSUMER CONTENT) (includes all steps from postconsumer material collection through fabrication of packaging material)

Raw Materials			
Postconsumer EPS collection	1,100	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	834	kwh	9,336
Natural gas	7,563	cu ft	8,773
Total Process			18,109
Transportation Energy			
Combination truck	604	ton-miles	
Diesel	5.68	gal	887
Single unit truck	300	ton-miles	
Diesel	7.96	gal	1,243
Rail	604	ton-miles	
Diesel	1.45	gal	226
Total Transportation			2,356
Environmental Emissions*			
Atmospheric Emissions			
Nitrogen Oxides	0.12	lb	
Hydrocarbons	0.84	lb	
Carbon Monoxide	0.020	lb	
Solid Wastes	100	lb	

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Cornstarch Foam Fabrication

Cornstarch foam is produced by an extrusion process. Starch and water are mixed in an extruder; a composition of 21 percent water by weight is desired (Reference C-108). The extruding equipment is equipped with heaters, but the majority of heat in the cornstarch and water mixture arises from the shear force of the rotating screws in the extruder (Reference C-106). When the mixture exits the small holes of the extruder, the water instantly flashes into steam, forming the foam. The foam is cut to length as it exits the extruder. Cradle-to-gate data for the production of cornstarch loose fill are shown in Table C-16.

Molded Pulp Cushion Cubes Fabrication

Molded pulp cubes are used as dunnage in shipping containers. The steps in the production of molded pulp cubes are shown in Figure C-9 and include the following processes:

- Old newspaper (ONP) Collection
- Repulping
- Molded Pulp Loosefill Production

Old newspaper collection and repulping are discussed previously in this appendix and are not repeated here. The manufacture of molded pulp loosefill is discussed below.

Molded Pulp Loosefill Production. The molding of pulp starts in a slurry tank that is constantly replenished with pulp. The slurry tank feeds into forming equipment that use metal plates to press the pulp into the desired shape. The molded pulp is then transferred to a gas-fired heater that dries the product. Cradle-to-gate data for the production of molded pulp loose fill from 100% postconsumer newspaper are shown in Table C-17.

Table C-16

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF CORNSTARCH LOOSE FILL
(includes all steps from raw material extraction through fabrication of packaging material)

Raw Materials

Nitrogen Fertilizer	15.9	lb
Phosphate Fertilizer	6.19	lb
Potash Fertilizer	7.59	lb
Corn Growing & Harvesting	1,092	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			234
Total Resource			234
Process Energy			
Electricity	465	kwh	5,207
Natural gas	708	cu ft	821
Coal	17.0	lb	195
Distillate oil	0.0060	gal	0.93
Residual oil	0.73	gal	123
Gasoline	0.0017	gal	0.24
Diesel	0.69	gal	107
Total Process			6,455
Transportation Energy			
Combination truck	443	ton-miles	
Diesel	4.16	gal	650
Rail	449	ton-miles	
Diesel	1.08	gal	168
Barge	1.24	ton-miles	
Diesel	0.0025	gal	0.39
Residual oil	0.0010	gal	0.17
Ocean freighter	5.84	ton-miles	
Diesel	5.8E-04	gal	0.091
Residual	0.011	gal	1.77
Pipeline-natural gas	0.80	ton-miles	
Natural gas	1.83	cu ft	2.12
Pipeline-petroleum products	0.35	ton-miles	
Electricity	0.0077	kwh	0.086
Total Transportation			823

Table C-16 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF CORNSTARCH LOOSE FILL

Environmental Emissions*

Atmospheric Emissions		
Particulates	0.82	lb
Nitrogen Oxides	5.2E-04	lb
Hydrocarbons	0.36	lb
Sulfur Oxides	0.89	lb
Carbon Monoxide	0.0035	lb
Aldehydes	1.2E-04	lb
Ammonia	0.020	lb
Carbon Dioxide (non-fossil)	0.33	lb
Solid Wastes	46.0	lb
Waterborne Emissions		
Acid	0.10	lb
Dissolved Solids	3.36	lb
SuspendedSolids	11.1	lb
BOD	1.22	lb
COD	1.95	lb
Phenol	1.9E-06	lb
Oil	0.0017	lb
Iron	6.8E-04	lb
Cyanide	3.8E-06	lb
Chromium	4.7E-07	lb
Phosphates	0.29	lb
Nitrogen	1.29	lb
Ammonia	0.0012	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Figure C-9. Flow diagram for the production of molded pulp loosefill.

Table C-17

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF MOLDED PULP LOOSE FILL MADE FROM 100% POSTCONSUMER NEWSPAPER (includes all steps from postconsumer material collection through fabrication of packaging material)

Raw Materials			
Postconsumer paper collection	1,050	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	663	kwh	7,426
Natural gas	7,256	cu ft	8,417
Diesel	0.15	gal	23.0
Total Process			15,866
Transportation Energy			
Single unit truck	78.8	ton-miles	
Diesel	2.09	gal	326
Total Transportation			326
Environmental Emissions*			
Solid Wastes	50.0	lb	

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Corrugated Box Fabrication

The fabrication of corrugated boxes includes cutting, folding, and gluing operations. Data for the fabrication of corrugated boxes are based on confidential data provided by industry sources (Reference C-87). Cradle-to-gate data for the production of average postconsumer recycled content corrugated boxes are shown in Table C-18, and data for 80% postconsumer recycled content boxes are shown in Table C-19.

OCC Shredding

Shredding machinery is used to reduce corrugated material into dunnage. Local shredding operations reduce the need for transporting the shredded material. In this analysis, the energy requirements for OCC shredding are based on the equipment specifications and throughput available from leading equipment manufacturers. Cradle-to-gate data for the production of shredded corrugated loose fill are shown in Table C-20.

Paper Shredding

When paper is used as dunnage, it must be shredded. Industrial shredding equipment uses rotating blades to shred high volumes of paper. Actual energy used for shredding will vary with the type of shredding equipment used. Cradle-to-gate data for the production of shredded paper loose fill are shown in Table C-21. Cradle-to-gate data for the production of shredded paper padding for shipping bags are shown in Table C-22.

Table C-18

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF CORRUGATED BOXES WITH AVERAGE POSTCONSUMER RECYCLED CONTENT (38%)

(includes all steps from raw material extraction and postconsumer material collection through box production and shipment to order fulfillment center)

Raw Materials		
Roundwood	4,119	lb
Wood residues	427	lb
Postconsumer corrugated	502	lb
Kraft clippings	51.2	lb
Salt mining	3.33	lb
Soda ash	3.31	lb
Sodium sulfate	17.2	lb
Limestone mining	17.5	lb
Sulfur production	1.08	lb
N2 fertilizer	0.55	lb
Phosphate fertilizer	0.21	lb
Potash fertilizer	0.26	lb
Corn growing	37.6	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			6.22
Total Resource			6.22
Process Energy			
Electricity	254	kwh	2,845
Natural gas	1,256	cu ft	1,457
LPG	0.012	gal	1.22
Coal	218	lb	2,508
Distillate oil	0.020	gal	3.19
Residual oil	0.41	gal	68.4
Gasoline	7.4E-04	gal	0.10
Diesel	0.89	gal	139
Wood	5,405	thou Btu	5,405
Total Process			12,427
Transportation Energy			
Combination truck	176	ton-miles	
Diesel	1.65	gal	258
Single unit truck	4.10	ton-miles	
Diesel	0.11	gal	17.0
Rail	70.8	ton-miles	
Diesel	0.17	gal	26.5
Barge	1.33	ton-miles	
Diesel	0.0027	gal	0.42
Residual oil	0.0011	gal	0.18
Ocean freighter	0.81	ton-miles	
Diesel	8.1E-05	gal	0.013
Residual	0.0015	gal	0.25
Pipeline-natural gas	0.042	ton-miles	
Natural gas	0.096	cu ft	0.11
Pipeline-petroleum products	0.055	ton-miles	
Electricity	0.0012	kwh	0.014
Total Transportation			303

Table C-18 (continued)

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF CORRUGATED BOXES WITH AVERAGE POSTCONSUMER RECYCLED CONTENT (38%)

Environmental Emissions*

Atmospheric Emissions		
Particulates	1.95	lb
Nitrogen Oxides	3.47	lb
Hydrocarbons	0.020	lb
Sulfur Oxides	5.89	lb
Carbon Monoxide	4.04	lb
Aldehydes	0.0060	lb
Other Organics	9.3E-06	lb
Odorous Sulfur	0.029	lb
Ammonia	0.045	lb
Lead	1.2E-09	lb
Mercury	5.0E-05	lb
Chlorine	4.7E-07	lb
Hydrogen Chloride	5.0E-08	lb
Carbon Dioxide (fossil)	4.06	lb
Carbon Dioxide (non-fossil)	0.0029	lb
Solid Wastes	69.5	lb
Waterborne Emissions		
Acid	0.014	lb
Metal Ion	7.8E-06	lb
Dissolved Solids	0.15	lb
SuspendedSolids	3.04	lb
BOD	2.45	lb
COD	9.19	lb
Phenol	8.6E-04	lb
Sulfides	0.072	lb
Oil	0.072	lb
Iron	0.072	lb
Cyanide	1.0E-07	lb
Chromium	1.4E-08	lb
Aluminum	0.090	lb
Nickel	1.5E-09	lb
Mercury	2.0E-09	lb
Lead	2.1E-09	lb
Phosphates	0.075	lb
Phosphorus	0.032	lb
Nitrogen	0.034	lb
Zinc	0.0010	lb
Ammonia	0.023	lb
Pesticides	8.7E-04	lb
Nitrates	0.0012	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-19

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF CORRUGATED BOXES WITH HIGH POSTCONSUMER RECYCLED CONTENT (80%)

(includes all steps from raw material extraction and postconsumer material collection through box production and shipment to order fulfillment center)

Raw Materials

Roundwood	1,610	lb
Wood residues	173	lb
Postconsumer corrugated	901	lb
Kraft clippings	18.2	lb
Salt mining	0.91	lb
Sodium sulfate	5.90	lb
Limestone mining	7.29	lb
Sulfur production	0.51	lb
N2 fertilizer	0.39	lb
Phosphate fertilizer	0.15	lb
Potash fertilizer	0.19	lb
Corn growing	26.7	lb

Energy Usage			**Total Energy Thousand Btu**
Energy of Material Resource			
Natural Gas			4.98
Total Resource			4.98
Process Energy			
Electricity	294	kwh	3,296
Natural gas	1,093	cu ft	1,268
LPG	0.024	gal	2.55
Coal	234	lb	2,691
Distillate oil	0.021	gal	3.21
Residual oil	0.32	gal	53.5
Gasoline	2.7E-04	gal	0.038
Diesel	0.53	gal	82.6
Wood	1,850	thou Btu	1,850
Total Process			9,247
Transportation Energy			
Combination truck	182	ton-miles	
Diesel	1.71	gal	267
Single unit truck	8.64	ton-miles	
Diesel	0.23	gal	35.8
Rail	3.38	ton-miles	
Diesel	0.0081	gal	1.27
Barge	0.11	ton-miles	
Diesel	2.3E-04	gal	0.036
Residual oil	9.1E-05	gal	0.015
Ocean freighter	0.46	ton-miles	
Diesel	4.6E-05	gal	0.0071
Residual	8.2E-04	gal	0.14
Pipeline-natural gas	0.027	ton-miles	
Natural gas	0.063	cu ft	0.073
Pipeline-petroleum products	0.031	ton-miles	
Electricity	6.8E-04	kwh	0.0076
Total Transportation			305

Table C-19

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF CORRUGATED BOXES WITH HIGH POSTCONSUMER RECYCLED CONTENT (80%)

Environmental Emissions*

Atmospheric Emissions		
Particulates	1.41	lb
Nitrogen Oxides	1.39	lb
Hydrocarbons	0.013	lb
Sulfur Oxides	2.36	lb
Carbon Monoxide	1.62	lb
Aldehydes	0.0024	lb
Odorous Sulfur	0.011	lb
Ammonia	0.018	lb
Lead	9.8E-10	lb
Mercury	2.0E-05	lb
Chlorine	1.3E-07	lb
Hydrogen Chloride	2.5E-08	lb
Carbon Dioxide (fossil)	1.63	lb
Carbon Dioxide (non-fossil)	0.0012	lb
Solid Wastes	52.2	lb
Waterborne Emissions		
Acid	0.0067	lb
Metal Ion	4.0E-06	lb
Dissolved Solids	0.26	lb
SuspendedSolids	3.11	lb
BOD	2.81	lb
COD	6.55	lb
Phenol	0.0019	lb
Sulfides	0.16	lb
Oil	0.16	lb
Iron	0.16	lb
Cyanide	8.0E-08	lb
Chromium	1.1E-08	lb
Aluminum	0.10	lb
Nickel	3.4E-10	lb
Mercury	4.8E-10	lb
Lead	6.8E-10	lb
Phosphates	0.076	lb
Phosphorus	0.013	lb
Nitrogen	0.027	lb
Zinc	0.0023	lb
Ammonia	0.013	lb
Pesticides	8.7E-04	lb
Nitrates	4.7E-04	lb

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* Total process emissions. Fuel-related emissions (associated with the extraction, processing, delivery, and combustion of the process and transportation fuels shown in this table) are calculated by the model based on data shown in Appendix A tables and are not shown here.

Source: Franklin Associates.

Table C-20

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF LOOSE FILL (100% SHREDDED POSTCONSUMER CORRUGATED)
(includes shredding of postconsumer material collected at order fulfillment center)

Raw Materials			
OCC Collection	1,000	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	7.00	kwh	78.4
Total Process			78.4

Source: Franklin Associates.

Table C-21

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF LOOSE FILL (100% SHREDDED POSTCONSUMER OFFICE PAPER)
(includes shredding of postconsumer material collected at order fulfillment center)

Raw Materials			
Paper Collection	1,000	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	22.0	kwh	246
Total Process			246

Source: Franklin Associates.

Table C-22

DATA FOR THE PRODUCTION OF 1,000 POUNDS OF PADDING FOR SHIPPING BAGS (100% SHREDDED POSTCONSUMER NEWSPAPER)

(includes all steps from postconsumer material collection through shipment to bag manufacturer and shredding)

Raw Materials			
Paper Collection	1,000	lb	
Energy Usage			**Total Energy Thousand Btu**
Process Energy			
Electricity	23.0	kwh	257
Diesel	0.14	gal	21.9
Total Process			279
Transportation Energy			
Single unit truck	75.0	ton-miles	
Diesel	1.99	gal	310
Total Transportation			310

Source: Franklin Associates.

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APPENDIX D

TRANSPORTATION

OVERVIEW OF TRANSPORTATION SEGMENTS

A Life Cycle Inventory includes the resource and energy use, solid wastes, and emissions not only for all the processes in the life cycle of a product system from cradle-to-grave, but also for the transportation steps required to move materials between these processes. For this study, transportation steps are grouped into three basic segments: (1) transportation of raw materials and intermediate materials from point of extraction to the location where they are manufactured into packaging materials, (2) transportation of packaging materials from the manufacturer to the mail order distribution center (order fulfillment center), and (3) transportation of packaged goods from the order fulfillment center to the mail-order goods customer.

For the purposes of this study, it is assumed that the order fulfillment center (packaging user) is located in Oregon, and that the final customer (household) is located in the United States. To simplify the analysis, the study assumes a single order fulfillment center and a single "average" customer, intended to represent reasonable averages for the purpose of estimating transportation requirements and associated environmental burdens.

To arrive at reasonable locations for the order fulfillment center and customer, the study begins with the year 2000 population centers of the United States and the State of Oregon, as determined by the U.S. Department of Commerce, Census Bureau. The population center is determined as the place where an imaginary, flat, weightless and rigid map of the United States (or Oregon) would balance perfectly if all residents were of identical weight. The population center of the United States for the 2000 Census is three miles to the east of Edgar Springs, Missouri. The population center of the State of Oregon is located near Lyons, Oregon.

Both Edgar Springs (population 190) and Lyons (population 1,008) are located in areas that are rural in nature. This is not surprising, given that the majority of the land in the U.S. is rural. In contrast, the majority of the U.S. population lives in suburban or urban areas, and direct-to-customer order fulfillment centers may be more likely to be sited in more urbanized areas, closer to population centers and a larger number of road, rail, and air freight options. To make the shipping scenario more representative of assumed industry averages, the study assumes that the order fulfillment center is located not in Lyons but in Salem, OR. Salem (2000 population 136,924) is approximately 26 miles to the west of Lyons and is located on Interstate 5. It is also the capital city of Oregon.

The authors recognize that this configuration of locations is unique and not representative of all possible configurations. The results of this study can be adapted to represent different transportation scenarios.

SHIPPING MODES/DISTANCES FOR RAW MATERIALS TO PACKAGING MANUFACTURERS

It is not practical to attempt to trace back the entire specific supply chain for each packaging material for several reasons. First, as can be seen in the flow diagrams in Appendix C, the "process tree" from raw material extraction to packaging manufacture consists of multiple processes that would be extremely time-consuming to research for a specific chain of suppliers. Also, many of the inputs to processes preceding packaging manufacture are commodity materials that can be obtained from any number of suppliers at various locations.

The shipping modes and distances used to model the transportation of raw materials and intermediate materials through all transportation steps up to the packaging manufacturer are based on Franklin Associates' LCI database for US processes. The transportation distances reflect the average distance that the output of each process is transported to a subsequent user of the material. These transportation distances and modes have been determined in previous in-depth analyses of these processes, taking into account locations of manufacturing plants and subsequent users, and are believed to be sufficiently representative for use in this study. Where DEQ was able to provide specific information on transportation of inputs to packaging material production, these data were used in place of industry average data. Transportation data specific to this study are summarized in Table D-1.

SHIPMENT OF PACKAGING MATERIALS TO ORDER FULFILLMENT CENTER

This section describes the assumed transportation distances and modes for packaging materials shipped to the order fulfillment center. The study assumes that the order fulfillment center (packaging user) is located in Salem, Oregon.

Corrugated Box: Average Post-Consumer Content

Corrugated cartons are manufactured from roll stock of kraft linerboard and corrugated medium. Box plants in Oregon purchase most of their linerboard and corrugated medium from mills located in the states of Oregon and Washington, although purchases from mills in California, British Columbia, and Montana are not unheard of. According to the *2002 Lockwood-Post's Directory of the Pulp, Paper, and Allied Trades*, there are 8 mills manufacturing kraft linerboard (or linerboard) and 4 mills manufacturing corrugated medium in Oregon and Washington. The Lockwood-Post's Directory also lists 20 box plants in Oregon and Washington. Some of these box plants are vertically integrated with mills (such as Weyerhaeuser and Boise Cascade) while others are independent (such as Tharco). Sourcing of materials by box plants is very complex. Even the vertically integrated box plants may purchase linerboard and medium from mills owned by other companies, and mills may sell linerboard and medium to box plants owned by other companies. Box plants may use linerboard from one company and corrugated medium from another.

Table D-1

TRANSPORTATION MODES AND DISTANCES FOR PACKAGING MATERIALS
(all distances in miles)

	Diesel Tractor-Trailer Truck	Single-Unit Diesel Truck	Rail	Ocean Freighter
Corrugated Box (1)				
linerboard -avg box	82			
linerboard - 80% postconsumer recycled content box	145			
medium - avg box	115			
medium - 80% postconsumer recycled content box	156			
Inflated Polyethylene Air Packets				
LDPE resin (TN) to tube stock mfr (CA)	959		959	
LDPE tube stock to dist ctr	1180			
EPS Loose Fill				
EPS resin (virgin) to loose fill mfr	1211		1211	
EPS resin (postconsumer) to loose fill mfr	1208		1208	
EPS loose fill (virgin) to dist ctr	105			
EPS loose fill (recycled) to dist ctr	214			
Starch-based Loose Fill				
cornstarch (KS) to loose fill mfr (WA)	883.5		883.5	
cornstarch loose fill to dist ctr	231			
Molded Pulp Loose Fill				
postconsumer newspaper to molded pulp loose fill mfr		150		
molded pulp loose fill to dist ctr	752			
Kraft Paper (Crumpled) (2)				
unbleached kraft from mill to converter to dist ctr	122			
Newsprint (Crumpled) (3)				
newsprint from mill to converter to dist ctr	101			
On-Site PC Shredded Office Paper/Corrugated	0			

(1) Includes transportation from mill to box manufacturer to distribution center.
(2) Same transportation data used for virgin and recycled content material.
(3) Same transportation data used for both levels of recycled content material.

Table D-1 (cont.)

TRANSPORTATION MODES AND DISTANCES FOR PACKAGING MATERIALS
(all distances in miles)

	Diesel Tractor-Trailer Truck	Single-Unit Diesel Truck	Rail	Ocean Freighter
Unpadded Kraft Bag (2)				
bleached kraft to shipping bag mfr	200			
shipping bag to dist ctr	1180			
Kraft Bag with Paper Padding				
kraft paper to bag mfr (2)	200			
postconsumer newspaper to bag mfr		150		
bag to dist ctr	1180			
Kraft with Bubble Wrap (4)				
kraft paper to bag mfr	200			
LDPE resin to bag mfr	1000		1000	
LLDPE resin to bag mfr	1000		1000	
recycled LDPE resin to bag mfr	100			
recycled LLDPE resin to bag mfr	100			
bag mfr to dist ctr	1180			
Unlined LLDPE Film Bag (5)				
LLDPE resin to bag mfr	1000		1000	
recycled LLDPE resin to bag mfr	100			
LLDPE shipping bags to dist ctr	1274			4517.5
LLDPE Film Bag with Bubble Wrap (4)				
LLDPE resin to bag mfr	1000		1000	
LDPE resin to bag mfr	1000		1000	
recycled LLDPE resin to bag mfr	100			
recycled LDPE resin to bag mfr	100			
bag mfr to dist ctr	1180			

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(1) Includes transportation from mill to box manufacturer to distribution center.
(2) Same transportation data used for virgin and recycled content material.
(3) Same transportation data used for both levels of recycled content material.
(4) Bubble wrap extruded from resin at bag mfr; resin 50% LDPE, 50% LLDPE.
(5) Assumes 50% bags manufactured in US, 50% overseas.
Transportation of resin to bag manufacturer assumed to be the same in U.S. or Asia.
Data for transportation of bag to dist ctr is weighted average for foreign and domestic bags.

The market share of each of these mills and box plants in the corrugated box market in Salem is not known, would be difficult to research, and is also subject to change as market prices, long-term contracts, and mill conditions (fiber supply, energy prices, maintenance shutdowns, etc.) fluctuate. Instead, this study makes the simplifying assumption that market share in Salem is equally determined by two variables: mill capacity, and distance from Salem.

Mill capacity is known from the Lockwood-Post's Directory. All other things being equal, mills manufacturing more linerboard (or medium) are expected to have greater market share. Similarly, all other things being equal, mills that are closer to Salem are expected to have greater market share there.

If there are N mills (numbered 1, 2, . . . , N) , each with daily capacity of C_n and a distance from Salem of D_n (where n ranges from 1 to N), then assumed market share (MS) in Salem of mill n is estimated as follows:

$MS_n = (C_n \times (R - D_n))/\Sigma(C \times (R - D))$ [summed from 1 to N]

where $R = 0.5 \times (370 \text{ miles} + D_{max})$

D_{max} is the distance from Salem that the farthest mill that manufactures linerboard or corrugated medium is located while still being in Oregon or Washington. D_{max} for linerboard is 256 miles (the Port Townsend Paper mill in Port Townsend, WA) and D_{max} for medium is 263 miles (the Boise Cascade mill in Wallula, WA). According to the Lockwood-Post Directory, the closest mill manufacturing linerboard and corrugating medium outside of Oregon and Washington is the Norampac mill in Burnaby, British Columbia, approximately 370 miles from Salem. Thus, R equals the mid-point between D_{max} (the farthest mill still in Washington or Oregon) and Burnaby. The value of R can be thought of as the radius of a circle, centered on Salem, for which box plants will draw within when purchasing material for fabricating boxes to be sold in Salem. This simple estimation technique assumes that boxes used in Salem will be constructed from linerboard and medium manufactured at mills located within this circle.

Under this approach, the estimated market shares of major linerboard and corrugated mills are as follows:

Major Linerboard Mills

Company	Location	Miles from Salem	Capacity (TPD)	Market Share (Estimated)
Weyerhaeuser	Springfield OR	64	2,000	27%
Longview Fiber	Longview WA	95	2,200	26%
Weyerhaeuser	Albany OR	24	1,550	24%
Georgia Pacific	Toledo OR	83	1,175	15%
Simpson	Tacoma WA	190	870	6%

(Pt. Townsend Paper, Sonoco (Sumner, WA) and Smurfit-Stone (Tacoma, WA) each have an estimated market share of <2%.)

Corrugated Medium Mills

Company	Location	Miles from Salem	Capacity (TPD)	Market Share (Estimated)
Georgia Pacific	Toledo OR	83	1,100	57%
Weyerhaeuser	North Bend OR	174	620	20%
Longview Fiber	Longview WA	95	400	20%
Boise Cascade	Wallula WA	263	325	4%

After each mill's market share is estimated, it is expressed as a decimal and multiplied by its mileage to Salem. These mileages are then summed, in order to estimate market-share weighted distances from the mills to the order fulfillment center.

Five miles are added to each sum to account for travel to a box plant that might not be located on-route from the mill directly to the end user. With six box plants in the Portland area and two in the Salem area, it is assumed that linerboard and medium will not be sent from a mill through Salem to a box plant beyond Salem. Put differently, this assumption means that linerboard from mills in Albany, Springfield and Toledo, and corrugated medium from Toledo and North Bend (all of which are south of Salem) that is used in boxes in Salem will be converted at a box plant in Salem, rather than being shipped through Salem to Portland (or beyond) and then back south to Salem.

This results in an estimated travel distance for 82 miles for linerboard and 115 miles for corrugated medium. This study assumes that these materials are exclusively transported by truck, per a conversation with a representative of Weyerhaeuser's Springfield mill.

Corrugated Box: 80% Post-Consumer Content

The post-consumer content of products manufactured in different mills is not known to the authors. The requirement of 80% post-consumer content may cause the box plant(s) to cast farther afield for linerboard. For example, Tharco (a major box converter in the Pacific Northwest), told Pack Edge Development that when making their "high-recycled content" box (80% post-consumer content), they source material from the I-5 Corridor, as far away as the San Francisco Bay area.

According to the Lockwood-Post's Directory, there is one linerboard and two corrugating medium mills in the San Francisco Bay area. Thus, using the weighting formula described for "average" post-consumer corrugated boxes (above), D_{max} for linerboard is 600 miles (the Gaylord linerboard mill in Antioch, CA) and D_{max} for medium is 655 miles (the Inland Paper mill in Newark, CA). These higher values of D_{max} also bring several additional mills (in Montana and British Columbia) into the weighting formula. The next closest mills to Antioch and Newark are located in Southern California (the Smurfit-Stone linerboard mill in Vernon and Weyerhaeuser medium mill in Oxnard) and R is defined as the midpoint between D_{max} and these more-distant mills.

Using the same estimation methodology and assumptions as was done for the "average" corrugated box (above) results in an estimated transportation distance of 145 miles for high-recycled-content linerboard and 156 miles for high-recycled-content medium. Again, this study assumes that these materials are exclusively transported by truck.

Inflated Polyethylene Air Packets

The authors are aware of three major manufacturers of LDPE (or LDPE/LLDPE) inflatable polyethylene air packets in the U.S.: Storopack, Pactiv, and Sealed Air Corporation.

According to conversations between Pack Edge Development and representatives of Storopack, Storopack's "tube stock" for pillow packs is made in Los Angeles using resin shipped from Tennessee. From Los Angeles, tube stock is trucked to a warehouse in Kent, WA for sale to customers throughout the Pacific Northwest, including Oregon. Transportation modes from Tennessee to Los Angeles are not known, however, Pack Edge Development was told that polystyrene beads used at Storopack's Kent, WA facility are shipped there from Memphis using a combination of rail and truck. Having no further information, the study assumes that polyethylene resin shipped from Tennessee to Los Angeles is shipped 50% by rail, and 50% by truck.

Neither Sealed Air Corporation nor Pactiv informed the authors where their tube stock is fabricated, although when asked, one representative of Pactiv was willing to state that all of their packaging material is made in the United States, and that the largest Pactiv facility serving the Western U.S. is in Visalia, CA. This study assumes that Pactiv manufactures pillow pack tube stock at this facility, although this is not known as a fact. The source of the resin is also not known, so for the sake of consistency, it is assumed to be shipped from Memphis, consistent with Storopack (above). Pack Edge staff's experience purchasing items from Pactiv (in Oregon) is that materials are typically shipped to Oregon from a stocking warehouse in Kent, WA, so this study assumes that tube stock is trucked from Visalia, CA to Kent, and then from Kent to Salem for use.

The authors have no information from Sealed Air Corporation except that they have a facility in Hayward, CA. As with Pactiv, it is assumed that tube stock is manufactured at this facility, using resin shipped from Tennessee. Consistent with Storopack and Pactiv, the study assumes that this tube stock is shipped to a stocking warehouse in Kent, WA for sale to customers in Oregon.

Finally, it is assumed that each of the three companies have equal market shares in Salem (33.3%).

Distances are as follows (per MapQuest):

- Memphis, TN to Los Angeles (Storopack resin): 1,798 miles (50% rail/50% truck). Los Angeles to Kent, WA: 1,130 miles (100% truck).
- Memphis, TN to Visalia, CA (Pactiv resin, assumed): 1,884 miles (50% rail/50% truck). Visalia, CA to Kent, WA: 966 miles (100% truck).
- Memphis, TN to Hayward, CA (Sealed Air resin, assumed): 2,073 miles (50% rail/50% truck). Hayward, CA to Kent, WA: 802 miles (100% truck).
- Kent, WA to Salem, OR: 214 miles (100% truck).

- Average distance: resin to fabricator: 1,918 miles.
- Average distance: fabricator to stocking warehouse: 966 miles.
- Average distance: stocking warehouse to user (Salem): 214 miles.

Therefore, the study assumes that 50% of the resin travels an average of 1,918 miles by rail, and that 50% of the resin travels an average of 1,918 miles by truck. The finished product is assumed to be transported an average of 966 miles from California to Washington via truck, and then another 214 miles from Washington to Salem via truck for a total of 1,180 miles. These assumed distances apply to both the 0% recycled content and the 30% recycled content options.

Expanded Polystyrene (EPS) Loose Fill

Pack Edge Development identified the following fabricators as being closest to Salem: Space-Pak in Clackamas, OR (non-recycled only); Storopack in Kent, WA and Salt Lake City, UT; and FP International (Redwood City, CA). Given the very low density of these materials, this study assumes that the user in Salem will be purchasing from fabricators in the Pacific Northwest, and that fabricators outside of the Pacific Northwest will not be selling significant quantities of this product in Salem due to higher transportation distances and costs.

Not knowing the absolute or relative production quantities of Space-Pak (Clackamas) and Storopack (Kent), it is assumed that their relative market share in Salem is solely a function of transportation distance. While Space-Pak is 46 miles from Salem, Storopack is 214 miles. How will this effect Space-Pak's market share in Salem relative to Storopack's? All other things being equal, it seems reasonable that Space-Pak will have greater market share in Salem than Storopack.

Consistent with the methodology used to estimate market share for corrugated boxes (described above), the midpoint between the greater of the two distances (Storopack; 214 miles) and the next closest fabricator (FP International, Redwood City, CA; 615 miles) is used to define a circle, centered on Salem, with radius of 414 miles. It is assumed that fabricators located inside this circle will be selling products in Salem, and that their market share is proportional to 414 miles less their distance from Salem. This results in the assumption that Space-Pak supplies 65% of the Salem market, and Storopack supplies 35%.

Space-Pak only sells expanded polystyrene loose fill made from 100% virgin resin. The study assumes that all of the polystyrene loose fill containing recycled content used in Salem is fabricated at Storopack's facility in Kent, WA, for a transportation distance of 214 miles.

What about the primary feedstock, polystyrene beads? Pack Edge learned in interviewing Space-Pak (see Appendix B) that Space-Pak buys their resin from Inter-Pac in Tupelo, MS (distance from Clackamas: 2,426 miles). Inter-Pac's web site makes no reference to facilities other than their headquarters in Tupelo and a recycling plant in Georgia. In contrast, Storopack's web site cites 22 locations in North America, including Kent, WA and San Jose, Downey, and Anaheim, CA. But according to a sales representative for Storopack, polystyrene beads used in the fabrication of EPS loose-fill in Kent are shipped to Kent from Memphis, TN "via truck or container shipped via rail".

Lacking information on Inter-Pac's shipment method, as well as what percentage of Storopack resin shipments to Kent are rail vs. truck, the study assumes that 50% of shipments from Memphis to Kent (Storopack) and from Tupelo to Clackamas (Inter-Pac/Space-Pak) are via rail, and the other 50% of shipments are done via truck. Lacking information on rail lines, the study makes the simplifying assumption that the mileage by rail between two points is the same as the mileage on highways.

Therefore, for the post-consumer EPS loose fill (Storopack only), it is assumed that both types of beads (virgin and post-consumer) are shipped from Memphis, TN to Kent, WA (2,416 miles; 50% rail, 50% truck) and then the fabricated product travels from Kent, WA to Salem, OR (214 miles, 100% truck).

For the virgin EPS loose fill, it is assumed that the market share is 65% Space-Pak (Clackamas, OR) and 35% is Storopack. Storopack's beads and products are shipped as described in the previous paragraph. Space-Pak's beads are shipped from Tupelo, MS to Clackamas, OR (2,426 miles; 50% rail, 50% truck) and then the fabricated product travels from Clackamas, OR to Salem (46 miles, 100% truck). Thus, the weighted average for beads are: 1,211 miles by rail and 1,211 miles by truck. The weighted average for finished product is 105 miles by truck.

Bio-Based (Starch) Loose Fill

The closest fabricator to Salem of vegetable starch peanuts identified by Pack Edge Development is American Excelsior, in Yakima, Washington. No other fabricators were identified in the Pacific Northwest. Due to the low density of this material, and lack of other nearby fabricators, it is assumed that starch loose fill used in Salem, OR will be fabricated at this facility in Yakima.

According to a representative of American Excelsior's Yakima facility, their starch comes from "somewhere in the Midwest" and is transported to Yakima via truck. National Starch, who licenses the technology, manufactures corn starch in North Kansas City, MO and Indianapolis, IN. However, licensees (such as American Excelsior) are not required to buy starch from National Starch. In fact, American Excelsior's Yakima plant is currently using wheat starch, not corn starch. Not knowing exactly where American Excelsior is purchasing their wheat starch from, the study assumes North Kansas City, which is the same as the closer of National Starch's two locations.

Therefore, it is assumed that the raw starch is shipped 1,767 miles (North Kansas City to Yakima, per MapQuest) and the finished product (expanded starch peanuts) is shipped 231 miles (Yakima to Salem, per MapQuest) via truck. For consistency and ease of comparison of burdens with expanded polystyrene loose fill, it is assumed that the transportation of starch from North Kansas City to Yakima is 50% truck and 50% rail.

Molded Pulp Loose Fill

The only manufacturer of this material known to DEQ in the Western U.S. is UFP Technologies in Visalia, CA. Per MapQuest, the driving distance from Visalia CA to Salem OR is 752 miles. A representative of UFP in Visalia informed DEQ that "Cushion Cubes can only be shipped economically in truckload quantities using a 53' dry van. A high cube van will transport 390 - 10 cu ft bags - 5850 pounds of product. Materials are stored and shipped in 10 cu ft plastic bags." The average transportation distance and mode for collection of postconsumer newspaper is assumed to be 150 miles by single-unit diesel truck.

Unbleached Kraft Paper

As was done with linerboard (see section on corrugated boxes, above), the study assumes that market share of unbleached kraft paper used in Salem is an equal function of two variables: mill capacity and distance from Salem. All assumptions and methodologies to estimate market share are the same as described above for linerboard, except for the following changes:

- Oregon and Washington mills identified by the Lockwood-Post's Directory as making kraft papers other than linerboard were added to the list.

- Oregon and Washington mills identified by the Lockwood-Post's Directory as making kraft linerboard only were removed from this list. (Mills that were identified as producing "linerboard and other kraft paper" were retained in the list.)
- It is likely that rolls of kraft paper will not be shipped directly from the mills to an end user but rather would first go to a converter that will cut rolls into smaller rolls usable by a retail warehouse. The Lockwood-Post's Directory clearly identified only one site in the Pacific Northwest that might fit this category (Pac-Paper, Inc. in Vancouver, WA), although other companies may but are not clearly identified as such. As Vancouver is on the route between all but one of the kraft mills in this category and Salem, 5 miles was added to their distance from Salem to allow for a side trip to the converter. The one Oregon mill that might be manufacturing this type of paper, per the Lockwood-Post's Directory, is the Weyerhaeuser kraft mill in Albany, OR; the distance that its kraft paper travels to Salem is calculated as a trip from Albany to Vancouver (through Salem) and then back to Salem.

The resulting transportation distance using estimated market share is 122 miles. Because of the relatively small distances involved, it is assumed that all shipping is done by truck.

Because the study models 0% and 50% post-consumer content options, and 50% is attainable by several regional mills, the study assumes equal transportation distances for both options.

Newsprint (Unprinted)

The study uses the same method as described for kraft paper (above), with data from the Lockwood-Post Directory for the following 5 mills: Georgia-Pacific (Clatskanie, OR), SP Newsprint (Newberg, OR), Blue Heron Paper (Oregon City, OR), North Pacific Paper Corp. (Longview, WA), and Abitibi-Consolidated (Steilacoom, WA). R is the mid-point between the farthest of these five mills (Abitibi-Consolidated) and the closest newsprint mill outside of the Interstate-5 corridor of Oregon and Washington (Inland Empire Paper in Spokane).

All mileages are for two stages: first from the mill to Vancouver (Pac-Paper, Inc., the assumed location of the roll/sheet converter) and then from Vancouver to Salem, with an additional five miles added for travel within Vancouver to the converter. The resulting market-share-weighted transportation distance (estimated) is 101 miles. This distance is applied to both the 10% and the 50% post-consumer content options. As with other regionally-produced paper products, it is assumed that all shipping of this product is done via truck.

Shredded Corrugated

For the purposes of this study, it is assumed that the order fulfillment center can fully meet its void fill needs by shredding "waste" corrugated boxes that are available on-site. The burdens associated with shipping this corrugated, and recycling or disposing of it (rather than shredding it for reuse), are allocated to the inbound products that are shipped in the corrugated, not to outbound packaging options, and so are excluded from this study for all packaging options.

Shredded Office Paper

For the purposes of this study, it is assumed that the order fulfillment center can fully meet its void fill needs by shredding "waste" office paper that is available on-site. The burdens associated with shipping this office paper, and recycling or disposing of it (rather than shredding it for reuse), are allocated to non-related processes, such as office operations, and so are excluded from this study for all packaging options.

Non-Padded Kraft Paper Shipping Bag

Pack Edge Development and DEQ attempted to obtain information about the fabrication of these types of bags from two major suppliers: Pactiv and Sealed Air Corporation. Limited information was gathered from Pactiv only; no information was obtained from Sealed Air Corporation.

According to a Pactiv representative, all Pactiv products are manufactured in the United States. Pactiv has several manufacturing facilities; the largest facility serving the Western U.S. is located in Visalia, California. It is assumed that non-padded kraft paper shipping bags are fabricated here, although this is not known for a fact.

The Visalia plant is not a paper mill, so the rolls of kraft are manufactured off-site. There are several kraft mills in both the San Francisco area as well as Southern California. Visalia is roughly equidistant from these two metropolitan areas. It is assumed that the kraft paper is manufactured in one of these areas and shipped in rolls approximately 200 miles to Visalia.

Pack Edge Development's experience is that stock shipping bags sold in Oregon are typically first warehoused in the Seattle area (around Kent, WA), then transported to Portland (or Salem) by truck.

Per MapQuest, the distance from Visalia, CA to Kent, WA is 966 miles, and the distance from Kent, WA to Salem OR is 214 miles. Total kraft shipping distance is estimated at 1,380 miles (first 200 miles in rolls, then 966 + 214 miles as mailers). It is assumed that all materials (rolls of kraft and fabricated product) are transported via diesel tractor trailer.

Non-Padded Polyethylene Shipping Bag

Major vendors of poly bags known to Pack Edge Development are Elkay Plastics, Pactiv, and Sealed Air Corporation. Limited information was obtained from Elkay Plastics and Pactiv; no information was obtained from Sealed Air Corporation. For the purpose of estimating transportation distances, it is assumed that 50% of these types of shipping bags used in Salem are supplied by Elkay, and the other 50% are supplied by Pactiv.

According to a representative of Elkay Plastics, almost all of their polyethylene stock bags are made overseas and enter the U.S. primarily in Los Angeles and Chicago. This study assumes that the Elkay stock bags used in the Pacific Northwest are manufactured in Asia and enter the U.S. through Los Angeles.

The location of Elkay's suppliers in Asia is not known. This study assumes a simple average of three possible locations: Kaoshiung, Taiwan; Guangzhou, China; and Singapore. Nautical miles from these three locations to Los Angeles measure:

- Kaoshiung, Taiwan: 7318;
- Guangzhou, China: 7737; and
- Singapore: 8500;

for a simple average of 7,852 nautical miles (9,035 miles).

According to a Pactiv representative, all Pactiv products are manufactured in the United States. Pactiv has several manufacturing facilities; the largest facility serving the Western U.S. is located in Visalia, California. It is assumed that non-padded polyethylene shipping bags are fabricated here, although this is not known for a fact.

Pack Edge Development's experience is that stock shipping bags sold in Oregon are typically first warehoused in the Seattle area (around Kent, WA), then transported to Portland (or Salem) by truck.

According to MapQuest, other relevant distances are:

- Long Beach (Port of Los Angeles) to Kent, WA: 1154 miles.
- Visalia, CA to Kent, WA: 966 miles.
- Kent, WA to Salem OR: 214 miles.

Consistent with previously described materials, the study assumes that all West Coast shipments of materials are conducted using diesel tractor trailers.

Therefore, the study assumes that 50% of the bags are transported 9,035 miles by ocean freighter from Asia to Long Beach/Los Angeles; 1,154 miles by diesel tractor trailer to Kent, WA; and a final 214 miles by diesel tractor trailer to Salem. The other 50% are assumed to be transported 966 miles by diesel tractor trailer from Visalia, CA to Kent, WA; and then 214 miles by diesel tractor trailer to Salem.

Kraft Paper Shipping Bag with Newsprint Padding

Pack Edge Development and DEQ attempted to obtain information about the fabrication of these types of bags from two major suppliers: Pactiv and Sealed Air Corporation. Limited information was gathered from Pactiv only; no information was obtained from Sealed Air Corporation.

According to a Pactiv representative, all Pactiv products are manufactured in the United States. Pactiv has several manufacturing facilities; the largest facility serving the Western U.S. is located in Visalia, California. It is assumed that this product is fabricated here, although this is not known for a fact.

The Visalia plant is not a paper mill, so the kraft paper is manufactured off-site. There are several kraft mills in both the San Francisco area as well as Southern California. Visalia is roughly equidistant from these two metropolitan areas. The study assumes that the kraft paper is manufactured in one of these areas and shipped in rolls approximately 200 miles to Visalia. The study also assumes an average distance of 150 miles for collection and delivery of post-consumer newspaper used in the envelope padding.

Pack Edge Development's experience is that stock shipping bags sold in Oregon are typically warehoused in the Seattle area (around Kent, WA), then transported to Portland (or Salem) by truck.

Per MapQuest, the distance from Visalia, CA to Kent, WA is 966 miles, and the distance from Kent, WA to Salem OR is 214 miles.

Therefore, assumed transport distances for primary components of these mailers are 200 miles by diesel tractor trailer truck for kraft paper and 150 miles by single-unit diesel truck for the postconsumer newspaper used for the macerated padding. The mailers themselves are then shipped an assumed distance of 1,180 miles by tractor trailer from Visalia, CA to Salem, OR via Kent, WA.

Kraft Paper Shipping Bag with Polyethylene Bubble Padding

Pack Edge Development and DEQ attempted to obtain information about the fabrication of these types of bags from two major suppliers: Pactiv and Sealed Air Corporation. Limited information was gathered from Pactiv only; no information was obtained from Sealed Air Corporation.

According to a representative of Pactiv, all Pactiv bubble mailers sold in Oregon are manufactured in Visalia, California. Pactiv buys resin and extrudes plastic (both bubble and non-bubble film) themselves. The study assumes that the Visalia facility extrudes bubble on site, and then converts sheets of bubble and kraft into shipping bags. Franklin Associates estimated resin transportation distances based on the assumption that the virgin resin suppliers used by the packaging producers are located in the same general area and use the same transportation modes as suppliers providing EPS resin to packaging manufacturers on the west coast.

For postconsumer resin, a database of recycled plastics products and markets published on the website PlasticsResource.com for the American Plastics Council shows at least 30 sellers of recycled polyethylene in California. Assuming that most of recycled polyethylene is from within California, transportation of postconsumer resin is estimated to be 100 miles by tractor-trailer truck.

The Visalia plant is not a paper mill, so the kraft paper is manufactured off-site. There are several kraft mills in both the San Francisco area as well as Southern California. Visalia is roughly equidistant from these two metropolitan areas. The study assumes that the kraft paper is manufactured in one of these areas and shipped in rolls approximately 200 miles.

Pack Edge Development's experience is that stock shipping bags sold in Oregon are typically first warehoused in the Seattle area (around Kent, WA), then transported to Portland (or Salem) by truck.

Per MapQuest, the distance from Visalia, CA to Kent, WA is 966 miles, and the distance from Kent, WA to Salem OR is 214 miles.

Therefore, assumed transport distances for primary components of these mailers are 200 miles (kraft), 1,000 miles each by tractor trailer and by rail for virgin resins, and 100 miles by tractor trailer for recycled resins. The mailers themselves are then shipped an assumed distance of 1,180 miles by tractor trailer from Visalia, CA to Kent, WA and on to Salem, OR.

Polyethylene Shipping Bag with Polyethylene Bubble Padding

Pack Edge Development and DEQ attempted to obtain information about the fabrication of these types of bags from two major suppliers: Pactiv and Sealed Air Corporation. Limited information was gathered from Pactiv only; no information was obtained from Sealed Air Corporation.

According to a representative of Pactiv, all Pactiv bubble mailers sold in Oregon are manufactured in Visalia, California. Pactiv buys resin and extrudes plastic (both bubble and non-bubble film) themselves. The study assumes that the Visalia facility extrudes both the external barrier material and the internal bubble on site, and then converts rolls of both materials into shipping bags. Assumptions regarding the source of virgin and recycled resins and transportation modes are the same as for resins used in the bubble-padded kraft mailers.

Pack Edge Development’s experience is that stock shipping bags used in Oregon are typically first warehoused in the Seattle area (around Kent, WA), then transported to Portland (or Salem) by truck.

Per MapQuest, the distance from Visalia, CA to Kent, WA is 966 miles, and the distance from Kent, WA to Salem OR: 214 miles.

Therefore, assumed transport distances for primary components of these mailers are 1,000 miles each by tractor trailer and by rail for virgin resins, and 100 miles by tractor trailer for recycled resins. The mailers themselves are then shipped an assumed distance of 1,180 miles by tractor trailer from Visalia, CA to Kent, WA and then to Salem, OR.

SHIPMENT OF PACKAGED PRODUCT TO CUSTOMER

There are a number of different methods that the distribution center (order fulfillment center) could use to ship the packaged parcel to the residential customer. The U.S. Postal Service, Federal Express (FedEx) and United Parcel Service (UPS) are three of many organizations that provide this type of door-to-door delivery service. These and other shipping companies offer a variety of shipping options, including overnight delivery (typically air) as well as options that are slower (typically ground or ground/air combinations). Depending on the speed with which the parcel needs to be delivered, the locations of the sender and customer, and the hubs through which the parcel might travel, the parcel could be transported by airplane (cargo jet and/or smaller plane), rail car, a variety of different tractor trailer combinations, and/or delivery truck/van. In fact, there are a very large number of different routes and combinations of modes that the parcel might travel en route from the assumed start point (Salem, OR) to the assumed end point (Edgar Springs, MO). Representatives of both FedEx and UPS were unable to provide information on the more common routes that this parcel might travel.

Because of budget limitations, and also to simplify the analysis, the study assumes that the parcel will be shipped ground delivery, thus avoiding the need to model and estimate the impacts of air freight. Readers can adapt the results of this study to evaluate different ground shipping scenarios.

At the suggestion of UPS, Pack Edge Development shipped a box (empty) from Oregon to Rolla, MO. Rolla is approximately 20 miles from Edgar Springs and according to FedEx is the location of the local FedEx station that serves Edgar Springs. Pack Edge Development shipped a similar parcel using FedEx. Both items were shipped from Wilsonville, OR. (Items shipped from Salem via both UPS ground and FedEx ground would pass through Wilsonville on their way to Portland.) Pack Edge Development obtained tracking histories for these parcels, and then representatives from UPS and FedEx provided information on the types of delivery vehicles used to transport the parcels for each segment of their travel. Package starting segments (Salem to Portland) and ending segments (Rolla to Edgar Springs) are assumed.

Estimated UPS mileages are as follows, per MapQuest (unless noted otherwise):

- Point of collection to Salem, OR UPS station: 5 miles (assumed) in a P70 (delivery truck).
- Salem, OR to Portland, OR: 48 miles in a T28 (28' trailer).
- Portland, OR to Commerce City, CO: 1,256 miles in a T28.
- Commerce City, CO to Salina, KS: 428 miles in a T28.
- Salina, KS to Lenexa, KS: 176 miles in a T28.
- Lenexa, KS to Rolla, MO: 235 miles in a T28.
- Rolla, MO to Edgar Springs, MO: 20 miles in a P70 (assumed).

- P70 total: 25 miles.
- T28 total: 2,143 miles (98.8% of total mileage).
- Grand total: 2,168 miles.

Estimated FedEx mileages are as follows, per MapQuest (unless noted otherwise):

- Point of collection to Salem, OR FedEx station: 5 miles (assumed) in a delivery truck.
- Salem, OR to Portland, OR: 48 miles in a 28' pup trailer.
- Portland, OR to Kansas City, KS: 1,836 miles in a 28' pup trailer.
- Kansas City, KS to Rolla, MO: 223 miles in a 28' pup trailer.
- Rolla, MO to Edgar Springs, MO: 20 miles in a delivery truck (assumed).

- Delivery truck total: 25 miles.
- 28' pup trailer total: 2,107 miles (98.8% of total).
- Grand total: 2,133 miles.

For modeling purposes, this report takes a simple average of these two deliveries as a reasonable estimate of how the average parcel shipped via ground freight might travel from Salem, OR to Edgar Springs, MO. The simple averages are:

- Delivery truck total: 25 miles.
- Trailer total: 2,125 miles (98.8% of total).
- Grand total: 2,150 miles.

SHIPMENT OF RETURNED PRODUCT AND PACKAGING MATERIALS TO ORDER FULFILLMENT CENTER

It is assumed that when customers return product to the order fulfillment center, the returned packages will also be shipped ground freight and the average mileage in delivery truck and diesel tractor trailer will be the same as for delivery of the product from the order fulfillment center to the customer.

ENVIRONMENTAL BURDENS FOR TRANSPORTATION

The transportation data shown in Table D-1 (and in the Appendix C tables) are used in conjunction with the data in Appendix A for the relevant transportation mode(s) to determine the fuel consumption and environmental burdens for each transportation step.

Weight and Volume-Limited Shipments

Franklin Associates' LCI model calculates fuel use based on a fully weight loaded vehicle. For some low-density materials, however, a shipped load fills by volume before it reaches its weight limit. In this study, transportation of all types of loose fill (EPS, starch-based, and molded pulp) is calculated based on a volume-limited load.

In addition, DEQ performed calculations using the weight and volume of soft mail-order goods packaged in various box/dunnage combinations and shipping bag configurations, and the maximum weight and volume loads of the delivery vans and trailers most commonly used to deliver packaged mail-order goods to customers, to evaluate whether shipments of packaged goods would be weight-limited or volume-limited. As shown in Table D-2, the results indicate that delivery trucks and trailers fill by volume instead of weight. Thus, fuel use and emissions for transportation of packaged product are modeled based on the fuel economy for a volume-loaded vehicle rather than a fully weight-loaded vehicle.

Allocation of Transportation Burdens

Although delivery trucks and trailers fill by volume rather than weight, the fuel consumption of the vehicle is tied to the vehicle weight. Thus, the environmental burdens for transportation of packaged goods are allocated to the packaging based on its contribution to the vehicle load weight. Because the purpose of the vehicle trip is to deliver packaged product, all transportation burdens are allocated between the product and packaging (none are allocated to the weight of the vehicle itself). The fuel economy of the vehicle is calculated based on the weight of a full volume load of packaged product. Table D-3 shows the percentage of the package delivery fuel use and emissions allocated to the packaging for each packaging configuration in this study, based on the packaging's weight percentage of the packaged product.

Table D-2

WEIGHT AND VOLUME LOADING OF DELIVERY VEHICLES

		Lightest Bag (1)	**Heaviest Bag (2)**	**Lightest Box (3)**	**Heaviest Box (4)**
Weight of Packaging (lbs)		0.067	0.38	1.44	1.77
Product Weight (lbs)		1.28	1.28	1.28	1.28
Total Weight per Pkg (lbs)		1.35	1.66	2.72	3.05
Length (in)		20	20	21.5	21.5
Width (in)		14.25	14.25	17.5	17.5
Height (in)		2.5	2.75	3.5	3.5
Volume per Pkg (cu in)		713	784	1317	1317
	Maximum Vehicle Load	**Maximum Number of Packages**			
T28 trailer (5)					
By Weight (lb)	30,440	22,598	18,371	11,199	9,984
By Volume (cu in)	3,478,464	4,882	4,438	2,641	2,641
P70 delivery van (6)					
By Weight (lb)	5,600	4,157	3,380	2,060	1,837
By Volume (cu in)	1,209,600	1,698	1,543	919	919

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(1) unpadded polyethylene
(2) kraft bag w/macerated newsprint padding
(3) corrugated box + EPS loose fill
(4) corrugated box + molded pulp loose fill
(5) T28 trailer: gross vehicle weight 40,000 lb, unladen wt 9,560 lb, 2013 cu ft.
(6) P70 delivery van: gross vehicle weight 15,000 lb, unladen wt 9,400 lb, 700 cu ft.

Table D-3

ALLOCATION OF PACKAGED GOODS TRANSPORTATION BURDENS TO PACKAGING
(all weight in pounds)

Packaging Configuration	Component Wt/Pkg	Total Wt of Packaging	Wt of Packaged Product (1)	Wt % Packaging
Corrugated Box with	1.39			
Sealed Air Packets	0.084	1.47	2.75	54%
EPS Loose Fill	0.048	1.44	2.72	53%
Starch-Based Loose Fill	0.086	1.48	2.76	54%
Molded Pulp Loose Fill	0.379	1.77	3.05	58%
Crumpled Kraft Paper	0.184	1.57	2.85	55%
Crumpled Newsprint	0.168	1.56	2.84	55%
Shredded Corrugated	0.318	1.71	2.99	57%
Shredded Office Paper	0.148	1.54	2.82	55%
Shipping Bag				
Unlined Bleached Kraft		0.14	1.42	10%
Kraft with Paper Padding		0.38	1.66	23%
Kraft with Bubble Wrap		0.13	1.41	9%
Unlined LLDPE Film Bag		0.07	1.35	5%
LLDPE Film Bag with Bubble Wrap		0.13	1.41	9%

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(1) Product weight = 1.28 lb

REFERENCES

D-1 Research conducted for Oregon Department of Environmental Quality by David Allaway, DEQ.

D-2 Franklin Associates estimates.

D-3 PlasticsResource.com website.

APPENDIX E

WASTE MANAGEMENT

OVERVIEW

This appendix discusses the fate of packaging materials that have served their intended purpose of delivering packaged soft goods to a consumer. Options include the following:

- Reuse by the customer for returns of unwanted mail-order goods
- Reuse by the customer for shipping other outgoing goods
- Recycling by the customer
- Disposal by the customer
    - On-site burning (small percentage)
    - Littering (small percentage)
    - Managed municipal solid waste stream
        - Landfill
        - Combustion with energy recovery

Packaging used for returning unwanted goods may be reused, recycled, or disposed when received at the order fulfillment center.

Currently, it is estimated that about 80 percent of discarded municipal solid waste (MSW) in the U.S. that is not diverted for reuse, recycling, or composting is landfilled, and the remaining 20 percent is burned in waste-to-energy facilities (Reference E-1). Therefore, combustion of 20 percent of the postconsumer materials that are discarded and not reused, recycled, or composted is included in this study. In the LCI energy results, an energy credit for waste-to-energy combustion of 20 percent of disposed packaging components is assigned to each system.

Customer Management of Packaging Materials

The study assumes that 10% of the packaging materials sent to customers will be reused to return the packaged products to the distribution center/order fulfillment center. Customers may choose to return products because they are not wanted (gifts) or due to size, color, defects, or other reasons. Ten percent is an assumption based on very limited data from Norm Thompson Outfitters and the anecdotal experience of study contributors (Reference E-2). According to Norm Thompson, returns are typically shipped to its order fulfillment center in their original packaging materials.

Thus, decisions regarding ultimate end-of-life management of the packaging materials are made at two different locations: the residential customer (90%) and the order fulfillment center (10%).

Reuse/Recycling/Disposal of Packaging by Residential Customers. Although many of the packaging materials used in this study are technically recyclable and/or reusable, actual reuse and recycling by residential customers depends on many factors, including the following:

- Customer access
    - to recycling programs (curbside or drop-off)
    - to packaging stores that accept loose fill for reuse
- Types of materials accepted by recycling programs
- Customer awareness that materials are reusable/recyclable
- Availability of residential space to store materials until they can be recycled/reused
- Convenience of participation in recycling programs
- Customer level of environmental commitment

The following assumptions were made in assessing residential reuse/recycling of packaging:

- Because of the low value and relative bulk of packaging materials, they are likely to be recycled only by customers with access to curbside recycling.
- The only materials likely to be accepted by curbside recycling programs are unpadded, unlined kraft paper shipping bags and possibly other all-paper(board) packaging components such as crumpled kraft paper or newsprint, corrugated boxes, molded paper loose fill, and all-paper padded shipping bags. Few if any curbside programs would accept shredded loose fill, pillow packs, polyethylene film shipping bags, or composite shipping bags.
- Except for the 10% of packaging used for returns, the only materials expected to be reused by customers are EPS and cornstarch loose fill. Although molded pulp loose fill is equally reusable, it is a new product that customers are unlikely to be familiar with and thus less likely to save and reuse. The larger size of the cushion cubes compared to foam loose fill "peanuts" may also make the molded pulp less appealing to customers for storage and later reuse. Molded pulp loose fill is also unlikely to be accepted by packaging stores for reuse because its appearance is very different from EPS and starch-based foam loose fill shapes, and stores would not be expected to store and reuse molded pulp loose fill separately from foam loose fill. Because the lower reuse of molded pulp shapes is based on expected customer behavior rather than functionality of the product, the LCI report will provide guidance on how to adapt molded pulp results to reflect reuse equivalent to foam loose fill.

Residential recovery/recycling of various paper grades was analyzed in the study **Recovered Paper: Future Challenges and Opportunities**, prepared for the American Forest & Paper Association by Franklin Associates, Ltd., July 9, 2002. Table 5-4 in that report, "Residential Postconsumer Generation and Recovery, 2000", showed 12% recovery of residential corrugated, but residential recovery of shipping bags and other packaging paper was insignificant.

Reuse of EPS loose fill was addressed in the study **Waste Management and Reduction Trends in the Polystyrene Industry, 1974 – 1994**, prepared by Franklin Associates, Ltd. for the Polystyrene Packaging Council in August 1996. A survey of 39 mailing services and catalogue businesses indicated that 50% of the loose fill that they used was loose fill returned to their stores by consumers (standard deviation 40-65%). It is assumed that a similar percentage of customers that do not have access to packaging stores (e.g., rural mail-order customers) would save and reuse loose fill at home.

Reuse/Recycling/Disposal of Packaging by Order Fulfillment Centers. Table E-1 shows assumed rates of recycling and reuse for packaging materials used for return shipments of goods. (This is not the same as consumer returns of packaging materials to mailing service stores for use, discussed in the preceding section.) Reuse of packaging materials to return unwanted items to order fulfillment centers represents a second useful life of the packaging material, replacing the need for the customer to purchase new boxes, shipping bags, or envelopes.

The study assumes that all loose fill materials are reused at a rate of 80%, as long as they are received and can be stored and returned to packing stations in the same format (same volume) as new (purchased) loose fill. This applies to inflated polyethylene air packets, polystyrene loose fill, corn starch loose fill, molded paper loose fill, shredded OCC, and shredded office paper. Because the materials have much more financial value reused than recycled, the study assumes that if they aren't reused, these materials will be disposed, so the recycling rate for these materials is 0%.

Because corrugated boxes will have had labels affixed to them twice already (once to the customer and again for the return) the study assumes that the order fulfillment center will not reuse the boxes a third time. Most order fulfillment centers are likely to have corrugated cardboard recycling service, so the study assumes that the returned corrugated cardboard boxes are recycled at a rate of 90%, with the remaining 10% disposed.

Kraft paper void fill and newsprint void fill is reusable, but reuse of these materials requires greater effort and/or additional storage space (compared to unused product in flat sheets or rolls) because they have been crinkled/wadded up. The study assumes that these materials are less likely to be reused than the flowable and other loose fills, for which bulk dispenser systems and storage may already be in place. Kraft paper may be recycled with corrugated and newsprint/newspaper is a fairly common recyclable in warehouse/shipping environments as well. For these materials, the study assumes a 20% reuse rate and a 40% recycling rate, for a total diversion rate of 60%, with the remaining 40% disposed.

Table E-1.
Assumed Rates of Reuse and Recycling for Packaging Returned to Order fulfillment centers

Packaging Material	% Recycling	% Reuse
Corrugated	90%	0%
Inflated polyethylene air packets	0%	80%
Polystyrene foam peanuts	0%	80%
Cornstarch loosefill peanuts	0%	80%
Flowable loosefill made from recycled newsprint	0%	80%
Purchased Kraft paper (unbleached)	40%	20%
Purchased newsprint-style paper	40%	20%
Loosefill OCC shredded on-site	0%	80%
Loosefill high grade paper shredded on-site	0%	80%
PE bag(s) without liner	0%	0%
Kraft bag(s) without liner	40%	0%
Kraft paper bag with PE air-padded liner	0%	0%
Kraft bag with 100% news padding	0%	0%
PE bag with PE air-padded liner	0%	0%

It is very unlikely that shipping bags will be reused as they are designed for single-use but may be reusable if re-taped. Recycling for the kraft-only bag is assumed to be 40% (same as kraft void fill paper). Recycling for all other shipping bags is assumed to be 0% due to their low value (macerated newsprint), multi-material construction, and/or lack of recycling opportunities.

Management of Discarded Packaging

Packaging that is not reused or recycled by consumers typically becomes part of the managed municipal solid waste stream. It is recognized that some small fraction of postconsumer packaging may be burned by consumers, particularly in rural areas, or littered; however, no data exist to quantify these amounts or their impacts with any degree of confidence. Thus, disposal of postconsumer packaging by on-site burning or littering is not included in this analysis. This analysis considers only landfilling and WTE combustion as management options for postconsumer packaging.

Landfilling of Discarded Packaging. Approximately 80 percent of all discarded municipal solid waste in the U.S. that is not diverted for reuse, recycling, or composting is currently being landfilled. This analysis examines landfilling as a waste management option. The energy requirements for landfilling operations include the energy required to collect and transport solid waste to the landfill and to run the compacting equipment at the landfill.

The energy to transport materials to the landfill is derived by converting the weight of each material to the volume it occupies in the packer truck and multiplying the volume by the average fuel use per truckload. The packer truck densities used in this study are reported in Table E-2. A typical packer truck has a 25-cubic-yard volume and generally achieves a volume utilization of 80 percent. Packer trucks are assumed to use approximately 10.4 gallons of diesel per load (Reference E-6) on average, although actual fuel use will depend on the mode of transportation and distance to landfill, which can vary widely between communities. The amount of diesel fuel allocated to haul the postconsumer solid waste is calculated by the following equation:

$$\frac{Wt.of\ Discards}{Packer\ Truck\ Density\ of\ Discards}\ X\ \frac{10.4\ gal\ diesel}{25\ cu\ yd\ X\ 0.8} \qquad (Equation\ 1)$$

The diesel fuel requirements for the operation of landfill equipment are calculated using Equation 2.

$$\frac{Wt.\ of\ Discards}{Landfill\ Density\ of\ Discards}\ X\ \frac{500\ gal\ diesel}{2{,}667\ cu\ yd} \qquad (Equation\ 2)$$

The materials buried in the landfill are reported in the analysis as postconsumer solid waste. The solid waste is reported both by weight and by volume. The landfill density factors shown in Table E-2 are used to convert the weight of the discarded materials to the volume they occupy in the landfill. These factors are based on landfill samples and compaction tests.

Combustion with Energy Recovery. Approximately 20 percent of the nation’s disposed municipal solid waste is burned rather than buried in a landfill (Reference E-1). The majority of MSW incinerators recover the energy released from burning the wastes, primarily to generate electricity. This analysis reports the energy content of the materials burned in MSW incinerators. The energy content of the materials evaluated in this study is based on the higher heating values (HHVs) reported for the postconsumer materials. These values are listed in Table E-3. The weight of the material burned is multiplied by its HHV to determine the amount of energy released. Most MSW incineration facilities produce electricity but not steam. Usable energy production is actually HHV x (thermal efficiency) x (transmission efficiency). Thermal efficiency for the generation of electricity from WTE combustion of MSW is around 33 percent or lower. Transmission losses are about 8 percent. As a result, the usable energy delivered from combustion of MSW is HHV x 0.33 x (1/1.08), or about 28 percent of the HHV of the material. The energy credit is shown separately in the LCI energy results in the report.

Table E-2

PACKER TRUCK AND LANDFILL DENSITY FOR PACKAGING

	Packer truck density (lb./cu. yd.)	Landfill density (lb./cu. yd.)
Polyethylene Film Packaging	544	670
Polystyrene Packaging	200	240
Paper Packaging	602	740
Corn Starch Packaging	1700	2000
Molded Pulp Packaging	664	819
Newsprint/Newspaper Packaging	602	740
Corrugated boxes	609	750

References: E-1, E-7, and E-8

Source: Franklin Associates

Table E-3

HIGHER HEATING VALUES AND ASH CONTENT OF MATERIALS

	Ash Content (percent)	Higher Heating Value (HHV) (Btu/lb)
Kraft Paper	1.01%	7,261
Newsprint/Newspaper	1.43%	7,979
Low-density polyethylene (LDPE)	0%	19,965
Linear Low-density Polyethylene (LLDPE)	0%	19,985
Polystyrene, foam	0%	17,840
Corrugated	5.06%	7,945
Corn Starch	1.06% *	7,560
Molded Pulp	1.43% **	7,979

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* The ash content for food waste is assumed for corn starch.

** The ash content for newsprint is assumed for molded pulp.

References: E-8, E-9, and E-10.

Source: Franklin Associates

The quantity of solid waste for each system is reduced when postconsumer materials are burned. The ash content of the materials is used to determine the quantity of solid waste contributed by the portion of materials that is burned instead of landfilled. Air and waterborne emissions data from the combustion of specific postconsumer materials are not available. These emissions are also not available for landfilling of specific materials. Therefore, the air and water emissions associated with combustion and landfilling are not addressed in this report.

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E-1 U.S. EPA. **Municipal Solid Waste in the United States: 1999 Facts and Figures.** Franklin Associates, Ltd. June, 2001.

E-2 Research conducted for Oregon Department of Environmental Quality by David Allaway, DEQ.

E-3 "Curbside collection participation: Influences and motivations." Rebecca Davio, Ph.D. **Resource Recycling**, August 2001, Vol. XX, No. 8.

E-4 **Recovered Paper: Future Challenges and Opportunities.** Prepared for American Forest and Paper Association by Franklin Associates, Ltd. July 9, 2002. Table 5-4 Residential Postconsumer Generation and Recovery, 2000.

E-5 **Waste Management and Reduction Trends in the Polystyrene Industry, 1974 – 1994.** Prepared .for the Polystyrene Packaging Council by Franklin Associates, Ltd. August 1996. Page 18.

E-6 Personal communication between Franklin Associates, Ltd. and Bob Yost of Douglas County, Kansas. February, 2003.

E-7 **Estimates of the Volume of MSW and Selected Components in Trash Cans and Landfills.** Prepared for The Council for Solid Waste Solutions by Franklin Associates, Ltd. and The Garbage Project. February 1990.

E-8 Franklin Associates, Ltd. estimate.

E-9 **Thermodynamic Data for Biomass Materials and Waste Components.** American Society of Mechanical Engineers. 1987.

E-10 Fire, Frank L. **Combustibility of Plastics.** Van Nostrand Reinhold. 1991.