FINAL REPORT

LIFE CYCLE INVENTORY OF THE PRODUCTION OF PLASTIC AND METAL PIPES FOR USE IN THREE PIPING APPLICATIONS

Prepared for

THE PLASTIC PIPE AND FITTINGS ASSOCIATION

by

FRANKLIN ASSOCIATES,
A DIVISION OF EASTERN RESEARCH GROUP, INC.
Prairie Village, Kansas

June 24, 2008

Table of Contents

Table of Contents (Cont'd)

List of Tables

List of Figures

EXECUTIVE SUMMARY

INTRODUCTION

A life cycle inventory examines the sequence of steps in the life cycle of a product system, beginning with raw material extraction and continuing on through material production, product fabrication, use, reuse or recycling where applicable, and final disposition. For each life cycle step, the inventory identifies and quantifies the material inputs, energy consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes). The information from this type of analysis can be used as the basis for further study of the potential improvement of resource use and environmental emissions associated with product systems. It can also pinpoint areas (e.g., material components or processes) where changes would be most beneficial in terms of reduced energy use or environmental emissions.

In this LCI, the specific products evaluated are several types of plastic and metal pipes used in residential and commercial construction.

STUDY GOAL AND INTENDED USE

The Plastic Pipe and Fittings Association (PPFA) commissioned this study to evaluate the environmental profiles of selected plastic and metal pipes used in three types of building piping applications, using the most current and representative data available. Although the original scope of the study included cast iron soil (DWV) pipe, it was not possible to obtain data of sufficient quality and completeness to ensure an accurate representation of United States cast iron pipe production. Therefore, cast iron pipe has been excluded from the study.

Plastic pipes were modeled using resin production data released in 2007 for the Plastics Division of the American Chemistry Council (ACC) and published in the U.S. LCI Database (www.nrel.gov/lci). Current plastic pipe fabrication data were collected for this study from pipe producers.

The original goal of the study was to evaluate current United States production of each type of pipe; however, it was necessary to collect some fabrication data from Canadian producers to supplement the United States data sets so that the aggregated production data could be shown as a separate unit process without compromising the confidentiality of individual producers' data. Energy requirements for all pipe production steps were modeled using United States fuels and energy data from the U.S. LCI database.

The intended use of this study is to inform PPFA members about the environmental burdens associated with production and disposal of pipes manufactured for three use applications. This data will also be used by PPFA as the basis for future analyses of the full life cycle of piping systems, including pipe manufacture, installation, use, and end of life management. The LCI has been conducted following internationally accepted standards for LCI methodology so that the results are suitable for submission to the U.S. LCI Database and BEES.

SCOPE AND BOUNDARIES

The LCI includes all steps from raw material extraction through pipe fabrication and transportation from manufacturer to customer. Manufacture and disposal of transportation packaging is included. Installation processes are **not** included, nor does the analysis include fittings, adhesives, solder, etc. used to connect lengths of pipe.

There are several possible end-of-life management options for recovered pipe. Interviews with demolition contractors, recyclers, construction and demolition landfill operators, and a demolition trade association indicated that copper pipe is the only type of pipe modeled in this study that is currently being recovered and recycled at a significant level in the United States. Thus, this analysis includes burdens for transporting recovered copper pipe to a recycler and transporting all other types of pipe to a construction and demolition landfill mixed with other construction and demolition wastes. No burdens were included for building demolition, digging up underground pipe, or operation of landfill equipment.

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels. Emissions that may occur over time due to corrosion of pipes, erosion of pipe materials by flowing water, or leaching of pipe constituents into the water or earth are not included. The rates at which these types of emissions may occur are highly dependent upon water use patterns, soil conditions, etc. Assessment of these issues is beyond the scope of this analysis.

FUNCTIONAL UNIT

In a life cycle study, products are compared on the basis of providing the same defined function (called the **functional unit**). Within each defined pipe application, the different types of pipe are compared on the basis of equivalent length of pipe of corresponding nominal diameter. A basic assumption is that equivalent lengths of pipe of corresponding nominal diameter deliver equivalent volumes of fluid. In some cases, the same nominal diameter pipe was available with different wall thicknesses (and weight per unit length), in which case pipes were compared based on equivalent diameter *and* functionality (e.g., pressure rating).

SYSTEMS STUDIED

The piping applications and types evaluated in this study include:

- 4-inch pipe for Drain, Waste, & Vent (DWV) applications
    - Solid polyvinyl chloride (PVC) pipe, both virgin and 50% postconsumer recycled (PCR) content

  - Cellular core[1] PVC pipe
  - Solid acrylonitrile butadiene styrene (ABS) pipe
  - Cellular core ABS pipe

- 1-inch pipe for inlet pressurized water supply applications
  - Polyethylene (PE) pipe
  - PVC pipe
  - Copper pipe, types K and L

- ¾-inch pipe for pressurized Hot and Cold Water Distribution (HCWD) applications
  - Chlorinated polyvinyl chloride (CPVC) pipe
  - Cross-linked polyethylene (PEX) pipe
  - Copper pipe, types K. L, and M

The weights of 1,000 feet of each type of pipe for each application are shown in Table ES-1. Methodology, data sources, and data quality are discussed in Chapter 1. Production of pipe materials, pipe fabrication, and end-of-life management of pipe are described in Chapter 2.

Plastic Pipe Fabrication Data

A significant component of this analysis was the collection of plastic pipe fabrication data from producers. Pipe fabrication data were requested from PPFA member companies and other pipe producers in order to try to get the most complete representation of United States pipe production. These companies were provided with worksheets and instructions developed specifically for this project to use in gathering the necessary process data for their product(s).

Upon receipt of the completed worksheets, the data were evaluated for completeness and reviewed for any material inputs in addition to the basic pipe resins (e.g., fillers, stabilizers, etc.). In this way, the material inputs to pipe production were adjusted to represent current industrial practices.

After each data set was completed and verified, the individual fabrication data sets for each type of pipe were aggregated into a single data set for that pipe. The method used for aggregating material inputs and fabrication data for each pipe was a weighted average based on the relative quantities of pipe produced by each company providing data. Care was taken to aggregate the data for each type of pipe in such a way that individual company data cannot be calculated or identified. A minimum of three data sets were required for each type of pipe.

---

[1] Cellular core pipe consists of a layer of foamed material sandwiched between solid walls. This type of pipe is also commonly referred to as “foam core.”

Table ES-1

POUNDS PER 1000 FEET OF PIPE

	lb/ft*	lb/1000 ft
4” DWV (Drain, Waste, Vent)		
PVC Solid	2.02	2,021
PVC Cellular Core	1.27	1,267
ABS Solid	1.50	1,504
ABS Cellular Core	1.01	1,007
1” Water Supply		
PE (HDPE, LLDPE)	0.16	165
PVC	0.32	317
Copper K	0.84	838
Copper L	0.66	655
¾” HCWD (Hot and Cold Water Distribution)		
CPVC	0.14	137
PEX	0.11	112
Copper K	0.64	641
Copper L	0.46	455
Copper M	0.33	328

---

* For plastic pipe, weighted average values were calculated based on each company's data multiplied by their percentage of total pipe production reported by all companies providing data for that pipe. Weight of 50% PCR pipe was assumed same as corresponding virgin pipe.
Weight per foot of copper pipe is based on data found in the Copper Tube Handbook, accessible online at the Copper Development Association (www.copper.org).

Weighted average plastic pipe fabrication energy data and ranges are shown in Table ES-2. Although there are significant ranges in the energy reported by different producers for each type of pipe, fabrication energy is a relatively small contributor to total LCI results, as shown later in this chapter.

Table ES-2
SUMMARY OF DATA PROVIDED BY PLASTIC PIPE PRODUCERS

	Companies providing data	Wtd avg lb/ft	kWh/1000 lb wtd avg	kWh/1000 lb range	Wtd avg kWh/ 1000 ft
4" DWV (Drain, Waste, Vent)					
PVC Solid	5	2.02	101	79 - 284	**205**
PVC Cellular Core	3	1.27	121	113 - 152	**154**
ABS Solid	3	1.50	197	84 - 440	**297**
ABS Cellular Core	3	1.01	100	84 - 440	**101**
1" Water Supply					
PE (HDPE, LLDPE)	3	0.16	225	173 - 613	**37**
PVC	5	0.32	138	102 - 376	**44**
¾" HCWD (Hot and Cold Water Distribution)					
CPVC	5	0.14	165	112 - 477	**23**
PEX	3	0.11	343	216 - 440	**39**

Weighted averages were calculated based on each company's data multiplied by their percentage of total pipe production reported by all companies providing data for that pipe.

Ranges in energy per 1000 lb reflect the fact that several producers reported the same fabrication energy per 1000 lb for multiple types of pipe.

RESULTS

The presentation and discussion of results focuses on energy, solid waste, and greenhouse gas emissions (total global warming potential). Tables containing the full list of atmospheric and waterborne emissions for each system are provided in Chapter 3.

Energy Results

Energy results for the different types of pipe in each application are shown in Figures ES-1 through ES-3. In the figures, total energy is classified into three categories:

- **Process energy** includes energy for all processes required to produce the pipes, from acquisition of raw materials through pipe manufacturing.
- **Transportation energy** is the energy used to move material from location to location during its journey from raw material to product.
- **Energy of material resource (EMR)** is not an expended energy but the energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as material inputs for materials such as plastic resins. In this study, energy of material resource is reported for plastic pipes (and plastic pipe packaging components), which are produced from resins using natural gas and petroleum as material feedstocks. (Energy of material resource is described in more detail in Chapter 1.)

For plastic pipes, EMR accounts for a significant percentage of total energy, while the copper pipe systems have very small amounts of EMR, associated only with plastic components used in packaging pipe for shipment. EMR is lower for PVC and CPVC compared to other resins because PVC and CPVC have significant chlorine content rather than being derived totally from petroleum and natural gas resources.

Figure ES-1. Energy for 1000 Feet of 4" DWV Pipe by Energy Category

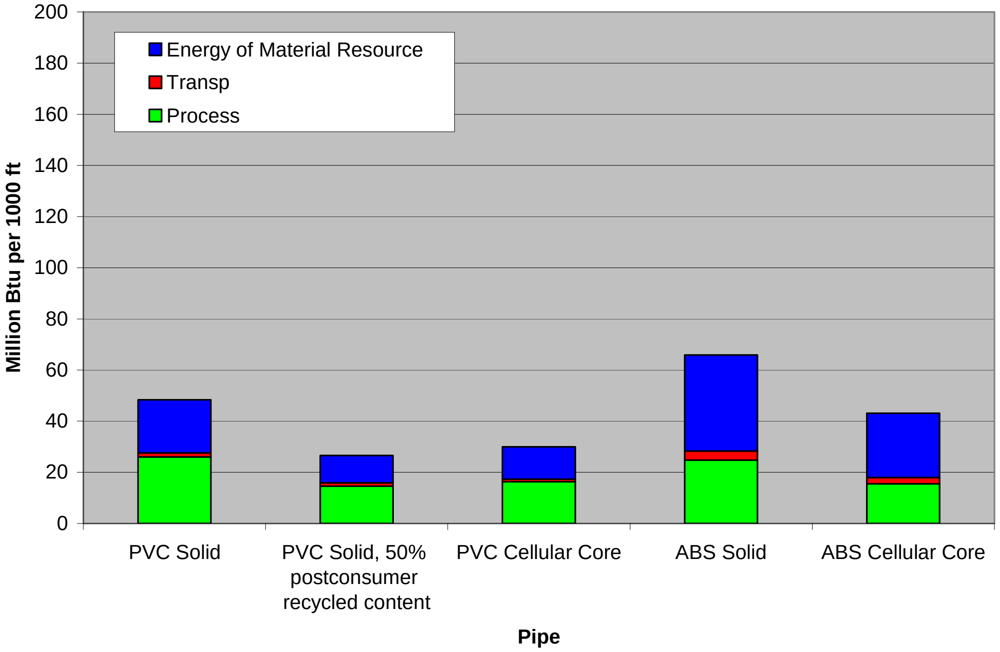


Figure ES-2. Energy for 1000 Feet of 1" Water Supply Pipe by Energy Category

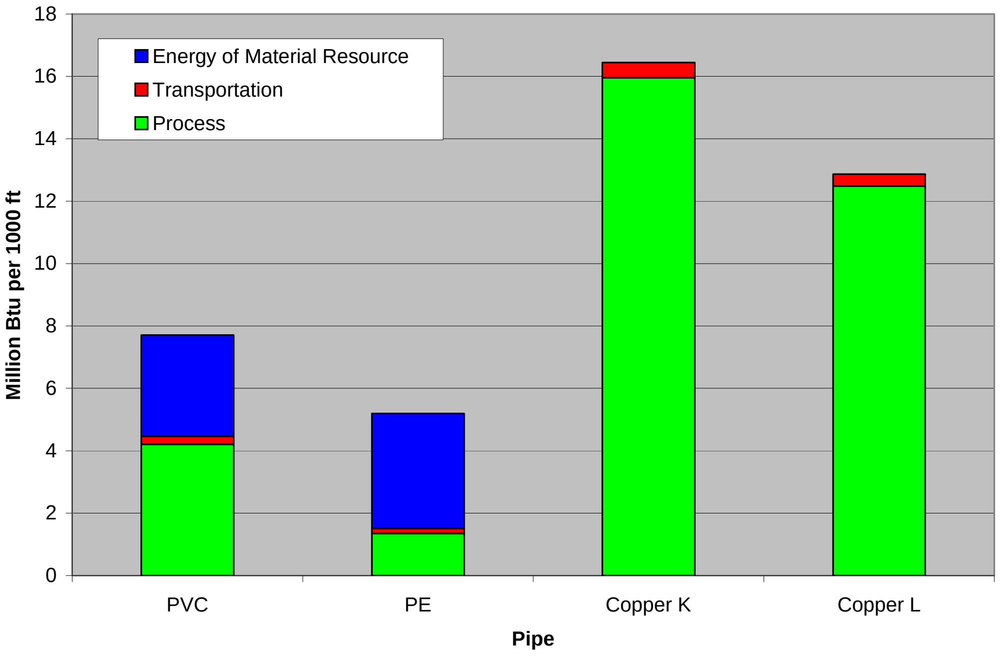
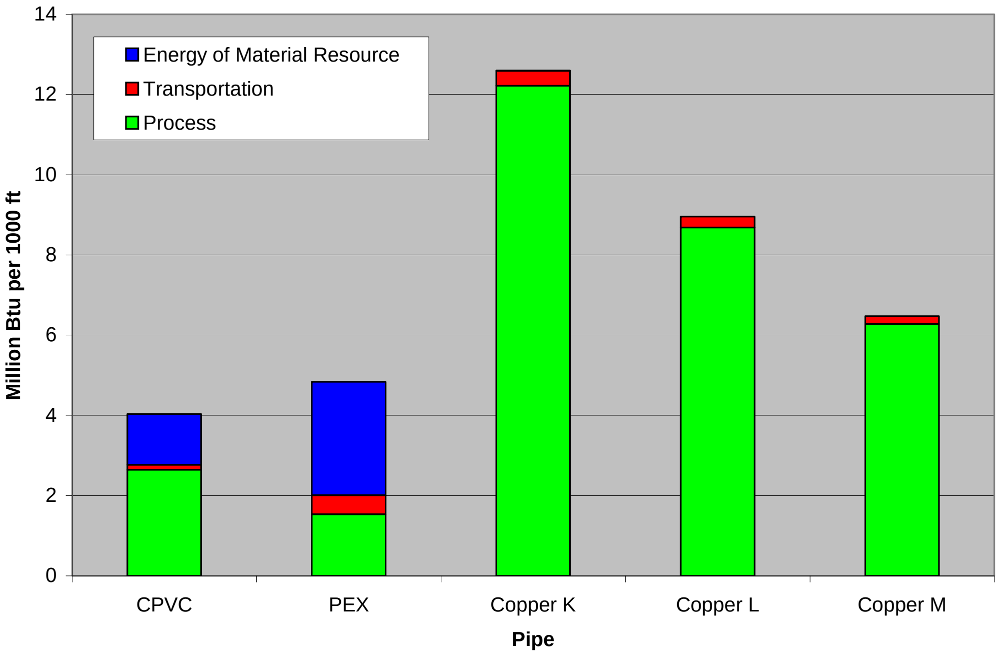


Figure ES-3. Energy for 1000 Feet of 3/4" HCWD Pipe by Energy Category



DWV Pipe. Cellular core DWV pipes have lower energy requirements per 1000 feet than the corresponding solid virgin resin pipes. The majority of the energy for plastic pipe is associated with production of the resins and additives rather than for the extrusion process. Thus, the energy savings from the reduced weight of resin required for the cellular core pipe more than offsets the higher extrusion energy per unit length.

An additional scenario modeled was a solid PVC pipe with a 50% postconsumer recycled content. This pipe would have the lowest energy requirements of the DWV systems modeled. The methodology used to model postconsumer recycled content for plastic and metal pipe in this study is consistent with the National Institute of Science and Technology's BEES (Building for Environmental and Economic Sustainability) model. In the BEES methodology, postconsumer material comes in free of all virgin material production burdens and carries only the burdens associated with collection and reprocessing. Similarly, this methodology assigns no postconsumer solid waste disposal burdens to material that is recovered at end of life for recycling or reuse.

Water Supply Pipe. For water supply pipe, Figure ES-2 shows that energy requirements for PE pipe are lower than for PVC pipe and both are significantly lower than the corresponding copper products. Although PVC requires less energy per pound to produce compared to PE, the higher weight per unit length of PVC pipe results in higher total energy requirements compared to PE pipe. The copper pipes require about twice as much total energy as the plastic pipes. Even though the copper pipe is modeled with a high recycled content, the heavier weight per unit length compared to plastic pipe and the high energy requirements for producing molten copper are the reasons for the difference.

HCWD Pipe. Plastic HCWD pipes require significantly less energy than corresponding diameter copper pipe to manufacture, although Figure ES-3 shows that the difference between plastic pipe results and copper pipe results narrows as the wall thickness (and weight per unit length) of copper pipe decreases.

The difference between CPVC and PEX energy results can be attributed to several differences between these pipes. The chlorine content of CPVC displaces petroleum- and natural gas-based content in the resin, so EMR for CPVC resin is lower than for PEX resin. Also, although PEX pipe is somewhat lighter per unit length than CPVC pipe, the weighted average pipe production energy per unit output of pipe is higher for PEX pipe than for CPVC pipe. Table ES-2 shows that there was a significant range in pipe production energy reported for both CPVC pipe and PEX pipe. When results using the highest fabrication energy for CPVC are compared to results using the lowest fabrication energy for PEX, CPVC energy is still lower than PEX energy, but the difference is small enough that it is not considered meaningful within the margin of error for life cycle energy results.

Fossil Energy. For plastic pipe systems, at least 94 percent of total energy is fossil energy. This includes not only the use of fossil fuels as process and transportation fuel but also the EMR of the plastic resins, petroleum- and natural gas-derived additives, and plastic packaging. Fossil energy accounts for about 90 percent of total energy requirements for the copper pipe systems. It is worth noting that process energy and transportation energy are associated with combustion of fuels, while EMR represents an inherent energy of the product, some of which can potentially be recovered if the material is burned with energy recovery.

Energy for Pipe Materials and Fabrication. For plastic pipe in all applications, production of pipe materials (resin and additives) accounts for 89 to 94 percent of total energy requirements. Pipe fabrication energy (extrusion energy) ranges from 4 to 8 percent of the total for all plastic pipes except for the 50% PCR PVC pipe and PEX pipe. Fabrication energy constitutes a larger percentage of the total for the PCR PVC pipe because the use of postconsumer resin reduces the energy requirements associated with the resin input. The relatively small contribution of fabrication energy to the total results for plastic pipe means that the variations in fabrication energy reported by different producers shown in Table ES-2 do not have a large effect on the energy results and conclusions. For copper pipe, the combined energy for copper production and pipe fabrication account for over 98 percent of the total energy requirements.

Solid Waste Results

Similar to energy results, solid waste results shown in Figures ES-4 through ES-6 are broken out into 3 categories:

- **Process wastes** are the solid wastes generated by the various processes from raw material acquisition through pipe production, including unrecycled fabrication scrap.
- **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy.
- **Postconsumer wastes** include the pipe packaging wastes and pipe disposed at end of life.

The results shown in the tables and figures are based on all pipe being transported to a construction and demolition landfill or to a recycler at end of life. Solid waste for all pipe systems is dominated by postconsumer pipe.

In the solid waste figures, the postconsumer pipe segments have been divided into sections to illustrate the effect of various levels of postconsumer recovery. For example, in Figure ES-5, the total weight of solid waste for PVC water supply pipe is about 380 pounds. The last column in Figure ES-5 shows that copper L water supply pipe would have to be recovered at a rate of over 50% to be comparable to the total weight of solid waste for PVC pipe at 0% recovery.

Figure ES-4. Solid Waste for 1000 Feet of 4" DWV Pipe by Solid Waste Category

(showing effects of various recovery levels)

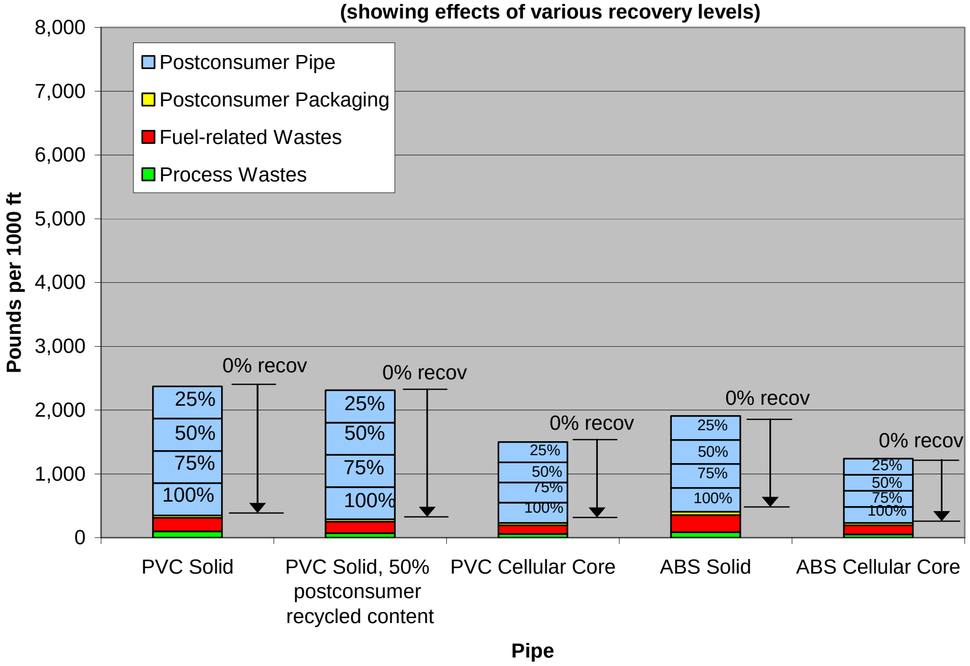


Figure ES-5. Solid Waste for 1000 Feet of 1" Water Supply Pipe by Solid Waste Category

(showing effects of various recovery levels)

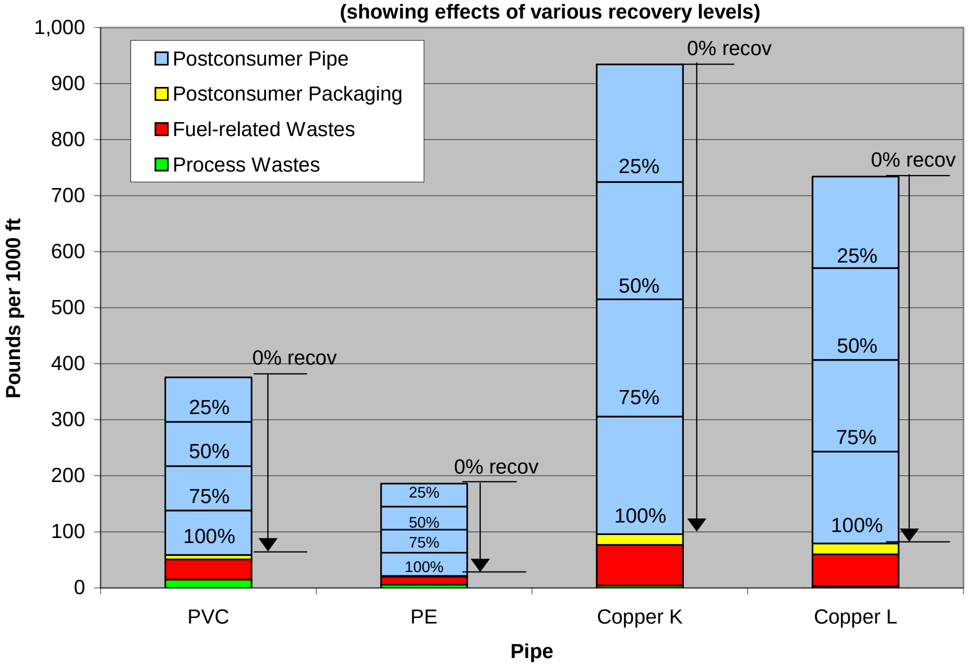
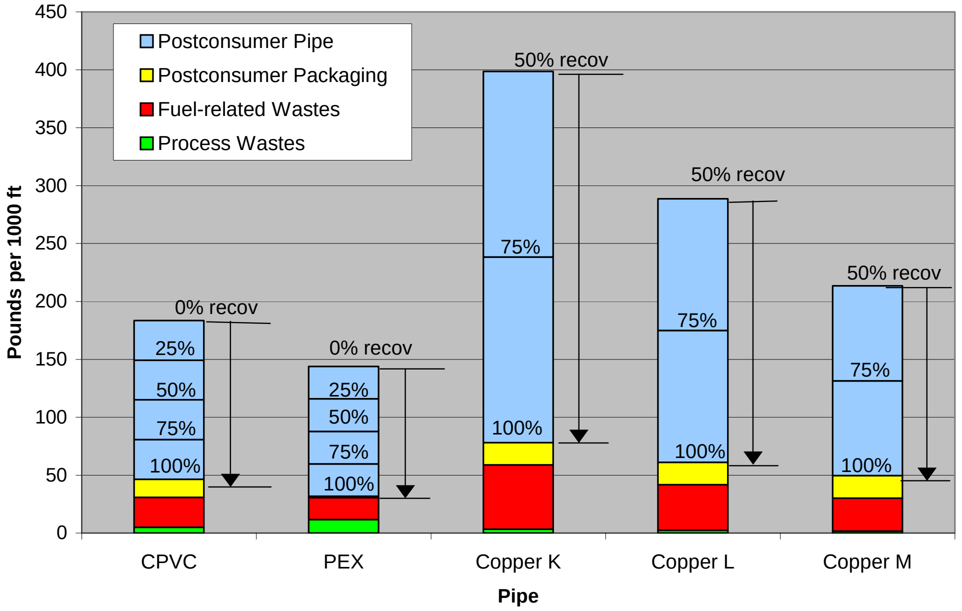


Figure ES-6. Solid Waste for 1000 Feet of 3/4" HCWD Pipe by Solid Waste Category
(showing effects of various recovery levels)



Fuel-related wastes are higher for the copper pipe systems compared to the plastic systems because of the large amounts of energy required to process the primary and secondary metal (extracting and refining virgin copper and melting postconsumer copper).

Global Warming Potential

The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Each greenhouse gas has a global warming potential (GWP) that represents the relative global warming contribution of a pound of that particular greenhouse gas compared to a pound of carbon dioxide. The weight of each greenhouse gas from each pipe system is multiplied by its GWP, then the GWPs for each greenhouse gas are added to arrive at a total GWP (expressed in pounds of CO_2 equivalents) for each pipe system. The majority of GWP for each system is from fossil carbon dioxide, followed by methane. GWP contributions of other substances emitted from the pipe systems (e.g., nitrous oxide, carbon tetrachloride, CFCs, etc.) are also included in the total; however, their contribution relative to fossil carbon dioxide and methane is negligible. The results for each type of pipe are shown graphically in Figures ES-7 through ES-9.

Figure ES-7. Global Warming Potential for Production of 1000 Feet of 4" DWV Pipe

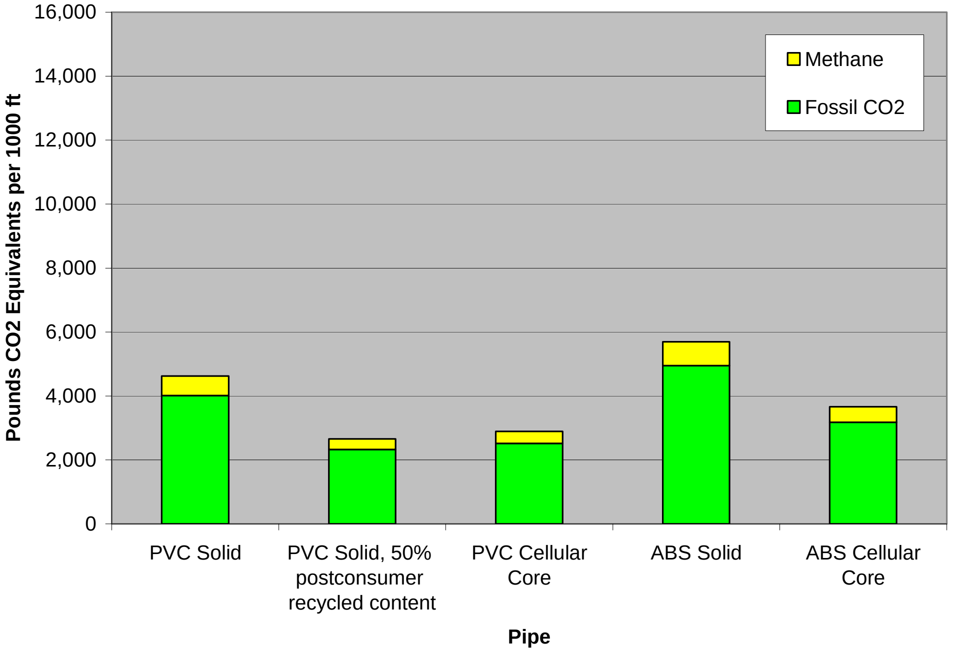


Figure ES-8. Global Warming Potential for Production of 1000 Feet of 1" Water Supply Pipe

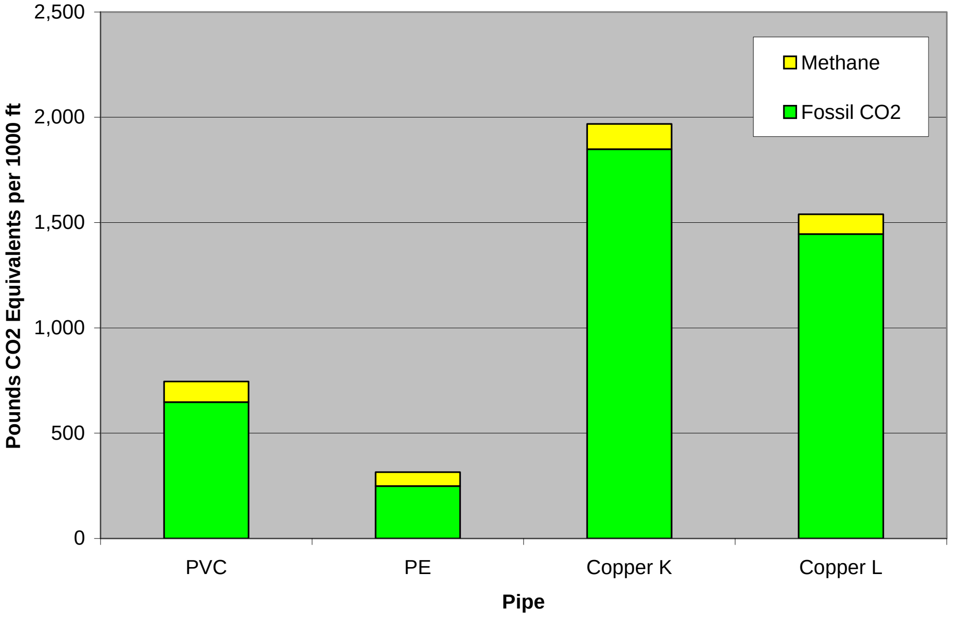
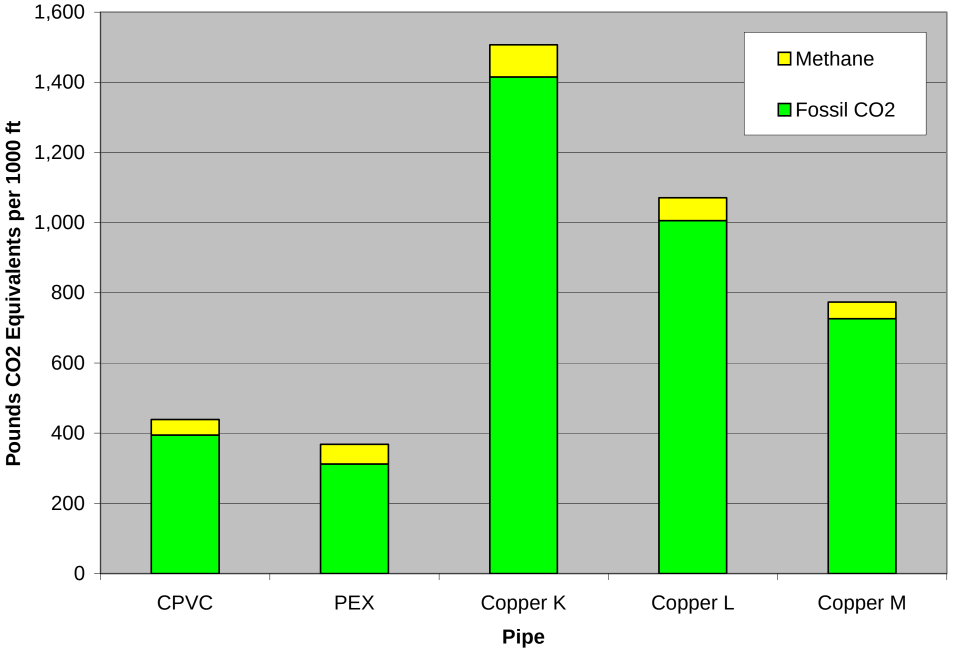


Figure ES-9. Global Warming Potential for Production of 1000 Feet of 3/4" HCWD Pipe



Global warming potential is largely a result of fossil fuel combustion. Thus, it might be expected that GWP comparisons would track closely with fossil energy requirements; however, this is not the case for plastics. Although fossil fuels account for at least 94 percent of total energy for all plastic pipe systems, about half of this is energy of material resource. This accounts for the energy content of the fossil fuel resources used to produce the resin but does not result in GWP (unless the pipe is burned). Therefore, the energy total that most closely matches the GWP total is the total fossil **process and transportation** energy.

CONCLUSIONS

The following conclusions can be drawn based on the results of the LCI:

- **Weight per unit length of pipe is a key factor in all LCI results.** Lighter pipes generally have lower environmental burdens.
- **Energy:** The use of energy resources as raw materials for plastic resins increases the total energy for plastic pipe systems; however, this is more than offset by the heavier weight of copper pipe and the large amounts of energy required to produce the primary and secondary copper.

- **Solid Waste:** Total solid wastes are dominated by the weight of the postconsumer pipe; thus, heavier pipes have higher total solid waste than lighter pipes. Copper HCWD pipe is widely recovered for recycling due to its high value so that there is likely to be little unrecovered postconsumer copper HCWD pipe going to construction and demolition landfills. Increased recovery of other types of pipe, either recovery prior to demolition or recovery from construction and demolition waste, would greatly reduce the solid waste associated with pipe systems. Recovered plastic pipe could be recycled or incinerated with energy recovery. Incineration of plastic pipe with energy recovery would reduce solid waste and recover some of the pipe’s energy of material resource but would increase fossil carbon dioxide emissions, increasing GWP.
- **Global Warming Potential:** Over 75 percent of total GWP for all pipe systems is from carbon dioxide from combustion of fossil fuels. Thus, pipe systems that require combustion of large amounts of fossil fuels for process and transportation energy have higher GWP.

CHAPTER 1
LIFE CYCLE METHODOLOGY

OVERVIEW

The life cycle inventory (LCI) presented in this study quantifies the total energy requirements, energy sources, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of several types of plastic and copper pipes used in three types of building piping applications.

This analysis does not include impact assessment. It does not attempt to determine the fate of emissions, or the relative risk to humans or to the environment due to emissions from the systems. (An exception is made in the case of global warming potential impacts, which are calculated based on internationally accepted factors for various greenhouse gases' global warming potentials relative to carbon dioxide.) No judgments are made as to the merit of obtaining natural resources from various sources, for example, whether it is preferable to produce pipe from fuel resources or mineral resources.

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

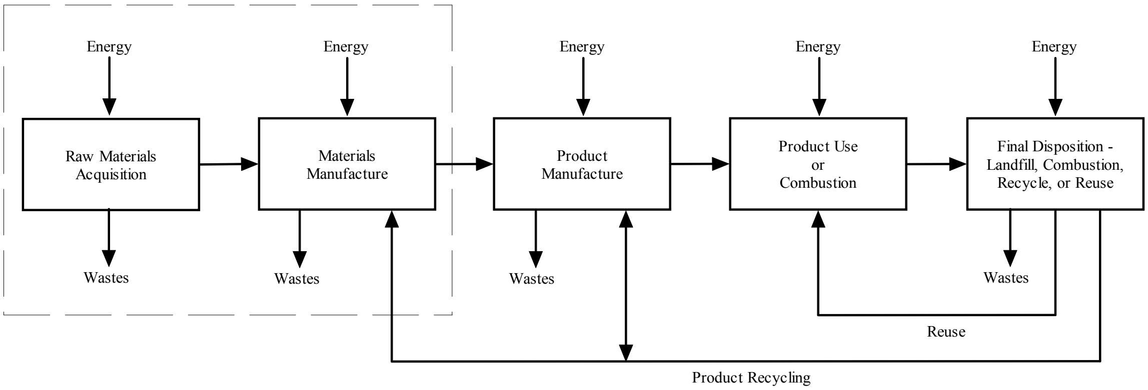


Figure 1-1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this LCI analysis. No recycled content or recycling is included in this analysis.

Study Goal and Intended Use

This study was commissioned by the Plastic Pipe and Fittings Association (PPFA) to evaluate the environmental profiles of selected plastic and metal pipes used in three types of piping applications, using the most current and representative data available. Although the original scope of the study included recycled cast iron DWV pipe, it was not possible to obtain sufficient quality data to ensure an accurate representation of United States cast iron pipe production, so it was excluded from the study.

Plastic pipes were modeled using resin production data released in 2007 for the Plastics Division of the American Chemistry Council (ACC) and published in the U.S. LCI Database (www.nrel.gov/lci). Current plastic pipe fabrication data were collected for this study from pipe producers.

The results are presented in sufficient detail to allow analysis of the contribution of different life cycle steps (resin production, plastic pipe fabrication via extrusion, pipe packaging, etc.) to the overall profile for each type of pipe studied.

The intended use of this study is to inform PPFA members about the environmental burdens associated with production and disposal of pipes manufactured for three use applications. This data will also be used by PPFA as the basis for future analyses of the full life cycle of piping systems, including pipe manufacture, installation, use, and end of life management. The LCI has been conducted following internationally accepted standards for LCI methodology so that the results are suitable for submission to the U.S. LCI Database and BEES.

Study Scope and Boundaries

This LCI encompasses the following steps in the life cycle of each pipe studied:

- Raw material extraction
- Processing of raw materials into pipe material
- Pipe fabrication
- Transport of pipe to customer
- Transport of pipe at end of life

Flow diagrams and descriptions for the production of pipe can be found in Chapter 2. The LCI quantifies energy and resource use, solid waste, and individual atmospheric and waterborne emissions for the life cycle stages listed above. Environmental burdens associated with end-of-life management of pipe are limited to transport of pipe to a recycler or construction and demolition landfill.

The scope of the project does not include the manufacture of some of the specific fillers or additives that may be added to the pipe resins analyzed. In some cases, suitable surrogate data were available, while in other cases insufficient information was available to include the material in the system modeling. These issues are discussed for individual types of pipe in Chapter 2 and summarized in the Data Quality section of this chapter.

LIFE CYCLE INVENTORY METHODOLOGY

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

Franklin Associates developed a methodology for performing resource and environmental profile analyses (REPA), commonly called life cycle inventories. This methodology has been documented for the United States Environmental Protection Agency and is incorporated in the EPA report **Product Life-Cycle Assessment Inventory Guidelines and Principles.** The data presented in this report were developed using this methodology, which has been in use for over 30 years.

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

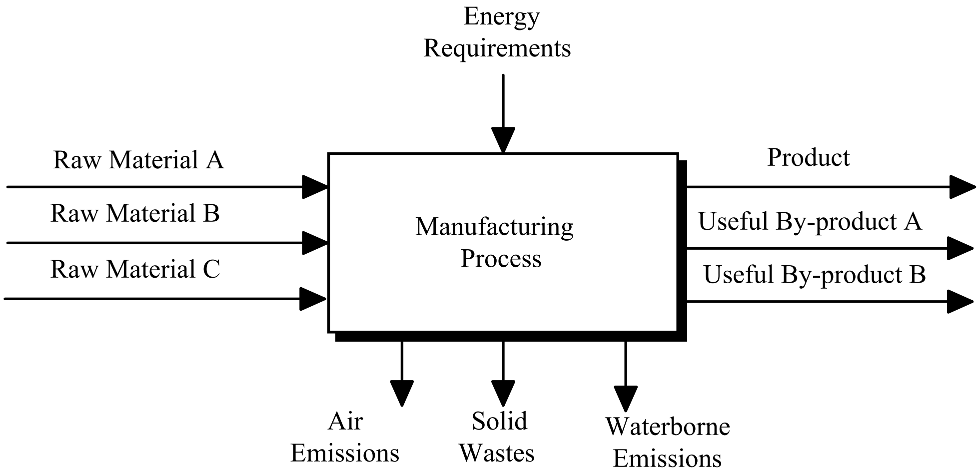


Figure 1-2. "Black box" concept for developing LCI data.

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

Material Requirements

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

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

Energy Requirements

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

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

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

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

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

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

The "other" category includes nonconventional sources, such as solar, biomass and geothermal energy. Also included in the LCI energy profile are the Btu values for all transportation steps and all fossil fuel-derived raw materials. Energy results for the pipes studied in this analysis are provided in Chapter 3.

Environmental Emissions

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

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

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

The emissions results discussion in Chapter 3 focuses on greenhouse gas emissions, expressed in pounds of carbon dioxide equivalents.

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

Solid Wastes. This category includes solid wastes generated from all sources that are landfilled or disposed of in some other way, such as incineration with or without energy recovery. These include industrial process- and fuel-related wastes, as well as the pipe that is disposed when a building is demolished. Examples of industrial process wastes are residuals from chemical processes and manufacturing scrap that is not recycled or sold. Examples of fuel-related solid wastes are ash generated by burning coal to produce electricity, or particulates from fuel combustion that are collected in air pollution control devices.

LCI PRACTITIONER METHODOLOGY VARIATION

There is general consensus among life cycle practitioners on the fundamental methodology for performing LCIs.[2] However, for some specific aspects of life cycle inventory, there is some minor variation in methodology used by experienced practitioners. These areas include the method used to allocate energy requirements and environmental releases among more than one useful product produced by a process, the method used to account for the energy contained in material feedstocks, and the methodology used to allocate environmental burdens for postconsumer recycled content and end-of-life recovery of materials for recycling. LCI practitioners vary to some extent in their approaches to these issues. The following sections describe the approach to each issue used in this study.

Co-product Credit

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

---

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

multiple products from a process is often referred to as "co-product credit"[3] or "partitioning"[4].

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

Franklin Associates follows the guidelines for allocating co-product credit shown in the ISO 14040 series of standards on Life Cycle Assessment. In the ISO 14040 series, the preferred hierarchy for handling allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. How product allocation is made will vary from one system to another but the choice of parameter is not arbitrary. The aim should be to find an allocation parameter that in some way reflects, as closely as possible, the physical behavior of the system itself.[5]

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

In this analysis, co-product credit is assigned to any useful process output that is produced and sold, whether it is produced by choice or as an unavoidable co-product together with the desired product. All scrap co-product in this analysis was allocated on a mass basis. Economic allocation was ruled out as it depends on the economic market, which can change dramatically over time depending on many factors unrelated to the chemical and physical relationships between process inputs and outputs. Useful scrap that is produced and sold should be allocated its share of the raw materials and energy required, as well as emissions released. When the co-product was heat or steam or a co-product sold for use as a fuel, the energy amount (Btu or J) of the heat, steam, or fuel was shown as recovered energy that reduced the net process energy assigned to the resin.

---

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

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

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

Energy of Material Resource

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

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

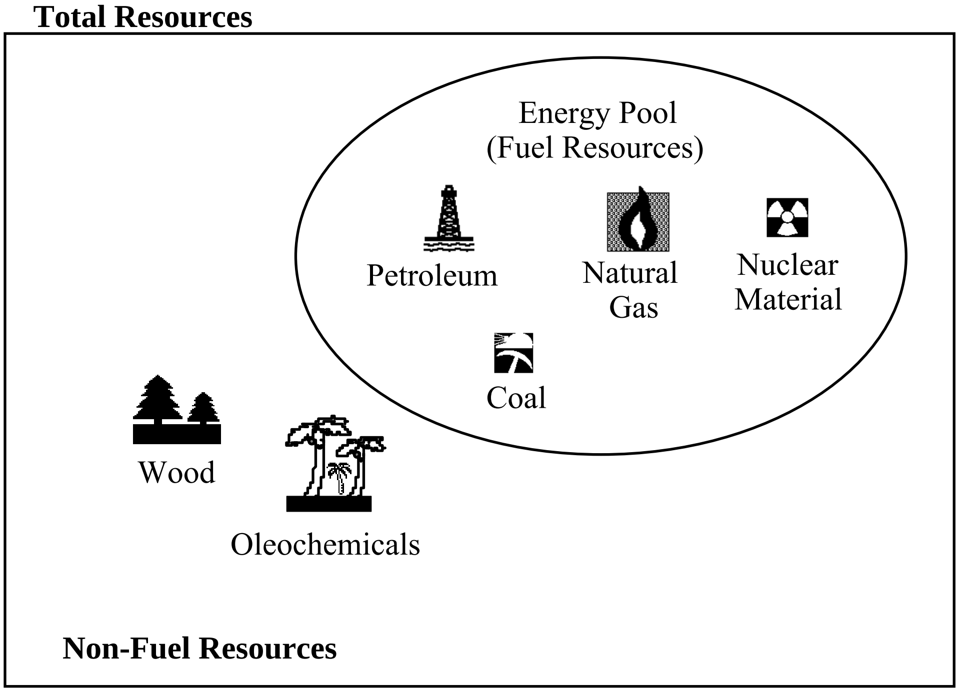


Figure 1-3. Illustration of the Energy of Material Resource Concept.

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

Once the feedstock is converted to a product, there is energy content that could be recovered, for instance through combustion in a waste-to-energy waste disposal facility. The energy that can be recovered in this manner is always somewhat less than the feedstock energy because the steps to convert from a gas or liquid to a solid material reduce the amount of energy left in the product itself.

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

Recycling Methodology

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

The methodology used in this analysis is the methodology used in the National Institute of Standards and Technology (NIST) life cycle model of building products, BEES (Building for Environmental and Economic Sustainability). In this methodology, boundaries are drawn between each product application in which a given quantity of material is used. When material is recovered after its useful life in one system and reused (recycled) in a subsequent application, no disposal burdens for that material are charged to the first system, and no material production burdens are carried with it into the second system. The only material burdens carried into the second use are the burdens for recovering and reprocessing the material. At the end of the material's second useful life, if any or all of the material is recovered for another use, that material leaves the second system with no associated disposal burdens.

This methodology is applied to the pipe systems in this analysis that utilize postconsumer recycled (PCR) content: the 50% PCR solid PVC DWV pipe and all the copper pipes, which are modeled as 64% PCR copper. For the copper HCWD pipe systems, not only does 64% of the copper come in free of virgin production burdens, but much of the pipe is assumed to be recovered at end of life for recycling, reducing solid waste disposal burdens.

DATA

The accuracy of the study is directly related to the quality of input data. The development of methodology for the collection of data is essential to obtaining quality data. Careful adherence to that methodology determines not only data quality but also objectivity. Data quality and uncertainty are discussed in more detail at the end of this section.

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

Process Data

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

Each process identified during the construction of the flow diagram is then researched to identify potential industry sources for data. In this study, pipe fabrication data were requested from PPFA member companies and other pipe producers in order to try to get the most complete representation of United States pipe production. These companies were provided with worksheets and instructions developed specifically for this project to use in gathering the necessary process data for their product(s).

Upon receipt of the completed worksheets, the data were evaluated for completeness and reviewed for any material inputs in addition to the basic pipe resins (e.g., fillers, stabilizers, etc.). In this way, the material inputs to pipe production were adjusted to represent current industrial practices. Data suppliers were then contacted again to resolve any questions regarding the data they provided on material inputs, fabrication energy, process wastes and emissions, and finished pipe packaging and transport.

After each data set was completed and verified, individual fabrication data sets for each pipe were aggregated into a single set of data for that pipe. The method used for aggregating material inputs and fabrication data for each pipe was a weighted average based on the relative quantities of pipe produced by each company providing data.

Confidentiality. The data provided in the worksheets are considered proprietary by the individual companies supplying the data. To protect the confidentiality of individual data sets, all data were submitted directly to Franklin Associates. Care was taken to aggregate the data for each type of pipe in such a way that individual company data cannot be calculated or identified. A minimum of three data sets were required for each type of pipe. In this study, it was necessary to collect some fabrication data from

Canadian producers to supplement the United States data sets so that the aggregated production data could be shown as a separate unit process without compromising the confidentiality of individual producers' data.

Objectivity. Each unit process in the life cycle study is researched independently of all other processes. No calculations are performed to link processes together with the production of their raw materials until *after* data gathering and review are complete. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. Also, because these data are reviewed individually, assumptions are reviewed based on their relevance to the process rather than their effect on the overall outcome of the study.

Data Sources. As stated in the **Study Goal** section, the intended purpose of the study was to evaluate the environmental profiles of several types of plastic and metal pipe commonly used in specific piping applications. The life cycle results were developed using the most up-to-date data available, including primary data collected from the companies producing each type of plastic pipe.

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

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

Fuel Data

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

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

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

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

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

Data Quality Goals for This Study

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

The data quality goal for this study was to use primary data collected from pipe producers to develop data that were representative of current United States pipe production in terms of time, geographic, and technology coverage. In order to get the minimum three data sets required for each type of resin, it was necessary to use pipe fabrication data sets from two Canadian producers. Because of the limited participation by United States pipe producers and the use of some Canadian producer data sets, it is not possible to determine the degree to which the pipe fabrication, packaging, and transport data collected for this study are representative of *total* ***United States*** *production* of these types of pipe.

Because the pipe fabrication energy reported by different producers showed some significant variations, each pipe producer was contacted requesting confirmation of the data provided. The weighted averages and ranges of energy data for each type of pipe are shown in Table 1-1. As described in the results section, the contribution of pipe fabrication to total energy results was generally small (less than 8 percent) for most plastic pipe systems.

Data for most other processes and materials in this study were taken from Franklin Associates' LCI database or estimated based on secondary data sources. The quality of these data vary in terms of age, representativeness, measured values or estimates, etc.; however, all materials and process data sets used in this study were thoroughly reviewed for accuracy and currency and updated to the best of our capabilities for this analysis. All fuel data were reviewed and extensively updated in 2003. Table 1-2 summarizes the sources of the key data used in this study.

As noted in the **Study Goal** section, the original scope of the study included recycled cast iron DWV pipe, but cast iron pipe had to be excluded from the study because it was not possible to obtain suitable quality data to ensure an accurate representation of this pipe.

Table 1-1
SUMMARY OF DATA PROVIDED BY PLASTIC PIPE PRODUCERS

	Companies providing data	Wtd avg lb/ft	kWh/1000 lb wtd avg	kWh/1000 lb range	Wtd avg kWh/ 1000 ft
4" DWV (Drain, Waste, Vent)					
PVC Solid	5	2.02	101	79 - 284	**205**
PVC Cellular Core	3	1.27	121	113 - 152	**154**
ABS Solid	3	1.50	197	84 - 440	**297**
ABS Cellular Core	3	1.01	100	84 - 440	**101**
1" Water Supply					
PE (HDPE, LLDPE)	3	0.16	225	173 - 613	**37**
PVC	5	0.32	138	102 - 376	**44**
¾" HCWD (Hot and Cold Water Distribution)					
CPVC	5	0.14	165	112 - 477	**23**
PEX	3	0.11	343	216 - 440	**39**

Weighted averages were calculated based on each company's data multiplied by their percentage of total pipe production reported by all companies providing data for that pipe.

Ranges in energy per 1000 lb reflect the fact that several producers reported the same fabrication energy per 1000 lb for multiple types of pipe.

As shown in Table 1-2, copper pipe was modeled using data from Franklin Associates' proprietary LCI database, developed from data provided by a copper producer. Results from Franklin's database were compared to other available LCI data for production of primary copper, secondary copper, and copper pipe fabrication. The most complete LCI data for comparison were found in the EcoInvent database. When material and energy usage from the EcoInvent primary copper unit processes were linked to United States data for fuels and electricity production and consumption, the resulting cradle-to-production energy for primary copper corresponded very closely with Franklin's primary copper production energy. Franklin's secondary copper energy were lower than EcoInvent energy results for secondary copper and slightly higher than energy data for secondary copper production from high-purity scrap reported in a 2002 report from the World Business Council on Sustainable Development.[6] Franklin's energy data for pipe production were somewhat lower than copper pipe production energy reported in the 2002 report. Thus, the energy data in this report can be considered to be a somewhat conservative representation of copper pipe production.

Table 1-2
SOURCES OF KEY DATA USED IN THE LIFE CYCLE INVENTORY

DATA CATEGORY	DATA SOURCE
Pipe weights	
Plastic pipes	Pipe producer LCI data collected for this project
Copper	Copper Tubing Handbook, accessed at www.copper.org
Postconsumer recycled content	
Solid PVC pipe	Level requested by PPFA to be modeled (June 2007)
Copper	Plumbing tube manufacture article on Copper Development Association website (http://www.copper.org/innovations/how/howdo_tube.html)
Production of pipe materials	
PVC, ABS, PE	US LCI Database (American Chemistry Council) May 2007
CPVC	Life cycle data published by Noveon in an environmental brochure for Temprite® CPVC resin
PEX	Process inputs, energy, and wastes provided by producers
Copper	Franklin Associates LCI database, based on confidential data provided by a copper producer for a 2002 study.
Production of resin additives used by pipe producers	
Types and weights of additives used	Pipe producer LCI data collected for this project
Polyethylene and paraffin waxes, titanium dioxide, calcium stearate, calcium carbonate	Franklin Associates LCI database
Impact modifier, described as an acrylic resin	Modeled as polymethylmethacrylate (PMMA), using Eco-profiles life cycle data downloaded from the PlasticsEurope website (http://lca.plasticseurope.org/). 1996 data from 5 plants.
Color concentrate (resin/colorant blend)	Modeled as corresponding resin
Organotin heat stabilizer, blowing agent for cell core pipe, masterbatch, PEX antioxidant and peroxide	Excluded: less than 1% by weight of pipe system and data not available on composition or production
Pipe fabrication	
Plastic pipes	Pipe producer LCI data collected for this project
Copper	Franklin Associates LCI database, updated for a 2002 study
Pipe packaging	
Plastic pipes	Pipe producer LCI data collected for this project
Copper	Data provided by pipe retailer, based on on-site measurements (2006)
Production and combustion of fuels and energy used for process and transportation energy	US LCI Database (as of May 2007)

---

[6] **The Life Cycle of Copper, Its Co-Products and By-Products.** Ayres et al. For the Mining, Minerals, and Sustainable Development project of IIED (International Institute for Environment and Development), World Business Council for Sustainable Development. No.24, January 2002.

Data Accuracy

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

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

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

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

In summary, for the particular data sources used and for the specific methodology described in this report, the results of this report are believed to be as accurate and reasonable as possible. The results discussions in Chapter 3 present guidelines for considering differences between system results to be meaningful (greater than the margin of error/uncertainty of the data). Appendix A presents sample statistical calculations that support these guidelines.

METHODOLOGY ISSUES

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

Precombustion Energy and Emissions

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

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

Electricity Grid Fuel Profile

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

Pipe fabrication data for this analysis was requested from producers in the United States; however, as noted earlier, in order to get the minimum three data sets required for each type of resin, pipe fabrication data sets from two Canadian producers were used. The production and combustion of fuels and energy used by the Canadian producers were modeled using United States data.

METHODOLOGICAL DECISIONS

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

Geographic Scope

Data collected for this analysis came from plants located in North America. The majority of the plants were located in the United States; however, fabrication data from two Canadian producers were also included.

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

System Components Not Included

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

Water Use. Because of the lack of availability of good data on water use for raw material and intermediate unit processes, Franklin Associates' LCI database does not include water use.

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

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

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

Miscellaneous Materials and Additives. Selected materials such as catalysts, pigments, or other additives which total less than one percent by weight of the net process inputs are typically not included in the assessment. Omitting miscellaneous materials and additives helps keep the scope of the study focused and manageable within budget and time constraints. However, it is possible that some toxic emissions may be released from the production of these materials and additives.

As noted earlier in this chapter, the availability of suitable data for modeling additives such as plasticizers, stabilizers, etc. reported for each type of pipe was evaluated on a case-by-case basis. Chapter 2 contains a description of the materials and total percentage of material inputs by weight that were modeled for each plastic pipe system.

CHAPTER 2
SYSTEMS STUDIED

INTRODUCTION

For the pipes studied in this analysis, this chapter presents a description of the production of the pipe materials, pipe fabrication processes, and end-of-life management of pipe.

PIPE MATERIAL PRODUCTION

Descriptions of the processes involved in producing each pipe material are provided in the following sections. Flow diagrams illustrating the sequence of steps required to produce each type of plastic pipe are presented at the end of each resin section, while the flow diagram for copper pipe production is shown at the end of the Copper Pipe Fabrication section.

Plastic Pipe Materials

PVC. Three of the pipes studied in this LCI are made from polyvinyl chloride (PVC). PVC resin is produced by suspension, emulsion, mass, or solution polymerization of VCM. A flow diagram for the production of PVC resin is shown in Figure 2-1. As of 2003, more than 90 percent of the PVC produced in North America is by the suspension route. In the suspension process, VCM and initiators are mixed with water and kept in the form of aqueous droplets by agitation and suspension stabilizers. The polymerization generally is carried out in a nitrogen atmosphere in large agitated reactors. The reaction time is typically about 12 hours, and conversion of VCM approaches 90 percent. After polymerization, the unreacted monomer is removed and recycled. The polymer is blended with additives and modifiers and centrifuged to remove water. The resin is then dried and packaged for shipment.

The additives and modifiers reported by pipe producers included organotin heat stabilizer, polyethylene and paraffin waxes, titanium dioxide, calcium stearate, calcium carbonate, and impact modifier. In addition, blowing agent use was reported for cellular core pipe. LCI data were available for the waxes, titanium dioxide, calcium stearate, and calcium carbonate. The impact modifier, described as an acrylic resin, was modeled as polymethylmethacrylate (PMMA) using PlasticsEurope data. No data were available for the stabilizer or blowing agent, and these substances together accounted for less than 1 percent of the total weight of each type of PVC pipe, so they were excluded from the modeling. Over 99 percent of the total weight of each pipe was accounted for in the modeling.

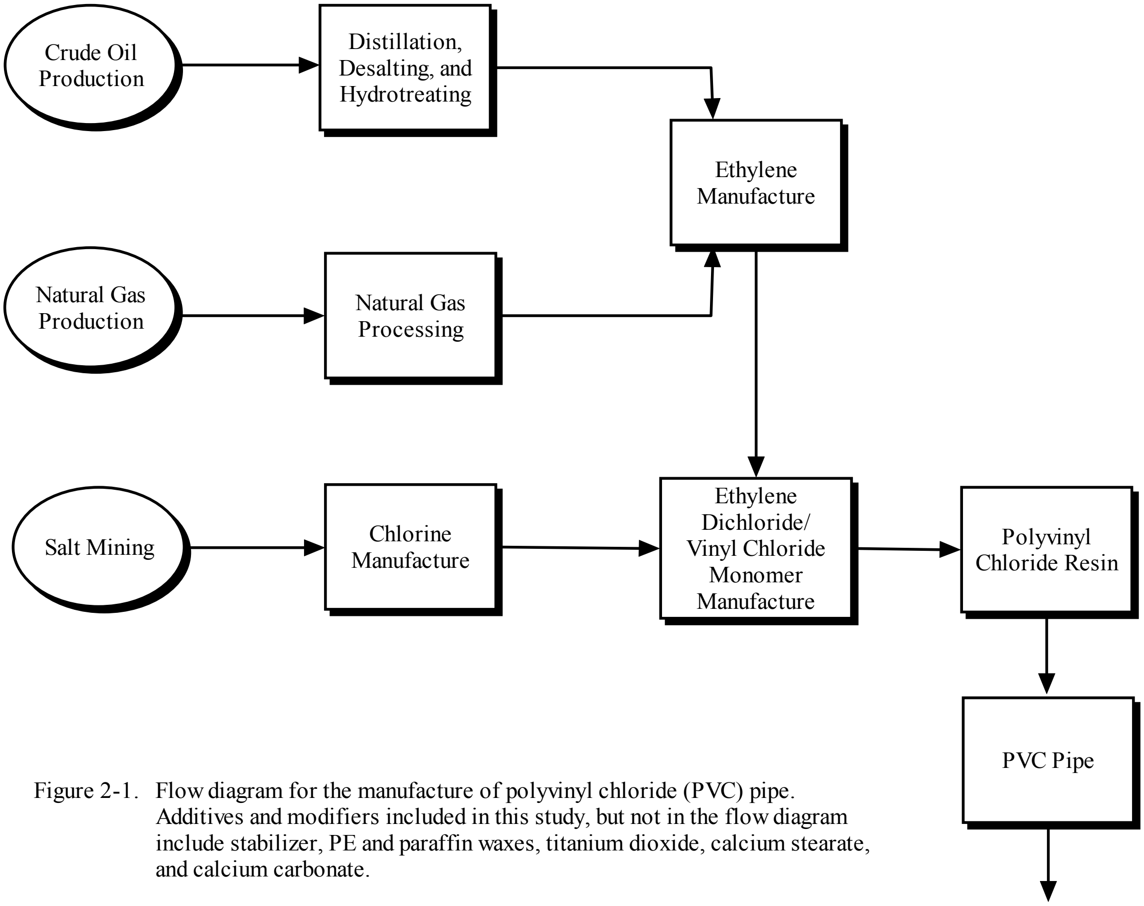


Figure 2-1. Flow diagram for the manufacture of polyvinyl chloride (PVC) pipe. Additives and modifiers included in this study, but not in the flow diagram include stabilizer, PE and paraffin waxes, titanium dioxide, calcium stearate, and calcium carbonate.

CPVC. A common material used for hot and cold water distribution piping applications is chlorinated PVC, or CPVC. Figure 2-2 shows the steps in the production of CPVC. To produce CPVC, the PVC discussed previously is combined with chlorine. A slurry of PVC and water is mixed with chlorine. The chlorination reaction is initiated with ultraviolet light. The chlorinated PVC slurry is dried and compounded with additives and modifiers to reach the desired properties of the resin for further processing.

The additives and modifiers reported by CPVC pipe producers included organotin heat stabilizer, polyethylene and paraffin waxes, titanium dioxide, calcium carbonate, and impact modifier. All inputs were included in the modeling except for organotin heat stabilizer. Ninety-eight percent of the total inputs were modeled.

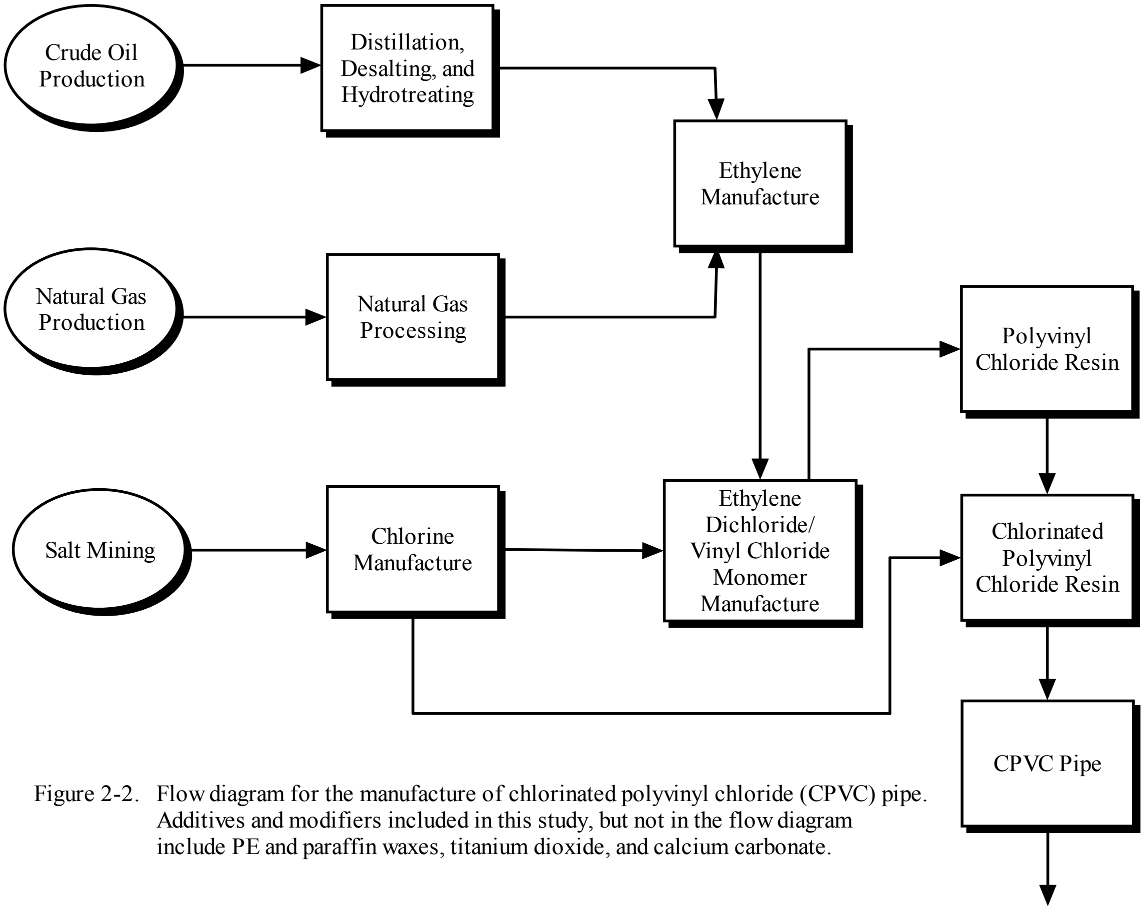


Figure 2-2. Flow diagram for the manufacture of chlorinated polyvinyl chloride (CPVC) pipe. Additives and modifiers included in this study, but not in the flow diagram include PE and paraffin waxes, titanium dioxide, and calcium carbonate.

ABS. Two types of ABS pipes, solid wall and cellular core, are included in the drain/waste/vent pipes studied in this analysis. Cellular core pipe currently dominates the ABS DWV pipe market.[7] The two standard technologies for ABS production in North America are suspension or mass polymerization. Both of these technologies are represented within the ABS production data set. A flow diagram for ABS resin production is shown in Figure 2-3.

ABS is produced by grafting styrene and acrylonitrile onto a polybutadiene matrix. The three basic steps in the suspension process are: prepolymerization, polymerization, and product separation. The processing steps for mass polymerization are: prepolymerization, polymerization, devolatilization, and extrusion. Mass polymerization generates a minimum of wastewater and eliminates the need for dewatering and drying. In both the suspension and mass processes the polybutadiene must be soluble in styrene. Polybutadiene resin may be added as a dry resin rather than a latex.

---

[7] Information provided by PPFA, August 2007.

The additives and modifiers reported by pipe producers included a small amount of colorant, and blowing agent for cellular core pipe, which were both excluded from the analysis. Over 99 percent of the total weight of pipe inputs was modeled for the solid pipe and nearly 98 percent by weight of the inputs for cellular core ABS pipe.

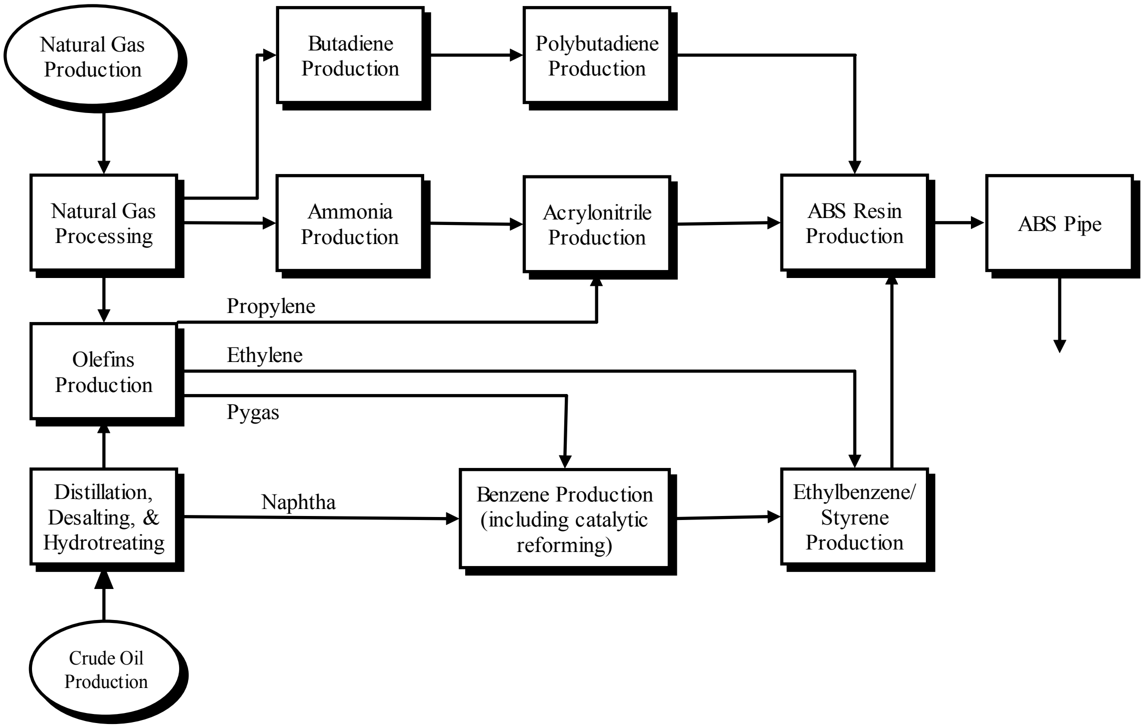


Figure 2-3. Flow diagram for the production of acrylonitrile-butadiene-styrene (ABS) pipe.

HDPE. High-density polyethylene (HDPE) is used in water supply piping. The process steps in the production of HDPE resin are shown in Figure 2-4. HDPE is produced through the polymerization of ethylene. Polyethylene is manufactured by a slurry, solution, or a gas phase process. The HDPE data set includes data for the slurry and gas phase processes, which are discussed here. Ethylene and small amounts of co-monomers are continuously fed with a catalyst into a reactor.

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

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

Some polyethylene water supply pipe is made from linear low density polyethylene (LLDPE) resin. The sequence of "upstream" steps leading to polymerization is the same for LLDPE as the steps shown in the HDPE flow diagram, and the energy requirements per pound are very similar for the two resins.

The additives and modifiers reported by PE pipe producers included a carbon black UV color concentrate and masterbatch black additive. The composition of the masterbatch was not known, and its weighted average contribution by weight was less than 0.5% (reported by only one producer), so it was excluded from the analysis. The relative weight percentages of carbon black and resin in the color concentrate were not specified, so the weight of concentrate was modeled as pure resin. Using the approach described, over 99 percent by weight of the pipe was modeled.

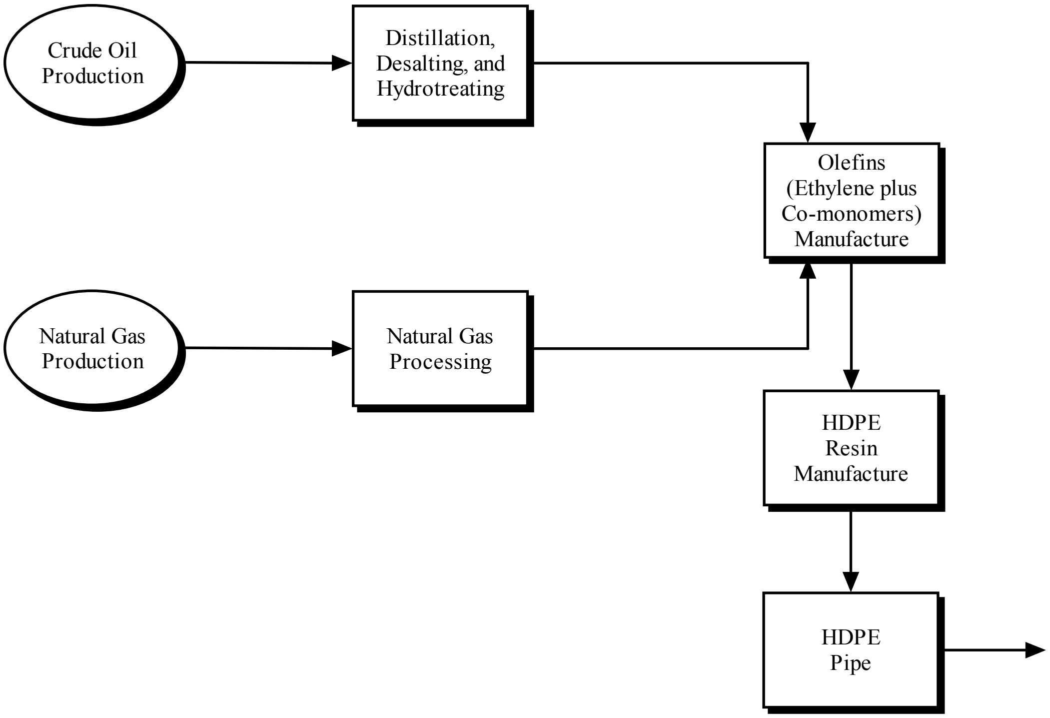


Figure 2-4. Flow diagram for the manufacture of virgin high-density polyethylene (HDPE) pipe.

Cross-linked Polyethylene (PEX). Cross-linked polyethylene (PEX), used in hot and cold water distribution piping applications, can be produced by one of three methods: Engel or peroxide method (PEX-a), Silane method (PEX-b), or the electronic beam or radiation method (PEX-c). No PEX pipe producers participating in this project reported using the PEX-c method; thus, only the PEX-a and PEX-b methods are considered in this study. Figures 2-5 and 2-6 show flow diagrams for the production of PEX-a and PEX-b resin, respectively.

PEX-a pipe producers reported inputs of PE resin, antioxidant, and peroxide, while PEX-b producers reported inputs of compounded PEX resin and small amounts of catalyst masterbatch (composition not specified). A PEX-b compound producer provided data on the material and energy inputs to compound production. No data were available on production of masterbatch, antioxidant, or peroxide. On a production-weighted basis, 98 percent by weight of the pipe was modeled.

PEX-a. The Engel or peroxide method (PEX-a) cross-links the polyethylene during the tubing manufacturing while the resin is in its amorphic state. The cross-linking is performed by adding peroxide and then applying high temperature and pressure to the polyethylene mix within a special extruder. The cross-linking bond takes place between the carbon molecules. Cross-linking rates of around 85% can be achieved with the PEX-a method.

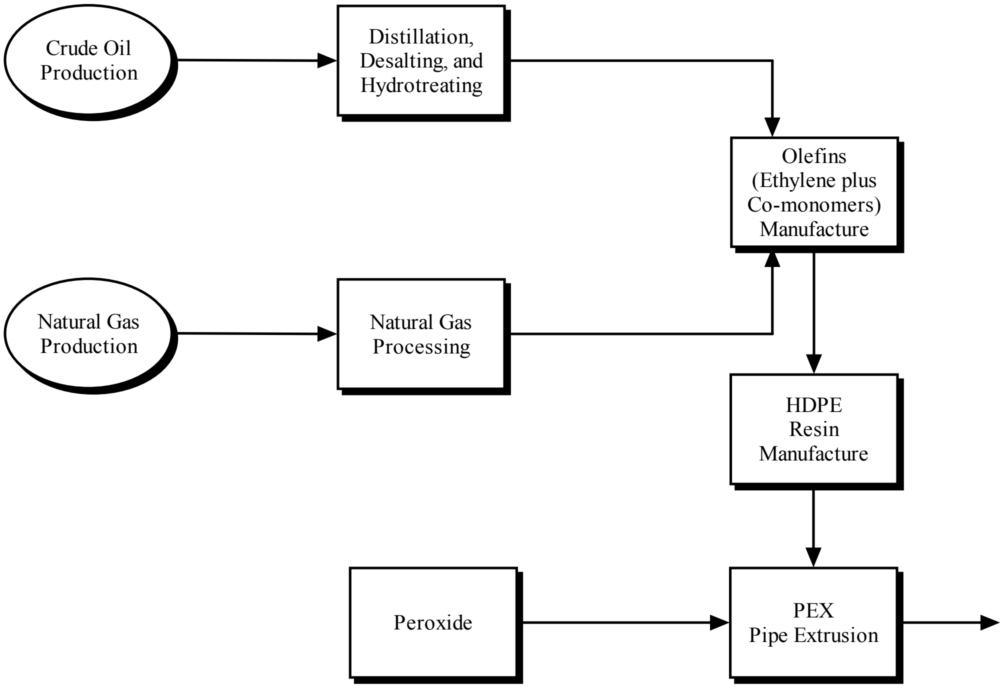


Figure 2-5. Flow diagram for the manufacture of cross-linked polyethylene (PEX-a) pipe.

PEX-b. The Silane method (PEX-b) involves grafting a reactive silane molecule to the polyethylene resin. This grafted compound is blended with a catalyst by either the Sioplas method (reactive extrusion) or by the Monosil method if using a special extruder. The Sioplas method is a two-step process. The first step is the silane grafting onto the polyethylene; the second is the mixing of the graft resin with a catalyst masterbatch. In the Monosil method, the grafting, mixing and finished product extrusion is done simultaneously using a special extruder. The final cross-linking reaction is not complete until after the tubing is extruded, as described in the PEX pipe fabrication section. The degree of cross-linking for PEX-b is between 65 to 70 percent.

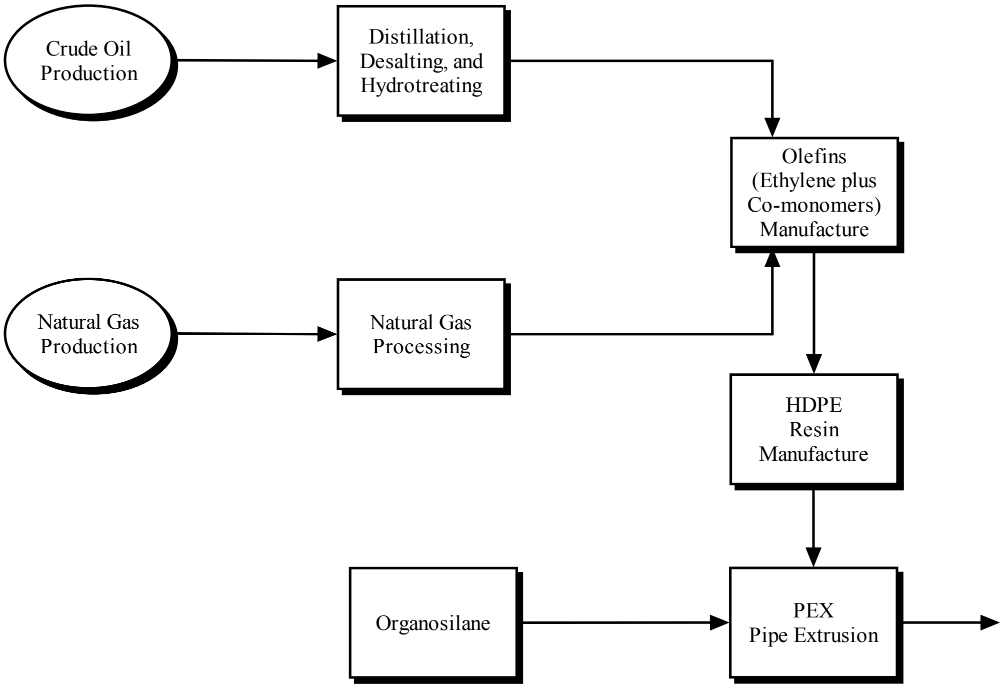


Figure 2-6. Flow diagram for the manufacture of cross-linked polyethylene (PEX-b) pipe.

PEX-c. In the PEX-c process, extruded polyethylene pipe is subjected to high-energy radiation in order to split carbon-hydrogen bonds so that the polymer chains can cross-link. No data on PEX-c pipe production were available for this study.

Copper

Copper is widely used in piping applications. According to an article in an online magazine from the Copper Development Association, on average 64 percent of the copper in plumbing tubes is derived from copper scrap. The remainder is produced from primary copper cathode. Only the highest grades of copper scrap are used to make secondary copper tube. Very little refining is needed to return the metal to the purity required for plumbing tube.

Figure 2-7 (shown at the end of the Copper Pipe Fabrication section) illustrates the steps in the production of copper. Primary copper is produced from sulfide and oxide ore mined primarily in Arizona, New Mexico, and Utah. Ore is mined mainly in open pit mines, then crushed and ground at the beneficiation plant. Depending on the ore, it is then either leached or concentrated. The data in this analysis only considers the leaching process, which produces a weak copper sulfate solution. In recent years, the production of primary copper has moved toward the solvent extraction-electrowinning (SXEW) process, which is typically cheaper than the conventional concentrator, smelting, refinery process. This analysis uses the SXEW process for the primary copper production. In the SXEW process, the leach solution is contacted with an organic copper extractant and diluent. An emulsion is formed and sent to a settler where the two phases separate. The copper is stripped from the organic phase. The electrolyte is sent to the electrowinning operation. Each electrowinning cell contains a number of stainless steel cathode plates as well as lead alloy anodes. As the electrolyte flows through the cells, DC power is applied to the anode/cathode electrical circuit. As copper metal is plated on the cathode, acid is produced, which is used to strip copper out of the loaded organic in the solvent extraction strip stage. The cathodes may remain in the cell for up to a week before they are taken to a wash bay.

If only primary copper cathode is being melted, then a simple shaft furnace may be used to melt for casting. If scrap is included, a reverbatory or hearth-type furnace must be used so that the copper may be refined. The secondary copper is fire-refined by contacting the melt with oxygen, which reacts with impurities to form oxides. These float to the surface, where they become trapped in slag. When the slag is skimmed off, only pure copper remains. This copper is essentially the same purity as the primary copper.

PIPE FABRICATION

Plastic Pipe Fabrication

Plastic pipes are produced by extrusion. Extrusion processes for each type of plastic pipe studied are discussed in the following sections.

Solid Extruded Pipe. Extrusion is a process that forms a tube by using mechanical and thermal energy to melt a thermoplastic resin and force it through a die. 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[8].

Extrusion relies on electrical energy to drive the screw in the extruder barrel and to power the ceramic heaters that heat the extruder barrel. 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[9]. One reference[10] asserts that the friction produced by the extruder screw producers enough heat to melt the resin mixture without the assistance of ceramic heaters.

For this study, energy and emissions data on pipe extrusion was collected directly from producers of each type of pipe studied. In most cases, producers did not provide separate detail on energy use for resin heating and mechanical extrusion processes.

Cellular Core Extruded Pipe. The cellular core pipe uses an extrusion process similar to that described above. However, cellular core construction involves the simultaneous extrusion of three layers into the pipe wall — a solid outer layer, a foam intermediate layer, and a solid inner layer. The inner surface provides the smooth, continuous surface necessary for satisfactory flow characteristics, and the outer segment develops the beam strength necessary for the product to behave like a pipe. The closed-cellular core holds the outer and inner layers in position with each other, but requires less material to do so compared to a solid layer.[11]

Cross-linked Polyethylene Pipe. The PEX-a pipe fabrication process uses a special extruder, which adds the peroxide and then applies high temperature and pressure to the polyethylene mix. This cross-linked mix is extruded into the PEX-a pipe.

For the PEX-b pipe, the grafted compound discussed previously is blended with a catalyst by either the Sioplas method or by the Monosil method if using a special extruder. The extruded tubing is then exposed to either steam or hot water to induce the final cross-linking reaction. With the Silane method, the crosslinking takes place across silicon and oxygen molecules.

Copper Pipe Fabrication

The molten copper (primary or secondary) is transferred to a holding furnace. In continuous casting, the metal is poured into water-cooled molds. The solidified copper is

---

[8] Bezigian, Thomas. **Extrusion Coating Manual, 4th Edition.** Tappi Press, Atlanta, Georgia. 1999.

[9] Ibid.

[10] APME. **Polyethylene (LD) Film.** Information produced in collaboration with European Plastics Converters and European Committee of Machine Manufacturers for Plastics and Rubber Industries. 1993.

[11] **Plumbing Apprentice Training Manual For Plastic Piping Systems**. PPFA Technical Committee. 2005.

withdrawn to produce a solid log of pure copper, which is cut into billets. The billets are reheated enough to make the copper pliable. A piercing mandrel is driven lengthwise through the center of the billet to create the inside wall of the plumbing tube. The billet is then placed in an extrusion press. The extruded tube is finally sent to the drawing step, which involves pulling the hollow tube through a series of hardened steel dies to reduce its diameter.

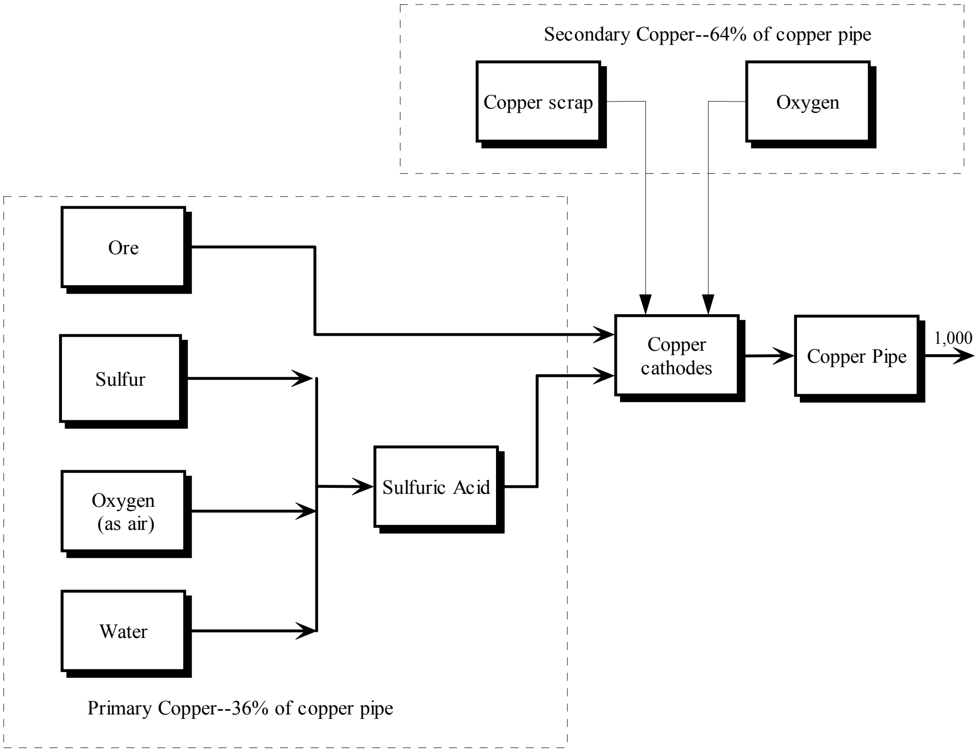


Figure 2-7. Flow diagram for the production of copper pipe from primary and secondary copper sources.

PIPE PACKAGING

Information on the types and quantities of packaging used in shipping the various types of plastic pipe from the manufacturer to a seller was collected from pipe manufacturers participating in this project. Types and quantities of packaging used to ship metal pipe were determined by collecting and weighing samples from a site visit to a pipe sales location.

Table 2-1 shows the types of packaging reported for each type of pipe, normalized to the basis of 1,000 feet of pipe shipped.

Table 2-1
PACKAGING PER 1000 FEET OF PIPE SHIPPED
(weighted average of pounds of packaging reported by all data providers)

	4" DWV				1" Water Supply			3/4" HCWD		
Packaging	**Solid PVC**	**Cell Core PVC**	**Solid ABS**	**Cell Core ABS**	**PE**	**PVC**	**Copper**	**CPVC**	**PEX**	**Copper**
Wood frame/boards	33.0	31.9	46.3	36.3		7.76	19.3	12.7		19.3
Metal strapping	5.79	5.35	2.89	0.17	1.10	0.33	8.05	0.45		8.05
Poly strapping	0.08	0.09	0.03	0.96		0.05	0.14			0.14
Plastic film, bags, tape	*				0.56	*		2.47	1.20	

---

* Packaging materials averaging less than .01 lb/1000 ft of pipe are not modeled.
For copper pipe, packaging data for the 3/4" pipe was also used for the 1" pipe.

END-OF-LIFE MANAGEMENT

At the end of a building's useful life, the structure is demolished. Some components may be recovered from the building for reuse or recycling, while the majority of above-ground components are hauled to a construction and demolition landfill. Depending on the future use of the site, some in-ground materials may be recovered, but often they are left in place.

This section provides a general description of current building demolition processes, material recovery, transportation of recovered pipe to recyclers, and transportation of remaining materials to a construction and demolition landfill.

Demolition and Recovery

Residential. Independent contractors are hired to demolish homes. Prior to demolition they may salvage some of the building components that are reusable or that have a high recycling value. These may include copper pipe, hardware, ferrous products, plumbing fixtures, windows, doors, etc. Once demolition gets underway, the structure is taken down as quickly as possible, and the debris is loaded into 20, 30, or 40 cubic yard roll-off containers. Generally, concrete and cinder block foundation materials are pushed into the basement and left on site. Underground pipe such as water supply lines, gas lines, and sewer lines are capped off but generally are not removed unless by special contract.

The demolition contractor may lease or rent roll-offs and then deliver them to the construction and demolition landfill, or the landfill operator may pick up the load and take it to the construction and demolition landfill. Demolition companies generally pay for disposal based on the volume of the roll-off, or payment may be based on tonnage if there are scales at the landfill.

Residential demolition loads generally have a relatively low density because the material is a jumble of wallboard, lumber, pipe, roofing, carpeting, flooring, and other miscellaneous materials. Most landfills simply crush and bury the loads of construction and demolition waste as received without attempting to salvage any materials from the mixed load.

Commercial. In general, the companies that demolish commercial buildings are larger organizations using larger trucks and roll-offs. Commercial demolition practices are driven by high labor costs; thus, building components must have a high value to justify the effort required to salvage them.

Separation of construction and demolition materials is usually done at the demolition site rather than at the construction and demolition landfill; however, a few construction and demolition landfills will separate materials from mixed loads (see landfill section below). Materials commonly recovered from construction and demolition operations include copper, ferrous products, and other metals such as aluminum. Recyclables are delivered directly to the recycler. Copper was reported to be delivered daily as it is recovered, to prevent theft due to the high value of copper scrap.

After salvaging valuable components, the residual wastes are loaded into trucks or roll-offs and hauled to a construction and demolition landfill. The average density for commercial demolition waste is higher than for residential demolition waste. Commercial buildings are often constructed of concrete, brick, and other high-density materials. In addition, commercial buildings are often multi-story structures located on commercially valuable sites; as a result, there is a large volume of high-density wall material to be disposed and there is less ability to leave material in place (e.g., pushed into basements and covered over) as may be done at a residential site. Underground pipe (water supply and underground DWV pipe) is usually capped off and left in place; however, if the site is being readied for some other purpose in which the elevation changes, underground pipe might be dug up and recovered or disposed.

On a large demolition project, some compaction of materials may be done on site to reduce the volume of waste hauled (and thus the disposal costs). Demolition contractors generally deliver to the construction and demolition landfill and pay by the size of the container.

Transportation

Environmental burdens for end-of-life transportation of pipe are based on the assumption that all pipe except copper will be transported in mixed loads of demolition waste. Surveyed operators reported that copper is hauled to recyclers as it is recovered, in order to prevent theft due to its high scrap value.

The best source of density data for transported construction and demolition waste was a construction and demolition landfill in Wichita where the size of incoming roll-off containers is recorded and the containers are weighed. Based on the records for one hauler who delivers residential demolition consistently in the same size of roll-off, the calculated density of construction and demolition waste hauled was 200 lbs/cu yd. As residential loads, these probably contained little or no concrete. Commercial construction and demolition waste including concrete may be 400-500 lb/cu yd, according to some sources surveyed.

Pipe hauled in mixed construction and demolition loads was modeled based on transport in a 40 cubic yard roll-off container hauled by a large diesel truck. The distance to the landfill was modeled as 40 miles. This is a conservative estimate based on surveys of construction and demolition operators in the Midwest. Hauling distances in other regions of the country may be significantly greater.

Copper pipe was modeled as hauled using a smaller gasoline-powered vehicle (such as a pickup truck or van). The distance transported was modeled as 40 miles. This is assumed to be representative of the distance from the demolition site to a metal recycler.

Construction and Demolition Landfills

Operations at a construction and demolition landfill are designed to get the material into the ground as quickly as possible, usually with no further salvage. Bulldozers or wheeled crushers are used to reduce the volume of materials because space is valuable in a landfill. According to surveyed construction and demolition operators, plastic pipe crushes easily when a compactor vehicle runs over it.

One surveyed construction and demolition landfill operator in Sedgwick County (Wichita, KS) reported some salvage of material. They have a market for “clean” concrete brought in separately. They also recover “clean” dimension lumber, metals (steel, aluminum, tin), and sheet rock. They also get very small quantities of copper (from residential demolition).

Pipe in Construction and Demolition Waste. There is virtually no copper pipe coming to landfills, as any pipe that is recovered from demolition sites is sold to recyclers. None of the operators surveyed reported seeing plastic pipe separated in a demolition situation, although they do see scraps of plastic pipe in construction debris. One detailed composition survey in Babylon, NY showed “PVC Pipe/other rigid plastic” as 0.04% of residential demolition waste and 2.08% of commercial demolition waste[12].

End-of-Life Modeling of Pipe

Based on the information obtained from the available literature sources and telephone interviews, copper HCWD pipe currently is widely recovered for recycling at end of life. Although copper water supply pipe is also valuable, it is less likely to be recovered from demolition sites because it must be dug up. The solid waste figures in

---

[12] Gershman, Brickner, & Bratton, Inc., for Town of Babylon, NY; Demolition Age, September 1993.

Chapter 3 show incremental results for different levels of recovery of copper water supply pipe and all types of plastic pipe in order to assess the effects of pipe recovery that may be occurring in different regions of the country, or that may occur in the future.

End-of-Life Management References

The descriptions of pipe end-of-life management in this chapter are based on **t**elephone interviews conducted in March and September 2007 with the following:

Construction and Demolition Landfills

- APAC Kansas – Jim Mangus (mostly residential demolition)
- Holland Corporation, South Quarry – Jim Holmes (mostly commercial demolition)
- Deffenbaugh Disposal Service – Darrell Basham (residential and commercial)

Construction and Demolition Recyclers

- Doug Sommers (residential and commercial), Wichita, KS
- Kansas Department of Health & Environment (KDH&E) – Kent Forester; Christine Mennicke (Data), Sam Sunderraj (Chief, Solid Waste Permitting)

Demolition Contractor

- Kaw Valley Wrecking (large demolition contractor)

Metal Recyclers

- Galamba Metals Group, LLC
- David J. Joseph Company – Chris Bedell, Mary Jo Colebrook
- River Metals Recycling, Louisville KY – George Bowles
- Western Metals, Salt Lake City UT – Vicki Nelson

Trade Associations

- National Demolition Association, Philadelphia, PA – Mike Taylor
- Institute of Scrap Recycling Industries, Inc. (ISRI) – Scott Horne

CHAPTER 3
LCI RESULTS FOR PLASTIC AND METAL PIPE

INTRODUCTION

A life cycle inventory examines the sequence of steps in the life cycle of a product system, beginning with raw material extraction and continuing on through material production, product fabrication, use, reuse or recycling where applicable, and final disposition. For each life cycle step, the inventory identifies and quantifies the material inputs, energy consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes). The information from this type of analysis can be used as the basis for further study of the potential improvement of resource use and environmental emissions associated with product systems. It can also pinpoint areas (e.g., material components or processes) where changes would be most beneficial in terms of reduced energy use or environmental emissions.

In this LCI, the specific products evaluated are several types of plastic and metal pipes used in residential and commercial construction.

STUDY GOAL AND INTENDED USE

The Plastic Pipe and Fittings Association (PPFA) commissioned this study to evaluate the environmental profiles of selected plastic and metal pipes used in three types of building piping applications, using the most current and representative data available. Although the original scope of the study included cast iron soil (DWV) pipe, it was not possible to obtain data of sufficient quality and completeness to ensure an accurate representation of United States cast iron pipe production. Therefore, cast iron pipe has been excluded from the study.

Plastic pipes were modeled using resin production data released in 2007 for the Plastics Division of the American Chemistry Council and published in the U.S. LCI Database (www.nrel.gov/lci). Current plastic pipe fabrication data were collected for this study from pipe producers.

The original goal of the study was to evaluate current United States production of each type of pipe; however, it was necessary to collect some fabrication data from Canadian producers to supplement the United States data sets so that the aggregated production data could be shown as a separate unit process without compromising the confidentiality of individual producers' data. Energy requirements for all pipe production steps were modeled using United States fuels and energy data from the U.S. LCI database.

The results are presented in sufficient detail to allow analysis of the contribution of different life cycle steps (resin production, plastic pipe fabrication via extrusion, pipe packaging, etc.) to the overall profile for each type of pipe studied.

The intended use of this study is to inform PPFA members about the environmental burdens associated with production and disposal of pipes manufactured for three use applications. This data will also be used by PPFA as the basis for future analyses of the full life cycle of piping systems, including pipe manufacture, installation, use, and end of life management. The LCI has been conducted following internationally accepted standards for LCI methodology so that the results are suitable for submission to the U.S. LCI Database and BEES.

SCOPE AND BOUNDARIES

The LCI includes all steps from raw material extraction through pipe fabrication and transportation from manufacturer to customer. Manufacture and disposal of transportation packaging is included. Installation processes are **not** included, nor does the analysis include fittings, adhesives, solder, etc. used to connect lengths of pipe.

There are several possible end-of-life management options for recovered pipe, including leaving underground pipe in place at the demolition site, recycling pipe recovered from the structure or site, waste-to-energy incineration and landfilling pipe with mixed construction and demolition waste. Although metal and plastic pipes studied in this analysis are technically recyclable, interviews with demolition contractors, recyclers, construction and demolition landfill operators, and a demolition trade association indicated that copper pipe is the only type of HCWD pipe modeled in this study that is currently being recovered and recycled at a significant level. Thus, this analysis includes burdens for transporting copper pipe to a recycler and transporting all other types of pipe to a construction and demolition landfill mixed with other construction and demolition wastes. Because pipe constitutes such a small percentage of construction and demolition waste, no burdens from building demolition operations or operation of construction and demolition landfill equipment are allocated to pipe. Transportation burdens are based on hauling 1000 feet of each type of pipe; however, in some cases underground water supply or DWV pipe may be left in place at the job site. No burdens were included for digging up underground pipe.

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels. Emissions that may occur over time due to corrosion of pipes, erosion of pipe materials by flowing water, or leaching of pipe constituents into the water or earth are not included. The rates at which these types of emissions may occur are highly dependent upon water use patterns, soil conditions, etc. Assessment of these issues is beyond the scope of this analysis.

FUNCTIONAL UNIT

In a life cycle study, products are compared on the basis of providing the same defined function (called the **functional unit**). Within each defined pipe application, the different types of pipe are compared on the basis of equivalent length of pipe of corresponding nominal diameter. A basic assumption is that equivalent lengths of pipe of corresponding nominal diameter deliver equivalent volumes of fluid. In some cases, the same nominal diameter pipe was available with different wall thicknesses (and weight per unit length), in which case pipes were compared based on equivalent diameter *and* functionality (e.g., pressure rating).

SYSTEMS STUDIED

The piping applications and types evaluated in this study include:

- 4-inch pipe for Drain, Waste, & Vent (DWV) applications
    - Solid polyvinyl chloride (PVC) pipe, both virgin and 50% postconsumer recycled (PCR) content
    - Cellular core PVC pipe
    - Solid acrylonitrile butadiene styrene (ABS) pipe
    - Cellular core ABS pipe

- 1-inch pipe for inlet pressurized water supply applications
    - Polyethylene (PE) pipe
    - PVC pipe.
    - Copper pipe, types K and L

- ¾-inch pipe for pressurized Hot and Cold Water Distribution (HCWD) applications
    - Chlorinated polyvinyl chloride (CPVC) pipe
    - Cross-linked polyethylene (PEX) pipe
    - Copper pipe, types K. L, and M

The weights of 1,000 feet of each type of pipe for each application are shown in Table 3-1. Methodology, data sources, and data quality are discussed in Chapter 1. Production of pipe materials, pipe fabrication, and end-of-life management of pipe are described in Chapter 2.

RESULTS

The presentation and discussion of results focuses on energy, solid waste, and greenhouse gas emissions (total global warming potential). Tables containing the full list of atmospheric and waterborne emissions for each system are also provided, but individual emissions are not discussed in depth.

The tables in this chapter present results broken out by the following life cycle stages:

- Extraction of raw materials through resin production
- Production of pipe additives
- Pipe fabrication
- Production and disposal of packaging used to ship pipe
- Transport of pipe to customer
- End of life transport of pipe

For plastic pipe containing additives or compounding agents, production of these additives is shown separately where possible. For metal pipe, the material production and pipe fabrication steps are combined.

Table 3-1
POUNDS PER 1000 FEET OF PIPE

	lb/ft*	**lb/1000 ft**
4” DWV (Drain, Waste, Vent)		
PVC Solid	2.02	2,021
PVC Cellular Core	1.27	1,267
ABS Solid	1.50	1,504
ABS Cellular Core	1.01	1,007
1” Water Supply		
PE (HDPE, LLDPE)	0.16	165
PVC	0.32	317
Copper K	0.84	838
Copper L	0.66	655
¾” HCWD (Hot and Cold Water Distribution)		
CPVC	0.14	137
PEX	0.11	112
Copper K	0.64	641
Copper L	0.46	455
Copper M	0.33	328

---

* For plastic pipe, weighted average values were calculated based on each company's data multiplied by their percentage of total pipe production reported by all companies providing data for that pipe. Weight of 50% PCR pipe was assumed same as corresponding virgin pipe.
Weight per foot of copper pipe is based on data found in the Copper Tube Handbook, accessible online at the Copper Development Association (www.copper.org).

Energy Results

Based on the uncertainty in the energy data, energy differences between systems are not considered meaningful unless the percent difference between systems is greater than 10 percent. (Percent difference between systems is defined as the difference between energy totals divided by the average of the two system totals.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix A).

Energy by Category. Tables 3-2 through 3-4 present energy results for the pipes in each application broken out into the categories of process energy, transportation energy, and energy of material resource (EMR).

The category of **process energy** includes totals for all processes required to produce the pipes, from acquisition of raw materials through pipe manufacturing. **Transportation energy** is the energy used to move material from location to location during its journey from raw material to product. **Energy of material resource** is not an expended energy but the energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as material inputs for materials such as plastic resins. Use of fuel resources as a material input is a depletion of fuel resources just as the combustion of fuels for energy. In this study, energy of material resource is reported for plastic pipes and plastic pipe packaging components, which are produced from resins using natural gas and petroleum as material feedstocks. (Energy of material resource is described in more detail in Chapter 1.)

Tables 3-2 through 3-4 show the percentage of the total energy contributed by each life cycle stage. Results by energy category are shown graphically in Figures 3-1 through 3-3.

For plastic pipes, energy of material resource (EMR) accounts for 31% of total energy requirements for CPVC pipe, 42-43% of the total for PVC pipes, and 57-71% of total energy for ABS, PE, and PEX pipe. EMR is lower for PVC and CPVC because these resins have significant chlorine content rather than being derived totally from petroleum and natural gas resources. In addition to the pipe resins themselves, many of the resin additive materials such as waxes, color concentrates, etc. used in the different plastic pipes are also derived partially or entirely from fuel resource materials. The copper pipe systems have very small amounts of EMR, associated only with plastic components used in packaging pipe for shipment.

Transportation energy accounts for 3 to 5 percent of total energy requirements for all types of pipe, both plastic and copper, with the exception of PEX. Transportation requirements are a higher percentage of the total for PEX due to the significant distances reported for transportation of PEX compound from producer to pipe manufacturer.

The remainder of the energy for each pipe system is process energy. Process energy is 97 percent of the total energy for the copper pipe systems. For plastic pipe systems, process energy ranges from 26 percent of total energy for PE pipe to 66 percent for CPVC.

DWV Pipe. In DWV applications, the cellular core pipes have lower energy requirements per 1000 feet than the corresponding solid resin pipes. The majority of the energy for plastic pipe is associated with production of the resins and additives rather than for the extrusion process. Thus, the energy savings from the reduced weight of resin required for the cellular core pipe more than offsets the higher extrusion energy per unit length.

Table 3-2
ENERGY BY CATEGORY FOR 1000 FEET OF 4" DWV PIPE

	Process	**Transp**	**EMR**	**Total**	**Process**	**Transp**	**EMR**	**Total**
Solid PVC								
Resin production & transp	23.1	0.98	20.1	44.2	52%	2%	45%	100%
Additives production	0.53	0.047	0.64	1.22	44%	4%	52%	100%
Pipe production & transp	2.19	0.47	0	2.66	82%	18%	0%	100%
Packaging	0.18	0.015	0.037	0.23	77%	6%	16%	100%
Transp to LF	0	0.068	0	0.068	0%	100%	0%	100%
TOTAL	**26.0**	**1.58**	**20.7**	**48.3**	**54%**	**3%**	**43%**	**100%**
Solid PVC 50% PCR								
Resin production & transp	11.7	0.74	10.0	22.4	52%	3%	45%	100%
Additives production	0.53	0.047	0.64	1.22	44%	4%	52%	100%
Pipe production & transp	2.19	0.47	0	2.66	82%	18%	0%	100%
Packaging	0.18	0.015	0.037	0.23	77%	6%	16%	100%
Transp to LF	0	0.068	0	0.068	0%	100%	0%	100%
TOTAL	**14.6**	**1.35**	**10.7**	**26.6**	**55%**	**5%**	**40%**	**100%**
Cell Core PVC								
Resin production & transp	13.7	0.59	11.9	26.2	52%	2%	45%	100%
Additives production	0.82	0.047	0.76	1.62	50%	3%	47%	100%
Pipe production & transp	1.64	0.30	0	1.94	85%	15%	0%	100%
Packaging	0.17	0.014	0.035	0.22	77%	6%	16%	100%
Transp to LF	0	0.043	0	0.043	0%	100%	0%	100%
TOTAL	**16.3**	**0.99**	**12.7**	**30.0**	**54%**	**3%**	**42%**	**100%**
Solid ABS								
Resin production & transp	21.4	2.38	37.6	61.4	35%	4%	61%	100%
Pipe production & transp	3.17	1.07	0	4.24	75%	25%	0%	100%
Packaging	0.18	0.016	0.019	0.21	83%	8%	9%	100%
Transp to LF	0	0.051	0	0.051	0%	100%	0%	100%
TOTAL	**24.8**	**3.52**	**37.6**	**65.9**	**38%**	**5%**	**57%**	**100%**
Cell Core ABS								
Resin production & transp	14.3	1.99	25.2	41.4	34%	5%	61%	100%
Pipe production & transp	1.08	0.41	0	1.49	72%	28%	0%	100%
Packaging	0.13	0.012	0.018	0.15	81%	8%	12%	100%
Transp to LF	0	0.034	0	0.034	0%	100%	0%	100%
TOTAL	**15.5**	**2.45**	**25.2**	**43.1**	**36%**	**6%**	**58%**	**100%**

Table 3-3
ENERGY BY CATEGORY FOR 1000 FEET OF 1" WATER SUPPLY PIPE

	Process	Transp	EMR	Total	Process	Transp	EMR	Total
PVC								
Resin production & transp	3.62	0.15	3.15	6.92	52%	2%	45%	100%
Additives production	0.089	0.0086	0.099	0.20	45%	4%	50%	100%
Pipe production & transp	0.47	0.080	0	0.55	85%	15%	0%	100%
Packaging	0.028	0.0026	0.0030	0.034	83%	8%	9%	100%
Transp to LF	0	0.011	0	0.011	0%	100%	0%	100%
TOTAL	**4.21**	**0.25**	**3.25**	**7.71**	**55%**	**3%**	**42%**	**100%**
PE								
Resin production & transp	0.95	0.12	3.67	4.74	20%	2%	77%	100%
Pipe production & transp	0.38	0.030	0	0.41	93%	7%	0%	100%
Packaging	0.021	0.0014	0.020	0.042	50%	3%	47%	100%
Transp to LF	0	0.0055	0	0.0055	0%	100%	0%	100%
TOTAL	**1.35**	**0.15**	**3.69**	**5.19**	**26%**	**3%**	**71%**	**100%**
Copper - K								
Cradle-to-pipe production & transp	15.9	0.43	0	16.3	97%	3%	0%	100%
Packaging	0.058	0.0058	6.8E-04	0.064	90%	9%	1%	100%
Transp to Recycle	0	0.054	0	0.054	0%	100%	0%	100%
TOTAL	**16.0**	**0.49**	**6.8E-04**	**16.4**	**97%**	**3%**	**0%**	**100%**
Copper - L								
Cradle-to-pipe production & transp	12.4	0.34	0	12.8	97%	3%	0%	100%
Packaging	0.058	0.0058	6.8E-04	0.064	90%	9%	1%	100%
Transp to Recycle	0	0.042	0	0.042	0%	100%	0%	100%
TOTAL	**12.5**	**0.39**	**6.8E-04**	**12.9**	**97%**	**3%**	**0%**	**100%**

Table 3-4
ENERGY BY CATEGORY FOR 1000 FEET OF 3/4" HCWD PIPE

	Process	Transp	EMR	Total	Process	Transp	EMR	Total
CPVC								
Resin production & transp	2.00	0.070	0.98	3.05	66%	2%	32%	100%
Additives production	0.33	0.0094	0.22	0.56	59%	2%	40%	100%
Pipe production & transp	0.24	0.039	0	0.28	86%	14%	0%	100%
Packaging	0.072	0.0065	0.062	0.14	51%	5%	44%	100%
Transp to LF	0	0.0046	0	0.0046	0%	100%	0%	100%
TOTAL	**2.64**	**0.13**	**1.26**	**4.03**	**66%**	**3%**	**31%**	**100%**
PEX								
Resin production & transp	1.07	0.30	2.80	4.17	26%	7%	67%	100%
Pipe production & transp	0.45	0.17	0	0.62	72%	28%	0%	100%
Packaging	0.014	0.0011	0.029	0.044	32%	3%	66%	
Transp to LF	0	0.0038	0	0.0038	0%	100%	0%	100%
TOTAL	**1.53**	**0.47**	**2.83**	**4.83**	**32%**	**10%**	**58%**	**100%**
Copper - K								
Cradle-to-pipe production & transp	12.2	0.33	0	12.5	97%	3%	0%	100%
Packaging	0.058	0.0058	6.8E-04	0.064	90%	9%	1%	100%
Transp to Recycle	0	0.041	0	0.041	0%	100%	0%	100%
TOTAL	**12.2**	**0.38**	**6.8E-04**	**12.6**	**97%**	**3%**	**0%**	**100%**
Copper - L								
Cradle-to-pipe production & transp	8.63	0.23	0	8.86	97%	3%	0%	100%
Packaging	0.058	0.0058	6.8E-04	0.064	90%	9%	1%	100%
Transp to Recycle	0	0.029	0	0.029	0%	100%	0%	100%
TOTAL	**8.69**	**0.27**	**6.8E-04**	**8.96**	**97%**	**3%**	**0%**	**100%**
Copper - M								
Cradle-to-pipe production & transp	6.22	0.17	0	6.39	97%	3%	0%	100%
Packaging	0.058	0.0058	6.8E-04	0.064	90%	9%	1%	100%
Transp to Recycle	0	0.021	0	0.021	0%	100%	0%	100%
TOTAL	**6.28**	**0.20**	**6.8E-04**	**6.48**	**97%**	**3%**	**0%**	**100%**

Figure 3-1. Energy for 1000 Feet of 4" DWV Pipe by Energy Category

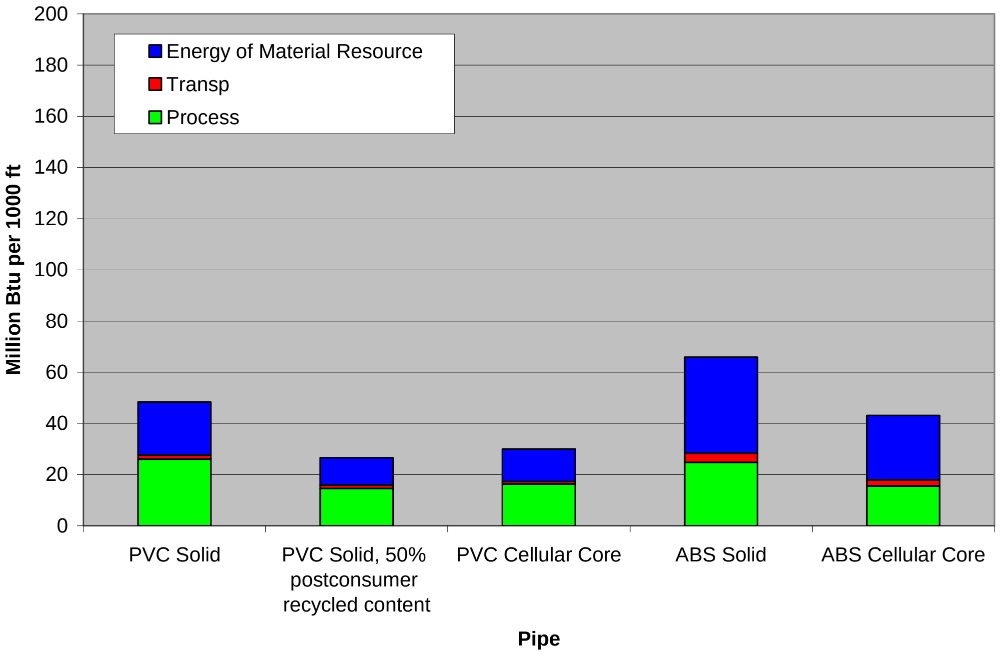


Figure 3-2. Energy for 1000 Feet of 1" Water Supply Pipe by Energy Category

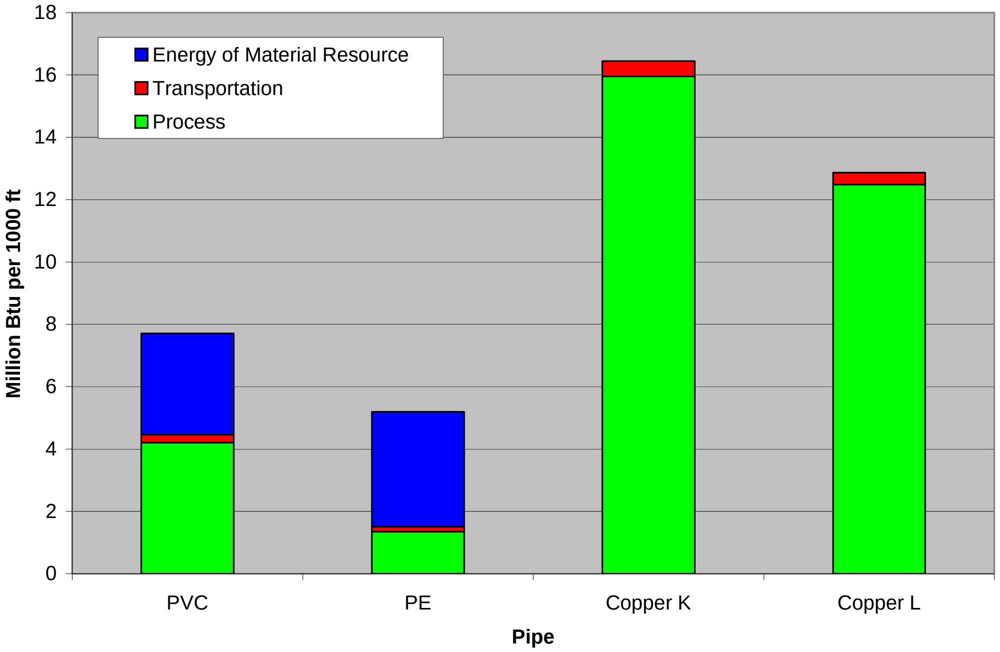
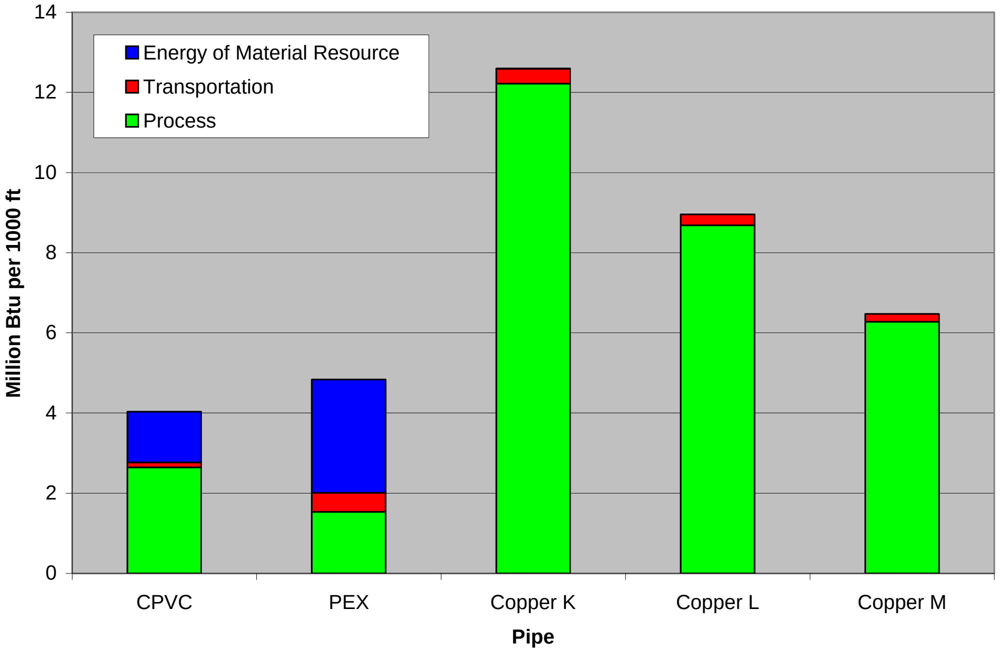


Figure 3-3. Energy for 1000 Feet of 3/4" HCWD Pipe by Energy Category



An additional DWV scenario modeled was a solid PVC pipe with a 50% postconsumer recycled content. This pipe would have the lowest energy requirements of the DWV systems modeled. The postconsumer material comes in free of all virgin material production burdens and carries only the burdens associated with collection and reprocessing.

Water Supply Pipe. For water supply pipe, Figure 3-2 shows that copper pipes require about twice as much total energy as the plastic pipes. Even though the copper pipe is modeled with a high recycled content, the heavier weight per unit length compared to plastic pipe and the high energy requirements for producing copper are the reasons for the difference.

Energy requirements for PE pipe are lower than for PVC pipe. Although PVC requires less energy per pound to produce compared to PE, the higher weight per unit length of PVC pipe results in higher total energy requirements compared to PE pipe.

HCWD Pipe. Plastic HCWD pipes require significantly less energy than corresponding diameter copper pipe, although Figure 3-3 shows that the difference between plastic pipe results and copper pipe results narrows as the wall thickness (and weight per unit length) of copper pipe decreases.

The difference between CPVC and PEX energy results can be attributed to several differences between these pipes. The chlorine content of CPVC displaces petroleum- and natural gas-based content in the resin, so EMR for CPVC resin is lower than for PEX resin. Also, although PEX pipe is somewhat lighter per unit length than CPVC pipe, the weighted average pipe production energy per unit output of pipe is higher for PEX pipe than for CPVC pipe. Table 1-1 shows that there was a significant range in pipe production energy reported for both CPVC pipe and PEX pipe. In a separate sensitivity analysis, results using the highest fabrication energy for CPVC were compared to results using the lowest fabrication energy for PEX. Total energy for the CPVC pipe was still lower than total PEX pipe energy, but the energy difference was small enough that it was not considered meaningful within the margin of error for life cycle energy results.

Energy Profiles. Tables 3-5 through 3-7 show total energy broken out by the sources of energy by fuel, including the fuels used to generate electricity. The "Credit" column reflects fuel use of process co-products (occurring in the upstream processes leading to resin production), reducing the net purchased energy required to produce resins used in the pipes themselves or in the plastic packaging components.

The energy shown in the tables includes not only the energy directly used for process and transportation processes, but also the **precombustion energy** (the energy used to extract and process fuels used for process energy and transportation energy). Fossil fuels — natural gas, petroleum and coal — are used for direct combustion as process and transportation fuels and also are used to generate some purchased grid electricity. The use of natural gas and petroleum as raw material inputs for the production of plastics (reported as energy of material resource in Tables 3-2 through 3-4) is included in the totals for natural gas and petroleum energy in Tables 3-5 through 3-7. Petroleum is the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in the table are used to generate purchased electricity along with the fossil fuels.

For plastic pipe systems, at least 94 percent of total energy is fossil energy. This includes not only the use of fossil fuels as process and transportation fuel but also the EMR of the plastic resins, petroleum- and natural gas-derived additives, and plastic packaging. Fossil energy accounts for about 90 percent of total energy requirements for the metal pipe systems. It is worth noting that process energy and transportation energy are associated with combustion of fuels, while EMR represents an inherent energy of the product, some of which can potentially be recovered if the material is incinerated with energy recovery.

Table 3-5
ENERGY PROFILE FOR 1000 FEET OF 4" DWV PIPE

	Nat. Gas	Petroleum	Coal	Hydro power	Nuclear	Other	Total	Credit	Net	Fossil % of Net	Subprocess % of Net
Solid PVC											
Resin production & transp	34.6	5.40	4.51	0.18	0.99	0.19	45.9	1.69	44.2	97%	**91.4%**
Additives production	0.26	0.68	0.25	0.0043	0.023	0.0045	1.22	0	1.22	97%	**2.5%**
Pipe production & transp	0.44	0.54	1.26	0.056	0.30	0.058	2.66	0	2.66	84%	**5.5%**
Packaging	0.054	0.027	0.076	0.0018	0.0097	0.059	0.23	3.5E-05	0.23	69%	**0.5%**
Transp to LF	0.0032	0.062	0.0017	8.1E-05	4.3E-04	8.5E-05	0.068	0	0.068	99%	**0.1%**
TOTAL	**35.3**	**6.72**	**6.09**	**0.25**	**1.32**	**0.31**	**50.0**	**1.69**	**48.3**	**96%**	**100.0%**
Solid PVC 50% PCR											
Resin production & transp	17.3	2.94	2.32	0.095	0.51	0.099	23.3	0.85	22.4	97%	**84.3%**
Additives production	0.26	0.68	0.25	0.0043	0.023	0.0045	1.22	0	1.22	97%	**4.6%**
Pipe production & transp	0.44	0.54	1.26	0.056	0.30	0.058	2.66	0	2.66	84%	**10.0%**
Packaging	0.054	0.027	0.076	0.0018	0.0097	0.059	0.23	3.5E-05	0.23	69%	**0.9%**
Transp to LF	0.0032	0.062	0.0017	8.1E-05	4.3E-04	8.5E-05	0.068	0	0.068	99%	**0.3%**
TOTAL	**18.1**	**4.25**	**3.91**	**0.16**	**0.84**	**0.22**	**27.5**	**0.85**	**26.6**	**95%**	**100.0%**
Cell Core PVC											
Resin production & transp	20.5	3.21	2.67	0.11	0.58	0.11	27.2	1.00	26.2	97%	**87.3%**
Additives production	0.54	0.83	0.21	0.0055	0.029	0.0057	1.62	0	1.62	98%	**5.4%**
Pipe production & transp	0.33	0.36	0.94	0.042	0.22	0.044	1.94	0	1.94	84%	**6.5%**
Packaging	0.051	0.026	0.071	0.0017	0.0091	0.057	0.22	4.0E-05	0.22	68%	**0.7%**
Transp to LF	0.0020	0.039	0.0011	5.1E-05	2.7E-04	5.3E-05	0.043	0	0.043	99%	**0.1%**
TOTAL	**21.4**	**4.46**	**3.89**	**0.16**	**0.85**	**0.22**	**31.0**	**1.00**	**30.0**	**96%**	**100.0%**
Solid ABS											
Resin production & transp	37.6	20.7	5.90	0.21	1.15	0.22	65.8	4.42	61.4	97%	**93.2%**
Pipe production & transp	0.66	1.15	1.83	0.082	0.44	0.085	4.24	0	4.24	86%	**6.4%**
Packaging	0.044	0.029	0.048	0.0014	0.0074	0.082	0.21	1.2E-05	0.21	57%	**0.3%**
Transp to LF	0.0024	0.046	0.0012	6.0E-05	3.2E-04	6.3E-05	0.051	0	0.051	99%	**0.1%**
TOTAL	**38.3**	**21.9**	**7.78**	**0.30**	**1.59**	**0.39**	**70.3**	**4.42**	**65.9**	**97%**	**100.0%**
Cell Core ABS											
Resin production & transp	25.2	14.2	3.96	0.14	0.77	0.15	44.5	3.03	41.4	97%	**96.1%**
Pipe production & transp	0.23	0.43	0.62	0.028	0.15	0.029	1.49	0	1.49	86%	**3.5%**
Packaging	0.034	0.033	0.019	7.8E-04	0.0042	0.064	0.16	4.4E-04	0.15	55%	**0.4%**
Transp to LF	0.0016	0.031	8.4E-04	4.0E-05	2.2E-04	4.2E-05	0.034	0	0.034	99%	**0.1%**
TOTAL	**25.5**	**14.7**	**4.61**	**0.17**	**0.93**	**0.24**	**46.2**	**3.03**	**43.1**	**97%**	**100.0%**

Table 3-6
ENERGY PROFILE FOR 1000 FEET OF 1" WATER SUPPLY PIPE

	Nat. Gas	Petroleum	Coal	Hydro power	Nuclear	Other	Total	Credit	Net	Fossil % of Net	Subprocess % of Net
PVC											
Resin production & transp	5.42	0.85	0.71	0.029	0.15	0.030	7.19	0.26	6.92	97%	**89.8%**
Additives production	0.042	0.11	0.041	7.2E-04	0.0038	7.4E-04	0.20	0	0.20	97%	**2.6%**
Pipe production & transp	0.094	0.098	0.27	0.012	0.064	0.012	0.55	0	0.55	84%	**7.1%**
Packaging	0.0069	0.0053	0.0066	2.0E-04	0.0011	0.014	0.034	2.2E-05	0.034	55%	**0.4%**
Transp to LF	5.1E-04	0.0098	2.6E-04	1.3E-05	6.8E-05	1.3E-05	0.011	0	0.011	99%	**0.1%**
TOTAL	**5.57**	**1.07**	**1.02**	**0.042**	**0.22**	**0.057**	**7.98**	**0.27**	**7.71**	**96%**	**100.0%**
PE											
Resin production & transp	3.96	0.86	0.17	0.0075	0.040	0.0078	5.05	0.31	4.74	99%	**91.2%**
Pipe production & transp	0.075	0.046	0.21	0.0096	0.051	0.010	0.41	0	0.41	83%	**7.8%**
Packaging	0.023	0.0048	0.013	3.0E-04	0.0016	7.4E-04	0.043	0.0011	0.042	94%	**0.8%**
Transp to LF	2.7E-04	0.0051	1.4E-04	6.6E-06	3.5E-05	6.9E-06	0.0055	0	0.0055	99%	**0.1%**
TOTAL	**4.06**	**0.92**	**0.40**	**0.017**	**0.093**	**0.018**	**5.50**	**0.31**	**5.19**	**98%**	**100.0%**
Copper - K											
Cradle-to-pipe production & transp	6.49	3.08	5.08	0.23	1.21	0.24	16.3	0	16.3	90%	**99.3%**
Packaging	0.011	0.010	0.0069	3.1E-04	0.0017	0.034	0.064	0	0.064	44%	**0.4%**
Transp to Recycle	0.0025	0.050	0.0013	6.1E-05	3.3E-04	6.4E-05	0.054	0	0.054	99%	**0.3%**
TOTAL	**6.50**	**3.14**	**5.08**	**0.23**	**1.22**	**0.27**	**16.4**	**0**	**16.4**	**90%**	**100.0%**
Copper - L											
Cradle-to-pipe production & transp	5.07	2.41	3.97	0.18	0.95	0.18	12.8	0	12.8	90%	**99.2%**
Packaging	0.011	0.010	0.0069	3.1E-04	0.0017	0.034	0.064	0	0.064	44%	**0.5%**
Transp to Recycle	0.0019	0.039	0.0010	4.8E-05	2.6E-04	5.0E-05	0.042	0	0.042	99%	**0.3%**
TOTAL	**5.09**	**2.46**	**3.98**	**0.18**	**0.95**	**0.22**	**12.9**	**0**	**12.9**	**90%**	**100.0%**

Table 3-7
ENERGY PROFILE FOR 1000 FEET OF 3/4" HCWD PIPE

	Nat. Gas	Petroleum	Coal	Hydro power	Nuclear	Other	Total	Credit	Net	Fossil % of Net	Subprocess % of Net
CPVC											
Resin production & transp	2.08	0.32	0.57	0.023	0.12	0.024	3.13	0.082	3.05	94%	**75.5%**
Additives production	0.26	0.23	0.056	0.0020	0.011	0.0021	0.56	0	0.56	97%	**13.9%**
Pipe production & transp	0.048	0.048	0.14	0.0062	0.033	0.0064	0.28	0	0.28	84%	**6.9%**
Packaging	0.081	0.022	0.015	5.6E-04	0.0030	0.025	0.15	0.0050	0.14	80%	**3.5%**
Transp to LF	2.2E-04	0.0042	1.1E-04	5.5E-06	2.9E-05	5.8E-06	0.0046	0	0.0046	99%	**0.1%**
TOTAL	**2.46**	**0.62**	**0.78**	**0.032**	**0.17**	**0.057**	**4.12**	**0.087**	**4.03**	**94%**	**100.0%**
PEX											
Resin production & transp	3.08	0.86	0.28	0.012	0.067	0.10	4.40	0.23	4.17	96%	**86.2%**
Pipe production & transp	0.10	0.18	0.25	0.011	0.060	0.012	0.62	0	0.62	86%	**12.8%**
Packaging	0.035	0.0070	0.0028	1.2E-04	6.6E-04	0.0010	0.046	0.0024	0.044	96%	**0.9%**
Transp to LF	1.8E-04	0.0035	9.3E-05	4.5E-06	2.4E-05	4.7E-06	0.0038	0	0.0038	99%	**0.1%**
TOTAL	**3.22**	**1.05**	**0.53**	**0.024**	**0.13**	**0.12**	**5.07**	**0.24**	**4.83**	**94%**	**100.0%**
Copper - K											
Cradle-to-pipe production & transp	4.97	2.36	3.88	0.17	0.93	0.18	12.5	0	12.5	90%	**99.2%**
Packaging	0.011	0.010	0.0069	3.1E-04	0.0017	0.034	0.064	0	0.064	44%	**0.5%**
Transp to Recycle	0.0019	0.038	9.7E-04	4.7E-05	2.5E-04	4.9E-05	0.041	0	0.041	99%	**0.3%**
TOTAL	**4.98**	**2.41**	**3.89**	**0.17**	**0.93**	**0.21**	**12.6**	**0**	**12.6**	**90%**	**100.0%**
Copper - L											
Cradle-to-pipe production & transp	3.52	1.67	2.76	0.12	0.66	0.13	8.86	0	8.86	90%	**99.0%**
Packaging	0.011	0.010	0.0069	3.1E-04	0.0017	0.034	0.064	0	0.064	44%	**0.7%**
Transp to Recycle	0.0013	0.027	6.9E-04	3.3E-05	1.8E-04	3.5E-05	0.029	0	0.029	99%	**0.3%**
TOTAL	**3.54**	**1.71**	**2.76**	**0.12**	**0.66**	**0.16**	**8.96**	**0**	**8.96**	**89%**	**100.0%**
Copper - M											
Cradle-to-pipe production & transp	2.54	1.21	1.99	0.089	0.47	0.092	6.39	0	6.39	90%	**98.7%**
Packaging	0.011	0.010	0.0069	3.1E-04	0.0017	0.034	0.064	0	0.064	44%	**1.0%**
Transp to Recycle	9.6E-04	0.020	5.0E-04	2.4E-05	1.3E-04	2.5E-05	0.021	0	0.021	99%	**0.3%**
TOTAL	**2.55**	**1.24**	**1.99**	**0.089**	**0.48**	**0.13**	**6.48**	**0**	**6.48**	**89%**	**100.0%**

Energy by Life Cycle Stage. Tables 3-5 through 3-7 also allow analysis of energy contributions by life cycle stage, shown in the final column in each table, "Subprocess % of Net." These results are shown graphically in Figures 3-4 through 3-6. For copper pipe, the "Pipe Mfr" segment includes production of copper (virgin and recycled) and pipe manufacture.

For plastic pipe in all applications, production of pipe materials (resin and additives) accounts for 89 to 94 percent of total energy requirements. Pipe fabrication energy (extrusion energy) ranges from 4 to 8 percent of the total for all plastic pipes except for the 50% PCR PVC pipe and PEX pipe. Fabrication energy constitutes a larger percentage of the total for the PCR PVC pipe because the postconsumer resin comes in free of virgin resin burdens, reducing the energy requirements associated with the resin input. For PEX, fabrication is 13% of total energy. In addition to high electricity requirements per pound for extrusion (as shown in Table 1-1), natural gas use was also reported for PEX-b pipe production. The relatively small contribution of fabrication energy to the total results for plastic pipe means that the variations in fabrication energy reported by different producers (shown in Table 1-1) do not have a large effect on the energy results and conclusions.

Figure 3-4. Energy for 1000 Feet of 4" DWV Pipe by Life Cycle Stage

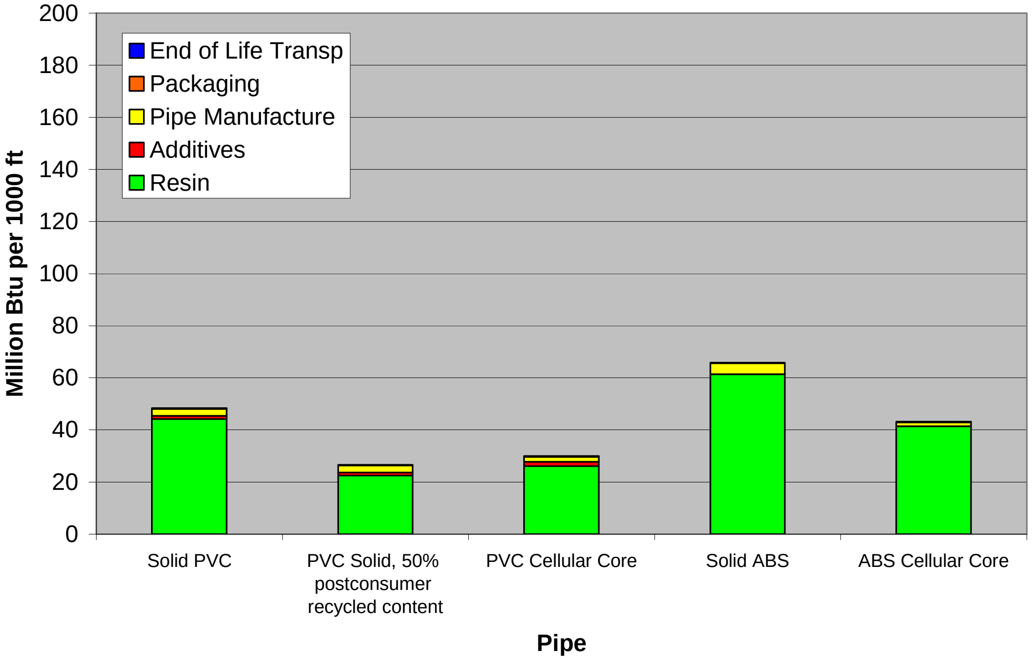


Figure 3-5. Energy for 1000 Feet of 1" Water Supply Pipe by Life Cycle Stage

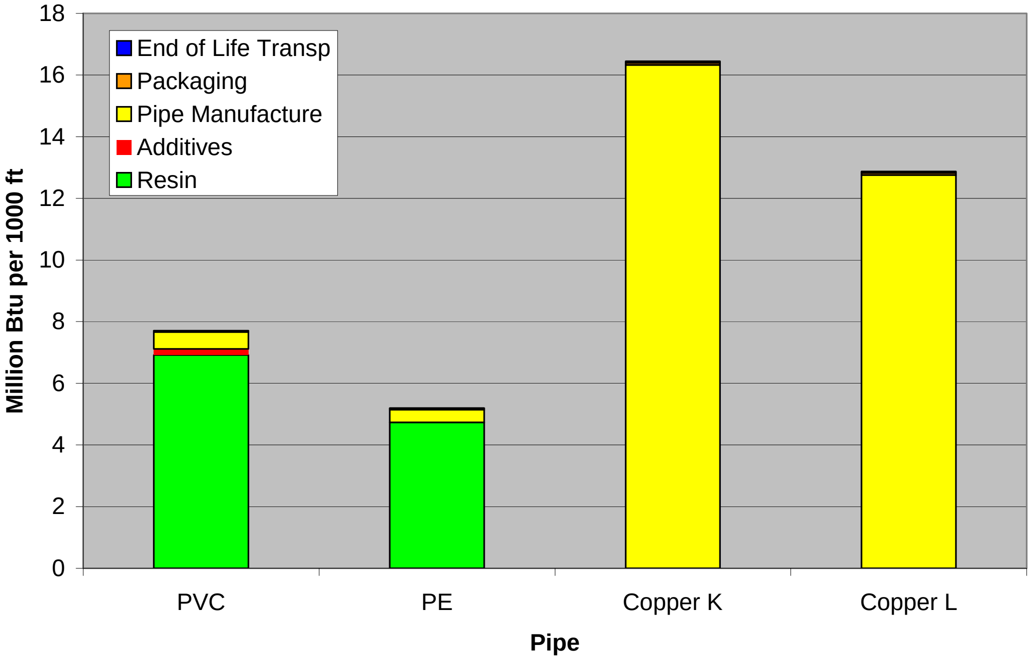
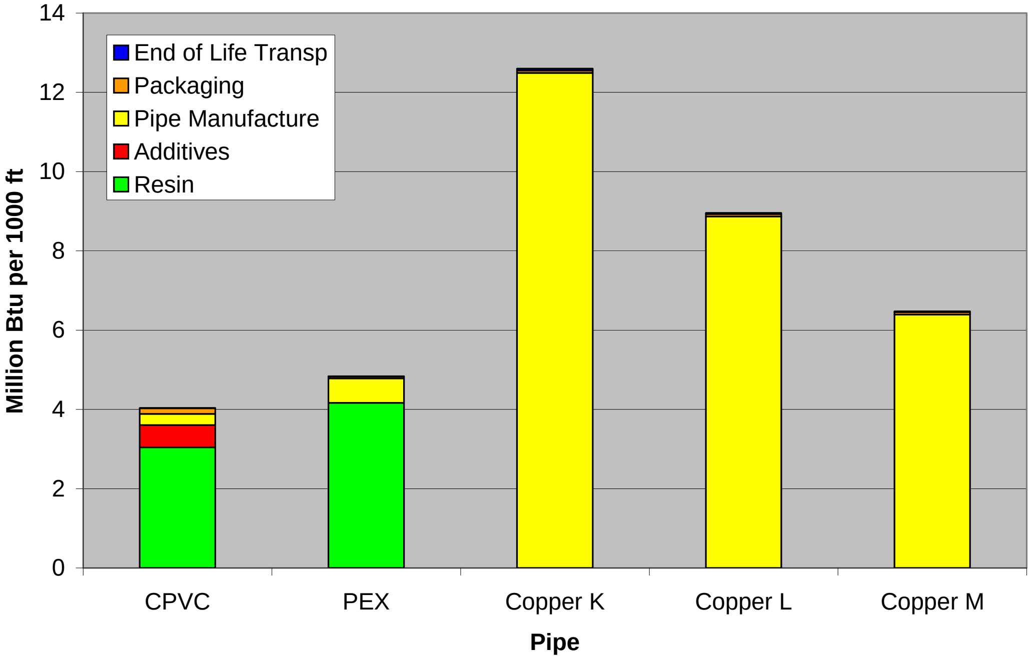


Figure 3-6. Energy for 1000 Feet of 3/4" HCWD Pipe by Life Cycle Stage



For copper pipe, the combined energy for metal production and pipe fabrication account for over 98 percent of the total energy requirements. Pipe packaging and pipe end-of-life transport each account for 1 percent or less of total energy for all metal and plastic pipe systems.

Solid Waste

Solid waste is broadly categorized into process wastes, fuel-related wastes, and postconsumer wastes. **Process wastes** are the solid wastes generated by the various processes from raw material acquisition through material manufacture. **Fuel-related wastes** are the wastes from the production and combustion of fuels used for process energy and transportation energy. **Postconsumer wastes** include the pipe packaging wastes and pipe disposed at end of life.

Based on the uncertainty in solid waste data, differences in solid waste results between systems are not considered meaningful unless the percent difference is greater than 25 percent for process and fuel-related wastes, or greater than 10 percent for postconsumer wastes. (Percent difference between systems is defined as the difference between solid waste totals divided by the average of the two system totals.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix A).

Solid waste results by weight are shown in Tables 3-8 through 3-10. As with energy results, the result tables show not only the quantity of solid waste by type but also show the contribution of different life cycle stages or components to the total. This analysis does not include the production or disposal of pipe that ends up as installation scrap.

Table 3-8
SOLID WASTE BY CATEGORY FOR 1000 FEET OF 4" DWV PIPE

	Process	Fuel	PC	Total	Process	Fuel	PC	Total	SW by Subprocess
Solid PVC									
Resin production & transp	81.9	166		248	33%	67%	0%	100%	10%
Additives production	10.8	5.43		16.2	67%	33%	0%	100%	1%
Pipe manufacture & transp	2.45	41.3	2,021	2,065	0%	2%	98%	100%	87%
Packaging	1.70	1.41	38.8	41.9	4%	3%	93%	100%	2%
Transp to LF	0	0.16		0.16	0%	100%	0%	100%	0.01%
TOTAL	**96.8**	**214**	**2,060**	**2,371**	**4%**	**9%**	**87%**	**100%**	**100%**
Solid PVC 50% PCR									
Resin production & transp	54.2	132		187	29%	71%	0%	100%	8%
Additives production	10.8	5.43		16.2	67%	33%	0%	100%	1%
Pipe manufacture & transp	2.45	41.3	2,021	2,065	0%	2%	98%	100%	89%
Packaging	1.70	1.41	38.8	41.9	4%	3%	93%	100%	2%
Transp to LF	0	0.16		0.16	0%	100%	0%	100%	0.01%
TOTAL	**69.1**	**181**	**2,060**	**2,310**	**3%**	**8%**	**89%**	**100%**	**100%**
Cell Core PVC									
Resin production & transp	48.5	98.4		147	33%	67%	0%	100%	10%
Additives production	6.18	5.83		12.0	51%	49%	0%	100%	1%
Pipe manufacture & transp	1.11	30.8	1,267	1,299	0%	2%	98%	100%	87%
Packaging	1.57	1.32	37.3	40.2	4%	3%	93%	100%	3%
Transp to LF	0	0.10		0.10	0%	100%	0%	100%	0.01%
TOTAL	**57.3**	**136**	**1,304**	**1,498**	**4%**	**9%**	**87%**	**100%**	**100%**
Solid ABS									
Resin production & transp	77.2	210		287	27%	73%	0%	100%	15%
Pipe manufacture & transp	5.99	60.8	1,504	1,570	0%	4%	96%	100%	82%
Packaging	0.85	1.08	49.2	51.1	2%	2%	96%	100%	3%
Transp to LF	0	0.12		0.12	0%	100%	0%	100%	0.01%
TOTAL	**84.1**	**272**	**1,553**	**1,908**	**4%**	**14%**	**81%**	**100%**	**100%**
Cell Core ABS									
Resin production & transp	51.7	139		191	27%	73%	0%	100%	15%
Pipe manufacture & transp	0.017	2.32	1,007	1,010	0%	0%	100%	100%	82%
Packaging	0.089	0.64	37.5	38.2	0%	2%	98%	100%	3%
Transp to LF	0	0.082		0.082	0%	100%	0%	100%	0.01%
TOTAL	**51.8**	**142**	**1,045**	**1,239**	**4%**	**11%**	**84%**	**100%**	**100%**

Table 3-9
SOLID WASTE BY CATEGORY FOR 1000 FEET OF 1" WATER SUPPLY PIPE

	Process	Fuel	PC	Total	Process	Fuel	PC	Total	SW by Subprocess
PVC									
Resin production & transp	12.8	26.0		38.9	33%	67%	0%	100%	10%
Additives production	1.78	0.91		2.69	66%	34%	0%	100%	1%
Pipe manufacture & transp	0.17	8.74	317	326	0%	3%	97%	100%	87%
Packaging	0.098	0.16	8.14	8.40	1%	2%	97%	100%	2%
Transp to LF	0	0.026		0.026	0%	100%	0%	100%	0.01%
TOTAL	**14.9**	**35.9**	**325**	**376**	**4%**	**10%**	**86%**	**100%**	**100%**
PE									
Resin production & transp	5.39	6.74		12.1	44%	56%	0%	100%	7%
Pipe manufacture & transp	0.083	6.99	165	172	0%	4%	96%	100%	92%
Packaging	0.34	0.23	1.66	2.23	15%	10%	74%	100%	1%
Transp to LF	0	0.013		0.013	0%	100%	0%	100%	0.01%
TOTAL	**5.81**	**14.0**	**167**	**186**	**3%**	**7%**	**89%**	**100%**	**100%**
Copper - K									
Cradle-to-pipe production & transp	4.35	72.1	838	914.4	0%	8%	92%	100%	98%
Packaging	0.0037	0.25	19.3	19.6	0%	1%	99%	100%	2%
Transp to Recycle	0	0.124		0.124	0%	100%	0%	100%	0.01%
TOTAL	**4.36**	**72.4**	**857.3**	**934.1**	**0%**	**8%**	**92%**	**100%**	**100%**
Copper - L									
Cradle-to-pipe production & transp	3.40	56.3	655	714.7	0%	8%	92%	100%	97%
Packaging	0.0037	0.25	19.3	19.6	0%	1%	99%	100%	3%
Transp to Recycle	0	0.097		0.097	0%	100%	0%	100%	0.01%
TOTAL	**3.41**	**56.7**	**674.3**	**734.4**	**0%**	**8%**	**92%**	**100%**	**100%**

Table 3-10
SOLID WASTE BY CATEGORY FOR 1000 FEET OF 3/4" HCWD PIPE

	Process	Fuel	PC	Total	Process	Fuel	PC	Total	SW by Subprocess
CPVC									
Resin production & transp	4.03	18.9		22.9	18%	82%	0%	100%	12%
Additives production	0.77	1.95		2.72	28%	72%	0%	100%	1%
Pipe manufacture & transp	0.037	4.52	137	142	0%	3%	97%	100%	77%
Packaging	0.22	0.45	15.6	16.3	1%	3%	96%	100%	9%
Transp to LF	0	0.011		0.011	0%	100%	0%	100%	0.01%
TOTAL	**5.06**	**25.8**	**153**	**184**	**3%**	**14%**	**83%**	**100%**	**100%**
PEX									
Resin production & transp	4.10	10.4		14.4	28%	72%	0%	100%	10%
Pipe manufacture & transp	7.48	8.45	112	128	6%	7%	88%	100%	89%
Packaging	0.044	0.10	1.20	1.35	3%	8%	89%	100%	1%
Transp to LF	0	0.0091		0.0091	0%	100%	0%	100%	0.01%
TOTAL	**11.6**	**18.9**	**113**	**144**	**8%**	**13%**	**79%**	**100%**	**100%**
Copper - K									
Cradle-to-pipe production & transp	3.33	55.1	0 *	58.4	6%	94%	0%	100%	75%
Packaging	0.0037	0.25	19.3	19.6	0%	1%	99%	100%	25%
Transp to Recycle	0	0.095		0.095	0%	100%	0%	100%	0.1%
TOTAL	**3.33**	**55.5**	**19.3**	**78.1**	**4%**	**71%**	**25%**	**100%**	**100%**
Copper - L									
Cradle-to-pipe production & transp	2.36	39.1	0 *	41.5	6%	94%	0%	100%	68%
Packaging	0.0037	0.25	19.3	19.6	0%	1%	99%	100%	32%
Transp to Recycle	0	0.068		0.068	0%	100%	0%	100%	0.1%
TOTAL	**2.37**	**39.4**	**19.3**	**61.2**	**4%**	**64%**	**32%**	**100%**	**100%**
Copper - M									
Cradle-to-pipe production & transp	1.70	28.2	0 *	29.9	6%	94%	0%	100%	60%
Packaging	0.0037	0.25	19.3	19.6	0%	1%	99%	100%	40%
Transp to Recycle	0	0.049		0.049	0%	100%	0%	100%	0.1%
TOTAL	**1.71**	**28.5**	**19.3**	**49.6**	**3%**	**58%**	**39%**	**100%**	**100%**

---

* Results shown for copper pipe are based on 100% recovery at end of life (no postconsumer pipe disposed).
The weight of 1000 feet of copper pipe is 641 lb for K, 455 lb for L, and 328 for M.

Figures 3-7 through 3-9 show solid wastes for each pipe system, reported by life cycle stage. For copper pipe, the "Pipe Mfr" segment includes both copper production and pipe manufacturing. Postconsumer pipe accounts for the majority of the weight of solid waste for all pipe systems. Wastes from pipe material production and pipe manufacturing are the next largest categories of total solid waste. Packaging wastes make only a small contribution to total solid waste for each pipe system. Fuel-related wastes associated with end-of-life pipe transportation are so small that including or excluding this transport step has a negligible effect on total solid waste results.

The results shown in Figures 3-7 through 3-9 include the full weight of the postconsumer pipe with no adjustment for recovery for recycling. Underground DWV and water supply pipe may be left in place when a structure is demolished, in which case the pipe would become in-ground solid waste at the building site rather than at a landfill, and the end-of-life transportation fuel-related wastes would not apply. HCWD pipe inside the structure is much more accessible and may be recovered at high rates, particularly if the pipe material has high scrap value.

The effect of different pipe recovery rates on total solid waste is shown in Figures 3-10 through 3-12. The postconsumer pipe segments in these solid waste figures are divided into sections to illustrate the effect of various levels of recovery. These figures can be used to evaluate the effects of regional pipe recovery practices or future recovery of plastic and underground pipe.

Figure 3-7. Solid Waste for 1000 Feet of 4" DWV Pipe by Life Cycle Stage

(includes no adjustment for pipe recovery for recycling)

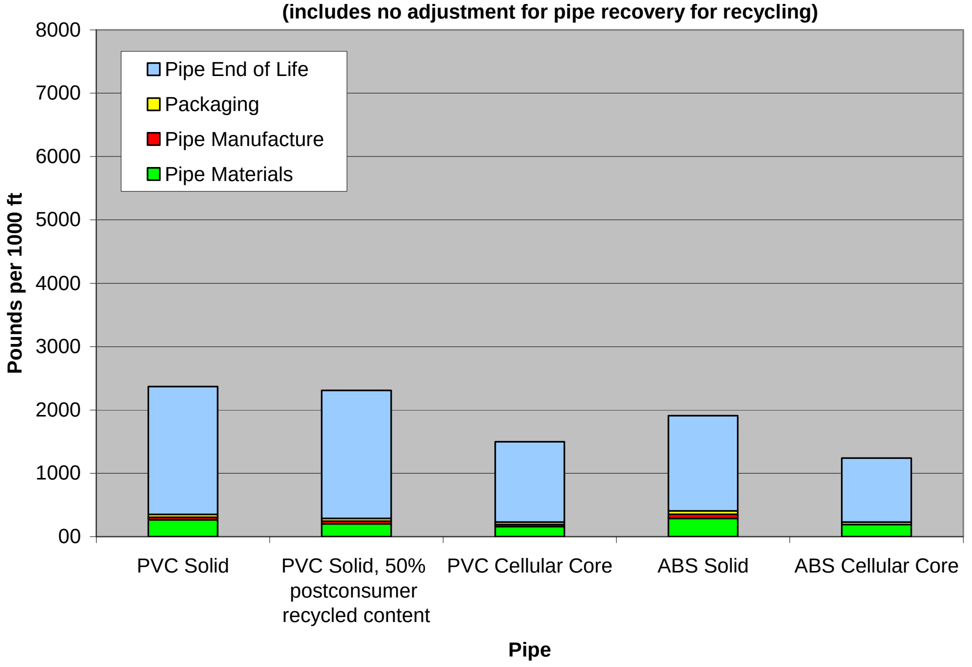


Figure 3-8. Solid Waste for 1000 Feet of 1" Water Supply Pipe by Life Cycle Stage

(includes no adjustment for pipe recovery for recycling)

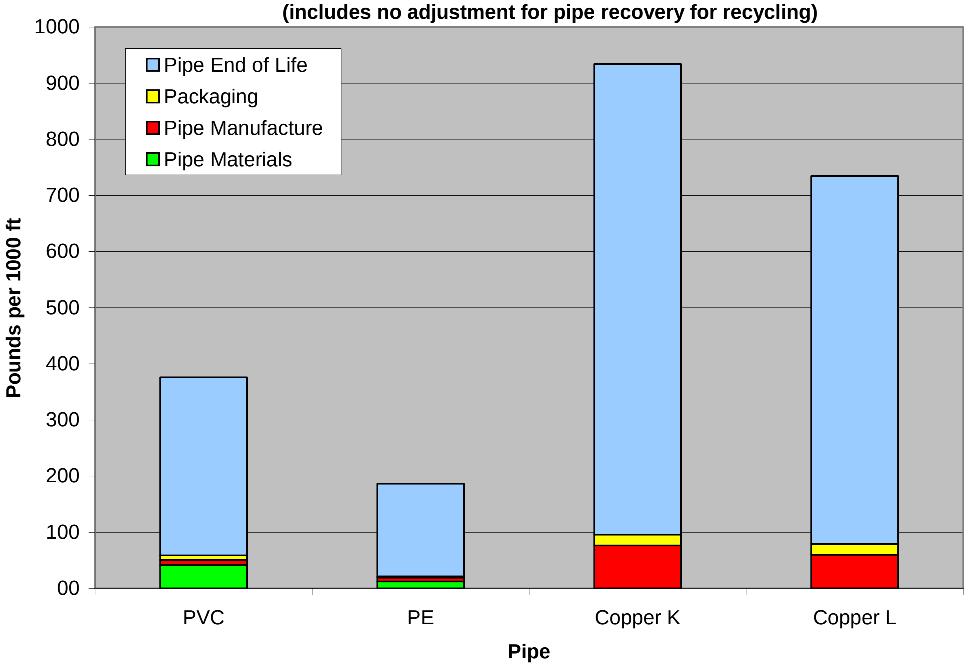


Figure 3-9. Solid Waste for 1000 Feet of 3/4" HCWD Pipe by Life Cycle Stage

(includes no adjustment for pipe recovery for recycling)

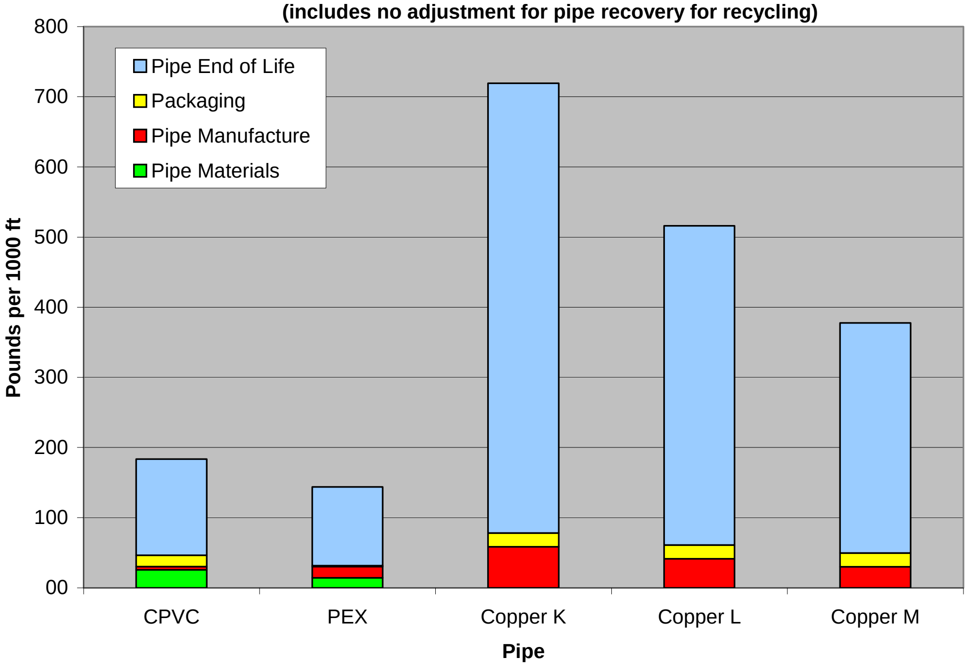


Figure 3-10. Solid Waste for 1000 Feet of 4" DWV Pipe by Solid Waste Category

(showing effects of various recovery levels)

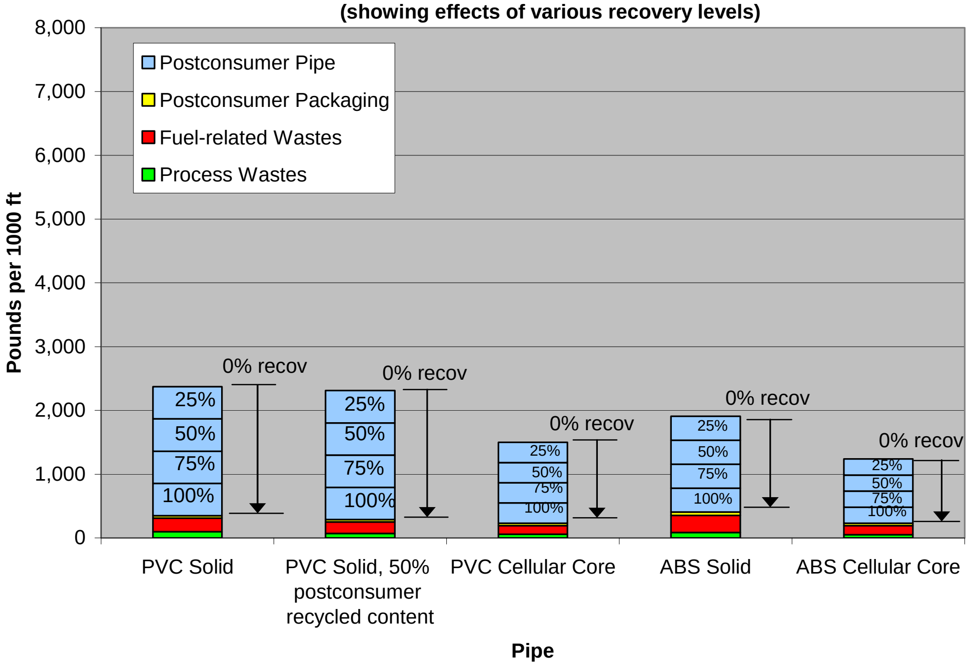


Figure 3-11. Solid Waste for 1000 Feet of 1" Water Supply Pipe by Solid Waste Category

(showing effects of various recovery levels)

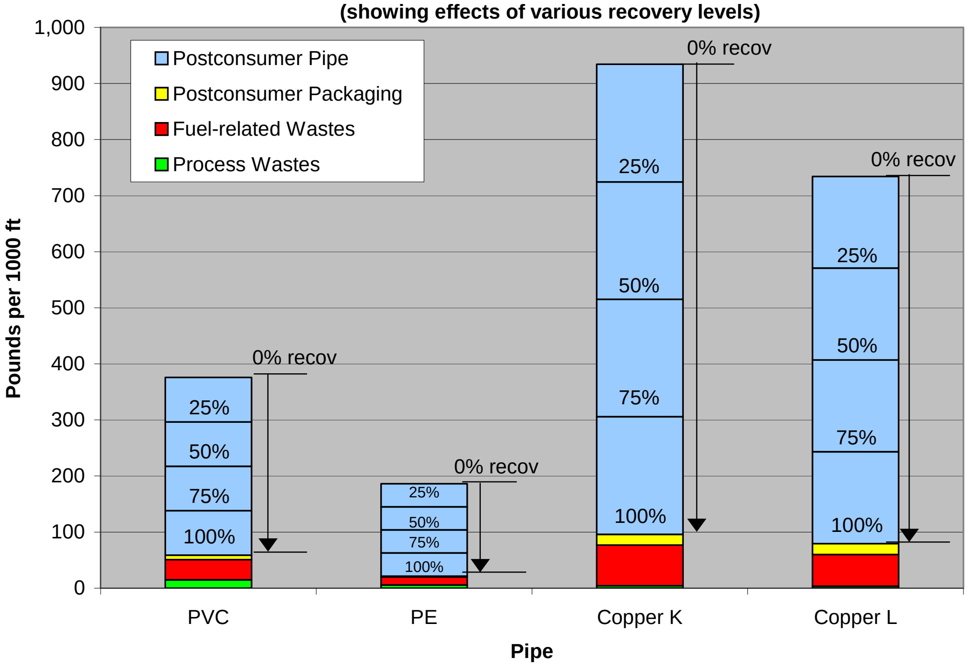
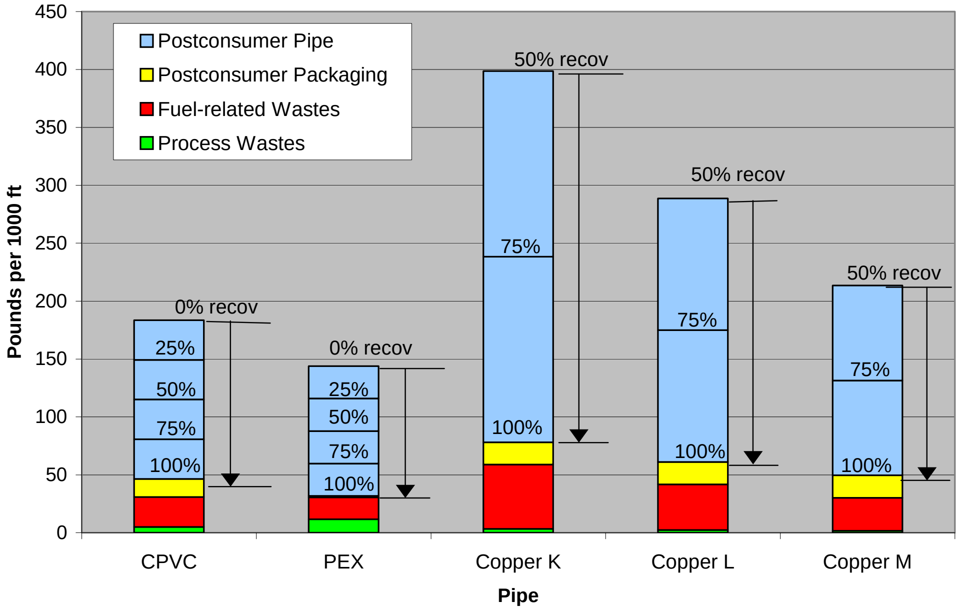


Figure 3-12. Solid Waste for 1000 Feet of 3/4" HCWD Pipe by Solid Waste Category

(showing effects of various recovery levels)



DWV Pipe. Since solid waste results are dominated by the weight of the installed pipe, the solid waste comparison tracks closely with the pipes' weight per unit length. For plastic DWV pipes, the solid PVC and ABS pipes produce more postconsumer solid waste than the corresponding cellular core pipes, although the distribution of solid waste by category is similar for solid and cellular core pipe. For both solid and cellular core PVC pipe, 87 percent of the solid waste is postconsumer, 9 percent is fuel-related waste, and 4 percent is process waste. The "SW by Subprocess" column in the solid waste tables shows that production of pipe resin and additives accounts for 11 percent of total energy for PVC pipe, while pipe packaging is less than 5 percent of the total. The solid waste profile for solid PVC pipe with 50% PCR is not significantly different from the virgin PVC pipes. For ABS pipe, postconsumer solid waste is 81 to 84 percent of the total, fuel-related waste is 11 to 14 percent, and process solid waste is 4 percent. Resin production is 15 percent of the total and packaging is 3 percent.

Water Supply Pipe. As discussed in the energy results, environmental burdens for PVC pipe are higher than for PE pipe because its weight per unit length is higher than PE pipe. The distribution of energy is similar by category. Postconsumer waste is 86 percent of the total for PVC pipe and 89 percent for PE pipe, fuel-related waste is 10 percent for PVC and 7 percent for PE, and process waste is 4 percent for PVC and 3 percent for PE. By subprocess, 11 percent of total solid waste for PVC is for production of resin and additives, while resin production is 7 percent of the total for PE. For both types of pipe, packaging is less than 3 percent, and end-of-life transport is less than 1 percent.

For the copper water supply pipes, postconsumer pipe accounts for about 90 percent of the total weight of solid waste, followed by fuel-related waste at 8 percent and postconsumer packaging waste at 2-3 percent. While it is very likely that any copper water supply pipe that is dug up would be recycled, much of this pipe is likely to remain left in place as on-site waste. Figure 3-11 shows that buried copper water supply pipe would need to be recovered at rates of over 50 percent to be comparable in total solid waste to PVC pipe at 0 percent recovery. Copper water supply pipe would need to be recovered at rates of over 75 percent to compare with total solid waste for PE pipe at 0 percent recovery.

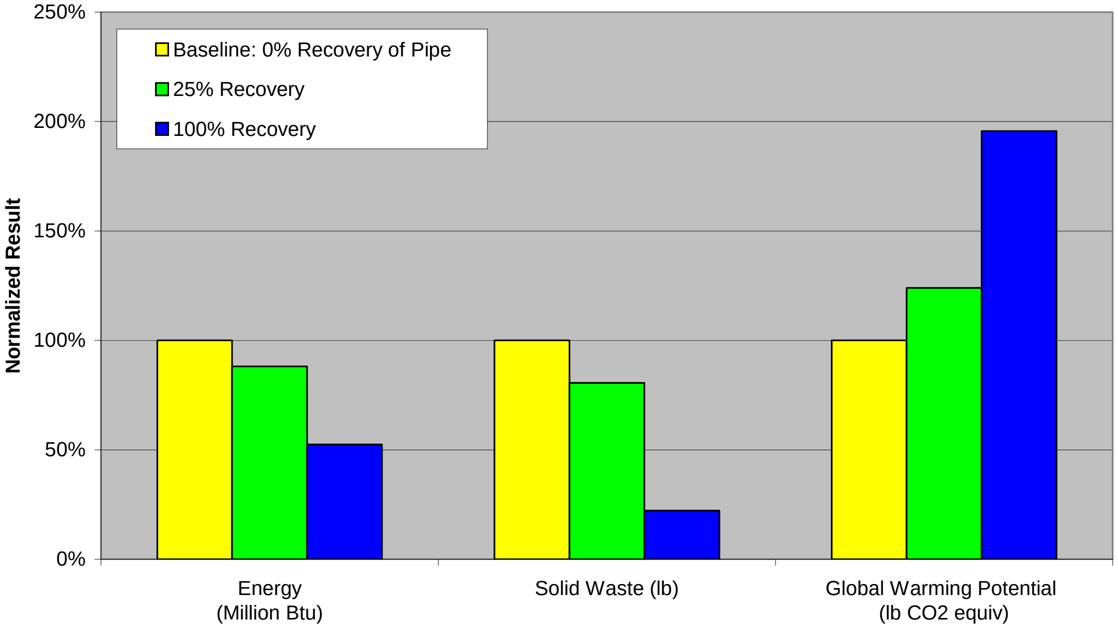
HCWD Pipe. Copper HCWD pipe is relatively easy to recover from a building and has high scrap value. As described in Chapter 2, the construction and demolition sources for this study all reported that copper pipe within buildings is commonly recovered and recycled at end of life, so for illustrative purposes Figure 3-12 uses a low-end recovery rate of 50 percent for copper HCWD pipe.

Figure 3-12 shows that copper pipe must be recovered at rates above 50 percent in order for the total solid waste to be comparable to plastic pipe systems at 0 percent recovery. Figure 3-12 shows that copper K pipe must be recovered at rates of 85 percent or higher in order to be comparable to the total weight of solid waste for plastic HCWD pipes at 0 percent recovery. At 75 percent recovery, copper L pipe is comparable to CPVC with 0 recovery, while copper L needs a recovery rate of about 85 percent to match PEX at 0 recovery. Copper M compares favorably to CPVC at copper pipe recovery rates above 60 percent, while total solid waste for copper M at 75 percent recovery is comparable to PEX at 0 recovery.

One postconsumer possibility besides recycling to explore for plastic piping is waste-to-energy (WTE) conversion. For example, this process could be used for PEX pipe recovered from building deconstruction. The energy credit gained from WTE incineration would reduce the net energy requirements for the pipe system, and WTE processing would also reduce the amount of postconsumer pipe wastes going to landfill. Incineration of the plastic to generate energy converts the carbon content of the polymer to CO_2, increasing the total GWP for the recovered pipe system. However, because the recovered energy would offset the use of other fuels, there would also be an offset of the GWP associated with production and combustion of the avoided fuels. In this way, the material resource associated with polymer products can be recovered to some extent.

Figure 3-13 illustrates the effects of using recovered postconsumer PEX pipe in a WTE incinerator. Results are shown for two recovery levels: 25% and 100%. Results for the base case at 0% recovery are normalized to 100%, and the results for the recovered pipe WTE scenarios are shown relative to the results for 0% recovery. The figure shows that 25% recovery of PEX followed by WTE incineration reduces net energy by about 10 percent and decreases total solid waste for the PEX pipe system by nearly 20 percent, but incineration causes GWP to increase by almost 25 percent. For a 100% recovery and WTE scenario, net energy is cut in half, solid waste is reduced by 75 percent, and the GWP is nearly doubled.

Figure 3-13. Effect of PEX Postconsumer Pipe Recovery with Waste-to-Energy Incineration of the Recovered Pipe



These are simplified estimates used here for illustrative purposes. The calculations are based on complete combustion of the PEX to CO_2. Energy offsets represent the gross heat of combustion of PEX and do not take into account the thermal efficiency for generation of electricity from WTE combustion of municipal solid waste, which is estimated to be around 33 percent. Because the calculations here do not include the efficiency of WTE electricity generation or the fuel displaced by the recovered energy, the GWP calculation does not include any offsetting emission credits due to avoided use of other fuels.

Environmental Emissions

The emissions reported in this analysis include those associated with production of materials and production and combustion of fuels. The emissions tables in this section present emission quantities based upon the best data available. However, some of the data are reported from industrial sources, some are from standard emissions tables, and some have been calculated. This means there are significant uncertainties with regards to the application of the data to these particular pipe systems. Because of these uncertainties, the difference in two systems' emissions of a given substance is not considered meaningful unless the percent difference exceeds 25 percent. (Percent difference is defined as the difference between two system totals divided by their average.) This minimum percent difference criterion was developed based on the experience and professional judgment of the analysts and supported by sample statistical calculations (see Appendix A).

Atmospheric and waterborne emissions for each system include emissions from processes and emissions associated with the combustion of fuels. **Process emissions** are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise effect changes on a material or product during its life cycle, while **fuel-related emissions** are those associated with the combustion of fuels used for process energy and transportation energy. The majority of atmospheric emissions are fuel-related, particularly in the case of greenhouse gas emissions, which are the focus of this discussion.

Global Warming Potential. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential (GWP) for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2001 report are: fossil carbon dioxide 1, methane 23, and nitrous oxide 296. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weight of each greenhouse gas is multiplied by its GWP and totaled in the GHG (greenhouse gas) section at the bottom of the table. Global warming potential for each type of pipe is shown graphically in Figures 3-14 through 3-16. These figures show that the majority of GWP for each system is from fossil carbon dioxide, followed by methane. GWP contributions of other substances emitted from the pipe systems (e.g., nitrous oxide, carbon tetrachloride, CFCs, etc.) are also included in the total; however, their contribution relative to fossil carbon dioxide and methane is negligible.

Global warming potential is largely a result of fossil fuel combustion. Thus, it might be expected that greenhouse gas comparisons would track closely with the fossil energy requirements presented in the Energy Results; however, this is not the case for plastics. As discussed in the Energy Profiles section, fossil fuels account for at least 94 percent of total energy for all plastic pipe systems, but about half of this is energy of material resource. EMR accounts for the energy content of the fossil fuel resources used to produce the resin but does not result in GWP (unless the pipe is burned, as in the PEX example presented previously). Therefore, the energy total that most closely matches the GWP total is the total fossil **process and transportation** energy.

Other Emissions. Full lists of atmospheric and waterborne emissions for the pipes in each application are shown at the end of this chapter in Tables 3-11 through 3-16. It is not practical to attempt to discuss individually all the emission categories listed in the tables (over 120 atmospheric substances and over 110 waterborne substances). It is important to realize that interpretation of air and water emission data requires great care. The effects of the various emissions on humans and on the environment are not fully known. The degree of potential environmental disruption due to environmental releases is not related to the weight of the releases in a simple way. Various impact assessment methodologies can be used to assess the potential impacts of emissions on human health and the environment; however, this analysis is limited to a life cycle inventory.

Figure 3-14. Global Warming Potential for Production of 1000 Feet of 4" DWV Pipe

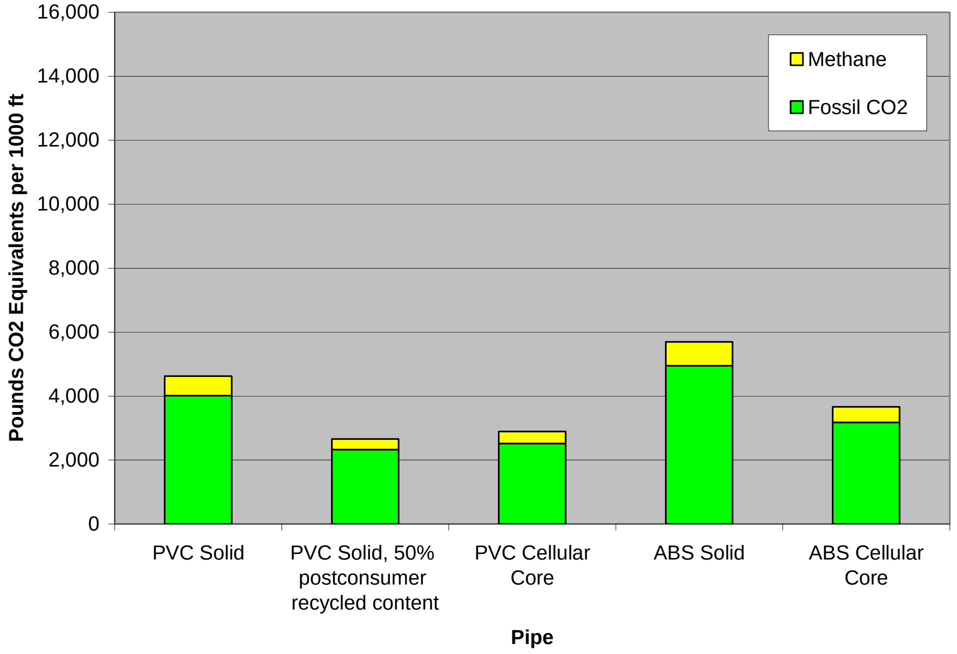


Figure 3-15. Global Warming Potential for Production of 1000 Feet of 1" Water Supply Pipe

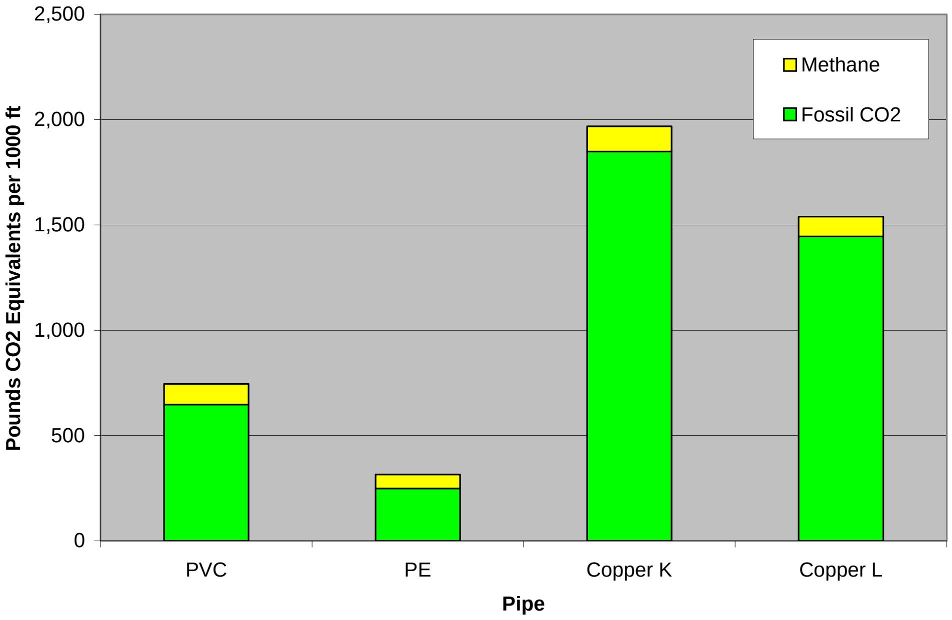
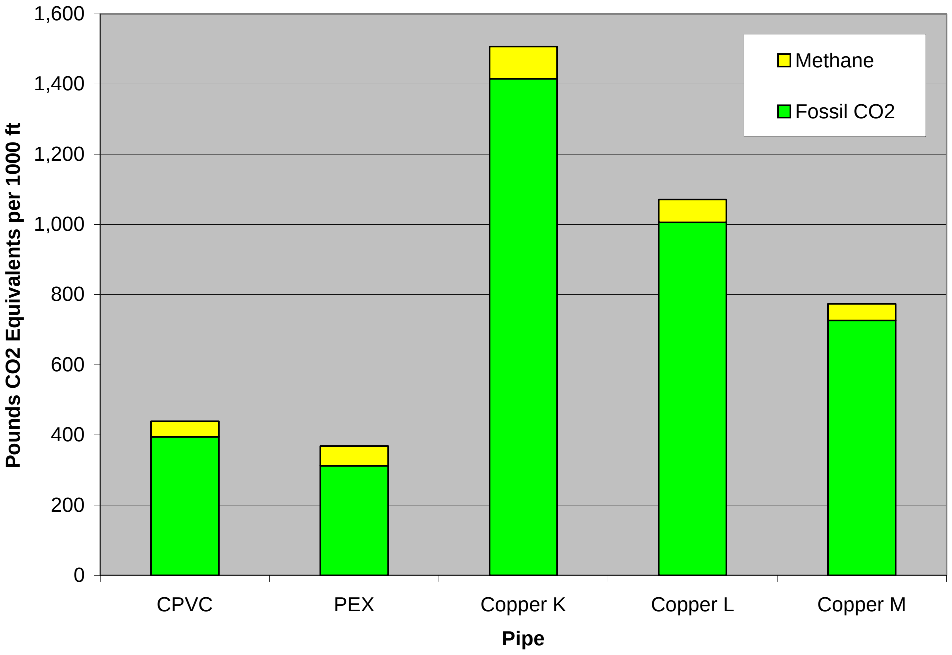


Figure 3-16. Global Warming Potential for Production of 1000 Feet of 3/4" HCWD Pipe



One emission that is worth mentioning individually is dioxins. PVC is often attacked from an environmental standpoint because the production of PVC emits small amounts of dioxin. The amount of dioxin released per 1,000 pounds of PVC resin produced is very small. Trace emissions of dioxin are also associated with combustion of fuels used for process energy and transportation energy. For water supply pipe, Table 3-12 (page 2 of 2) shows that dioxin emissions from PVC pipe are somewhat higher than dioxin emissions for copper pipe. Table 3-13 shows that dioxins for CPVC HCWD pipe are lower than dioxins for copper K pipe, comparable to copper L pipe, and higher than copper M pipe. Thus, the total process and fuel-related emissions of dioxins from PVC and CPVC pipe production can be more than offset by fuel-related dioxin emissions for other types of pipe with higher cradle-to-production energy requirements.

CONCLUSIONS

The following conclusions can be drawn based on the results of the LCI:

- **Weight per unit length of pipe is a key factor in all LCI results.** Lighter pipes generally have lower environmental burdens.
- **Energy:** The use of energy resources as raw materials for plastic resins increases the total energy for plastic pipe systems; however, this is more than offset by the heavier weight of copper pipe and the large amounts of energy required to produce primary and secondary copper.
- **Solid Waste:** Total solid wastes are dominated by the weight of the postconsumer pipe; thus, heavier pipes have higher total solid waste than lighter pipes. Copper HCWD pipe is widely recovered for recycling due to its high value so that there is likely to be little unrecovered postconsumer copper HCWD pipe going to construction and demolition landfills. Increased recovery of other types of pipe, either recovery prior to demolition or recovery from construction and demolition waste, would greatly reduce the solid waste associated with pipe systems. Recovered plastic pipe could be recycled or incinerated with energy recovery. Incineration of plastic pipe with energy recovery would reduce solid waste and recover some of the pipe's energy of material resource but would increase fossil carbon dioxide emissions, increasing GWP.
- **Global Warming Potential:** Over 75 percent of total GWP for all pipe systems is from carbon dioxide from combustion of fossil fuels. Thus, pipe systems that require combustion of large amounts of fossil fuels for process and transportation energy have higher GWP.

Table 3-11
ATMOSPHERIC EMISSIONS FOR 1000 FEET OF 4" DWV PIPE
(page 1 of 2)

Pounds/1000 ft of Pipe	PVC Solid	PVC Solid 50% PCR	PVC Cell Core	ABS Solid	ABS Cell Core
Particulates (unspecified)	1.34	0.86	0.85	1.79	1.10
Particulates (PM2.5)	0.0029	0.0014	0.0017	0.0083	0.0055
Particulates (PM10)	0.44	0.26	0.27	0.66	0.47
Nitrogen Oxides	9.56	6.64	6.08	17.3	12.5
Hydrocarbons (unspecified)	0.22	0.18	0.16	0.50	0.34
VOC (unspecified)	1.53	0.83	0.92	1.86	1.28
TNMOC (unspecified)	0.65	0.38	0.41	5.12	3.43
Sulfur Dioxide	29.5	16.3	18.2	30.8	19.6
Sulfur Oxides	20.1	10.3	12.0	28.1	19.0
Carbon Monoxide	7.99	5.11	5.06	19.7	13.3
Fossil CO2*	4,008	2,331	2,516	4,950	3,173
Non-Fossil CO2	4.89	4.29	3.49	2.05	1.30
Formaldehyde	0.0022	0.0012	0.0013	0.0026	0.0017
Acetaldehyde	7.5E-05	4.5E-05	4.8E-05	1.0E-04	7.0E-05
Propionaldehyde	8.2E-06	4.7E-06	4.8E-06	2.0E-05	1.3E-05
Aldehydes (unspecified)	0.016	0.010	0.010	0.049	0.033
Organics (unspecified)	0.088	0.045	0.053	0.21	0.14
Ammonia	0.0081	0.0052	0.0052	0.17	0.12
Ammonia Chloride	2.1E-04	1.3E-04	1.3E-04	2.5E-04	1.4E-04
Methane*	26.8	14.2	16.2	32.4	21.4
Kerosene	3.7E-04	2.4E-04	2.4E-04	4.5E-04	2.6E-04
Chlorine	0.022	0.011	0.013	1.8E-04	1.2E-04
HCl	0.34	0.22	0.22	0.43	0.25
HF	0.042	0.027	0.027	0.054	0.032
Metals (unspecified)	3.4E-04	2.1E-04	2.2E-04	4.4E-04	2.8E-04
Mercaptan	0.0054	0.0034	0.0033	0.011	0.0075
Antimony	5.3E-06	3.3E-06	3.4E-06	6.8E-06	4.1E-06
Arsenic	1.3E-04	8.0E-05	8.1E-05	1.7E-04	9.9E-05
Beryllium	7.1E-06	4.4E-06	4.6E-06	8.7E-06	5.2E-06
Cadmium	3.8E-05	2.2E-05	2.4E-05	4.4E-05	2.8E-05
Chromium (VI)	2.3E-05	1.4E-05	1.5E-05	3.0E-05	1.8E-05
Chromium	1.0E-04	6.3E-05	6.6E-05	1.3E-04	7.7E-05
Cobalt	5.3E-05	3.3E-05	3.6E-05	9.8E-05	6.1E-05
Copper	1.7E-06	1.0E-06	1.2E-06	1.3E-06	8.1E-07
Lead	2.1E-04	1.3E-04	1.3E-04	3.5E-04	2.2E-04
Magnesium	0.0032	0.0020	0.0020	0.0041	0.0024
Manganese	1.7E-04	1.1E-04	1.1E-04	2.3E-04	1.4E-04
Mercury	9.7E-05	5.6E-05	5.8E-05	1.0E-04	6.5E-05
Nickel	4.3E-04	2.7E-04	3.1E-04	9.7E-04	6.2E-04
Selenium	3.8E-04	2.4E-04	2.4E-04	5.0E-04	3.0E-04
Zinc	2.0E-06	1.5E-06	1.6E-06	1.4E-06	7.4E-07
Acetophenone	3.2E-07	1.9E-07	1.9E-07	7.7E-07	5.2E-07
Acrolein	1.2E-04	7.5E-05	7.7E-05	1.5E-04	9.2E-05
Nitrous Oxide*	0.094	0.055	0.059	0.13	0.082
Benzene	0.086	0.045	0.052	0.083	0.055
Benzyl Chloride	1.5E-05	8.7E-06	8.8E-06	3.6E-05	2.4E-05
Bis(2-ethylhexyl) Phthalate (DEHI	1.6E-06	9.1E-07	9.2E-07	3.8E-06	2.5E-06
1,3 Butadiene	1.9E-06	1.3E-06	1.3E-06	2.4E-06	1.6E-06
2-Chloroacetophenone	1.5E-07	8.7E-08	8.8E-08	3.6E-07	2.4E-07
Chlorobenzene	4.7E-07	2.7E-07	2.8E-07	1.1E-06	7.6E-07
2,4-Dinitrotoluene	6.0E-09	3.5E-09	3.5E-09	1.4E-08	9.7E-09
Ethyl Chloride	9.0E-07	5.2E-07	5.3E-07	2.2E-06	1.5E-06
Ethylbenzene	0.010	0.0052	0.0060	0.0093	0.0061
Ethylene Dibromide	2.6E-08	1.5E-08	1.5E-08	6.2E-08	4.1E-08
Ethylene Dichloride	8.6E-07	5.0E-07	5.0E-07	2.1E-06	1.4E-06
Ethylene Oxide	1.8E-06	1.8E-06	2.1E-06	6.2E-07	2.3E-05
Hexane	1.4E-06	8.3E-07	8.5E-07	3.5E-06	2.3E-06
C9H14O Isophorone	1.2E-05	7.2E-06	7.3E-06	3.0E-05	2.0E-05
Methyl Bromide*	3.4E-06	2.0E-06	2.0E-06	8.3E-06	5.5E-06
Methyl Chloride*	1.1E-05	6.6E-06	6.7E-06	2.7E-05	1.8E-05
Methyl Ethyl Ketone	8.4E-06	4.8E-06	4.9E-06	2.0E-05	1.3E-05

Table 3-11
ATMOSPHERIC EMISSIONS FOR 1000 FEET OF 4" DWV PIPE
(page 2 of 2)

Pounds/1000 ft of Pipe	PVC Solid	PVC Solid 50% PCR	PVC Cell Core	ABS Solid	ABS Cell Core
Methyl Hydrazine	3.7E-06	2.1E-06	2.1E-06	8.8E-06	5.9E-06
Methyl Methacrylate	4.3E-07	2.5E-07	2.5E-07	1.0E-06	6.9E-07
Methyl Tert Butyl Ether (MTBE)	7.5E-07	4.3E-07	4.4E-07	1.8E-06	1.2E-06
Naphthalene	1.7E-05	9.2E-06	1.1E-05	2.3E-05	1.5E-05
Propylene	1.3E-04	8.3E-05	8.6E-05	1.6E-04	1.0E-04
Styrene	5.4E-07	3.1E-07	3.2E-07	1.3E-06	8.6E-07
Toluene	0.13	0.067	0.078	0.12	0.079
Trichloroethane*	4.7E-07	2.7E-07	2.7E-07	1.1E-06	7.7E-07
Vinyl Acetate	1.6E-07	9.4E-08	9.6E-08	3.9E-07	2.6E-07
Xylenes	0.075	0.039	0.045	0.070	0.046
Acid (unknown)	0	0	0	0	0
Sulfuric Acid	0	0	0	0	0
Acetic Acid	3.8E-06	3.8E-06	4.4E-06	1.3E-06	4.9E-05
Bromine	5.9E-06	5.9E-06	6.9E-06	2.0E-06	7.6E-05
Bromoform	8.4E-07	4.8E-07	4.9E-07	2.0E-06	1.3E-06
Chloroform*	1.3E-06	7.3E-07	7.4E-07	3.0E-06	2.0E-06
Carbon Disulfide	2.8E-06	1.6E-06	1.6E-06	6.7E-06	4.5E-06
Dimethyl Sulfate	1.0E-06	6.0E-07	6.1E-07	2.5E-06	1.7E-06
Cumene	1.1E-07	6.6E-08	6.7E-08	2.7E-07	1.8E-07
Cyanide	5.4E-05	3.1E-05	3.2E-05	0.016	0.010
Perchloroethylene	1.3E-05	8.2E-06	8.2E-06	1.7E-05	1.0E-05
Methylene Chloride	1.2E-04	7.2E-05	7.6E-05	1.7E-04	1.0E-04
Carbon Tetrachloride*	1.9E-04	9.5E-05	1.1E-04	4.8E-07	3.1E-07
Phenols	2.5E-05	1.5E-05	1.8E-05	4.7E-05	3.0E-05
Fluorides	9.7E-04	5.6E-04	5.7E-04	0.0023	0.0016
Polyaromatic Hydrocarbons (total)	1.5E-05	9.3E-06	9.6E-06	1.8E-05	1.2E-05
Biphenyl	4.9E-07	3.1E-07	3.1E-07	6.4E-07	3.8E-07
Acenaphthene	1.5E-07	9.4E-08	9.4E-08	1.9E-07	1.1E-07
Acenaphthylene	7.2E-08	4.6E-08	4.6E-08	9.4E-08	5.6E-08
Anthracene	6.1E-08	3.9E-08	3.9E-08	7.9E-08	4.7E-08
Benzo(a)anthracene	2.3E-08	1.5E-08	1.5E-08	3.0E-08	1.8E-08
Benzo(a)pyrene	1.1E-08	7.0E-09	7.0E-09	1.4E-08	8.4E-09
Benzo(e)pyrene	0	0	0	0	0
Benzo(b,j,k)fluroanthene	3.2E-08	2.0E-08	2.0E-08	4.1E-08	2.4E-08
Benzo(g,h,i) perylene	7.8E-09	5.0E-09	5.0E-09	1.0E-08	6.0E-09
Chrysene	2.9E-08	1.8E-08	1.8E-08	3.7E-08	2.2E-08
Fluoranthene	2.1E-07	1.3E-07	1.3E-07	2.7E-07	1.6E-07
Fluorene	2.6E-07	1.7E-07	1.7E-07	3.4E-07	2.0E-07
Indeno(1,2,3-cd)pyrene	1.8E-08	1.1E-08	1.1E-08	2.3E-08	1.4E-08
Naphthanlene	3.8E-06	2.4E-06	2.4E-06	4.9E-06	2.9E-06
Phenanthrene	7.8E-07	5.0E-07	5.0E-07	1.0E-06	6.0E-07
Pyrene	9.5E-08	6.1E-08	6.1E-08	1.2E-07	7.3E-08
5-methyl Chrysene	6.4E-09	4.0E-09	4.1E-09	8.2E-09	4.9E-09
Dioxins (unspecified)	4.3E-08	2.3E-08	2.6E-08	1.8E-08	1.1E-08
Furans(unspecified)	1.2E-09	7.8E-10	7.8E-10	1.5E-09	8.6E-10
CFC12*	1.2E-08	9.9E-09	9.0E-09	2.8E-08	1.9E-08
CFCs (unspecified)*	3.1E-08	1.7E-08	1.9E-08	1.1E-07	7.3E-08
HCFC/HFCs*	0.0021	0.0010	0.0012	1.5E-04	1.0E-04
BTEX	0.26	0.13	0.15	0.33	0.22
Hydrogen	9.3E-04	4.7E-04	5.5E-04	0.0014	9.3E-04
Vinyl Chloride	0.073	0.036	0.043	0	0
Methanol	1.1E-07	1.1E-07	1.3E-07	3.8E-08	1.4E-06
TOC	6.1E-06	6.1E-06	7.0E-06	2.1E-06	7.8E-05
Methyl Acetate	3.0E-06	3.0E-06	3.5E-06	1.0E-06	3.8E-05
Radionuclides (unspecified)	0.021	0.013	0.013	0.025	0.015
TOTAL GWP (lb CO2 equivaler	4,657	2,676	2,910	5,734	3,690
% from fossil CO2	86%	87%	86%	86%	86%

---

* Indicates substances that contribute to global warming potential.

Table 3-12
ATMOSPHERIC EMISSIONS FOR 1000 FEET OF 1" WATER SUPPLY PIPE
(page 1 of 2)

Pounds/1000 ft of Pipe	**PVC**	**PE**	**Copper K**	**Copper L**
Particulates (unspecified)	0.22	0.087	6.23	4.87
Particulates (PM2.5)	4.5E-04	0.0024	0	0
Particulates (PM10)	0.070	0.034	2.26	1.76
Nitrogen Oxides	1.56	0.70	4.54	3.56
Hydrocarbons (unspecified)	0.037	0.019	0.13	0.11
VOC (unspecified)	0.24	0.17	0.36	0.28
TNMOC (unspecified)	0.10	0.19	0.031	0.026
Sulfur Dioxide	4.76	1.77	10.2	8.00
Sulfur Oxides	3.16	3.62	6.18	4.83
Carbon Monoxide	1.26	1.06	2.37	1.86
Fossil CO2*	648	248	1,848	1,446
Non-Fossil CO2	1.01	0.12	0.59	0.46
Formaldehyde	3.5E-04	1.5E-04	0.0013	0.0010
Acetaldehyde	1.3E-05	5.9E-06	2.2E-04	1.7E-04
Propionaldehyde	1.3E-06	4.3E-09	1.7E-05	1.4E-05
Aldehydes (unspecified)	0.0025	0.0027	0.0029	0.0023
Organics (unspecified)	0.014	0.0022	3.3E-04	2.6E-04
Ammonia	0.0013	0.0014	0.0014	0.0011
Ammonia Chloride	3.5E-05	1.5E-05	4.1E-05	3.2E-05
Methane*	4.25	2.89	5.20	4.07
Kerosene	6.3E-05	2.6E-05	7.4E-05	5.8E-05
Chlorine	0.0034	1.3E-04	2.4E-06	1.9E-06
HCl	0.058	0.023	0.095	0.074
HF	0.0072	0.0028	0.013	0.010
Metals (unspecified)	5.5E-05	2.2E-05	1.3E-04	1.0E-04
Mercaptan	9.1E-04	2.3E-06	0.010	0.0078
Antimony	8.9E-07	3.4E-07	1.8E-06	1.4E-06
Arsenic	2.1E-05	8.6E-06	4.2E-05	3.3E-05
Beryllium	1.2E-06	4.5E-07	2.2E-06	1.7E-06
Cadmium	6.1E-06	2.3E-06	1.5E-05	1.2E-05
Chromium (VI)	3.9E-06	1.5E-06	7.9E-06	6.2E-06
Chromium	1.7E-05	6.8E-06	3.4E-05	2.7E-05
Cobalt	8.8E-06	4.7E-06	2.7E-05	2.1E-05
Copper	2.7E-07	8.0E-08	4.6E-07	3.6E-07
Lead	3.4E-05	9.4E-06	0.018	0.014
Magnesium	5.4E-04	2.1E-04	0.0011	8.6E-04
Manganese	2.9E-05	1.2E-05	5.9E-05	4.6E-05
Mercury	1.6E-05	1.9E-06	6.7E-05	5.2E-05
Nickel	7.2E-05	4.6E-05	2.8E-04	2.2E-04
Selenium	6.5E-05	2.5E-05	1.3E-04	1.0E-04
Zinc	2.6E-07	1.8E-07	4.0E-07	3.3E-07
Acetophenone	5.1E-08	1.7E-10	6.9E-07	5.4E-07
Acrolein	2.0E-05	8.3E-06	5.8E-05	4.6E-05
Nitrous Oxide*	0.015	0.0054	0.058	0.045
Benzene	0.014	0.0049	0.033	0.026
Benzyl Chloride	2.4E-06	8.0E-09	3.2E-05	2.5E-05
Bis(2-ethylhexyl) Phthalate (DEHP)	2.5E-07	8.3E-10	3.4E-06	2.6E-06
1,3 Butadiene	3.4E-07	1.7E-07	9.7E-06	7.6E-06
2-Chloroacetophenone	2.4E-08	8.0E-11	3.2E-07	2.5E-07
Chlorobenzene	7.5E-08	2.5E-10	1.0E-06	7.9E-07
2,4-Dinitrotoluene	9.5E-10	3.2E-12	1.3E-08	1.0E-08
Ethyl Chloride	1.4E-07	4.8E-10	1.9E-06	1.5E-06
Ethylbenzene	0.0016	5.9E-04	0.0034	0.0026
Ethylene Dibromide	4.1E-09	1.4E-11	5.5E-08	4.3E-08
Ethylene Dichloride	1.4E-07	4.6E-10	1.8E-06	1.4E-06
Ethylene Oxide	1.2E-06	0	0	0
Hexane	2.3E-07	7.6E-10	3.1E-06	2.4E-06
C9H14O Isophorone	2.0E-06	6.6E-09	2.7E-05	2.1E-05
Methyl Bromide*	5.4E-07	1.8E-09	7.4E-06	5.7E-06
Methyl Chloride*	1.8E-06	6.0E-09	2.4E-05	1.9E-05
Methyl Ethyl Ketone	1.3E-06	4.4E-09	1.8E-05	1.4E-05

Table 3-12
ATMOSPHERIC EMISSIONS FOR 1000 FEET OF 1" WATER SUPPLY PIPE
(page 2 of 2)

Pounds/1000 ft of Pipe	**PVC**	**PE**	**Copper K**	**Copper L**
Methyl Hydrazine	5.8E-07	1.9E-09	7.8E-06	6.1E-06
Methyl Methacrylate	6.8E-08	2.3E-10	9.2E-07	7.2E-07
Methyl Tert Butyl Ether (MTBE)	1.2E-07	4.0E-10	1.6E-06	1.3E-06
Naphthalene	2.7E-06	1.3E-06	7.4E-06	5.8E-06
Propylene	2.3E-05	1.1E-05	6.4E-04	5.0E-04
Styrene	8.5E-08	2.8E-10	1.1E-06	9.0E-07
Toluene	0.020	0.0075	0.044	0.034
Trichloroethane*	7.4E-08	6.3E-09	9.3E-07	7.2E-07
Vinyl Acetate	2.6E-08	8.6E-11	3.5E-07	2.7E-07
Xylenes	0.012	0.0044	0.026	0.020
Acid (unknown)	0	8.3E-07	0	0
Sulfuric Acid	0	0	1.51	1.18
Acetic Acid	2.4E-06	0	0	0
Bromine	3.8E-06	0	0	0
Bromoform	1.3E-07	4.4E-10	1.8E-06	1.4E-06
Chloroform*	2.0E-07	6.7E-10	2.7E-06	2.1E-06
Carbon Disulfide	4.4E-07	1.5E-09	6.0E-06	4.7E-06
Dimethyl Sulfate	1.6E-07	5.5E-10	2.2E-06	1.7E-06
Cumene	1.8E-08	6.0E-11	2.4E-07	1.9E-07
Cyanide	8.5E-06	2.8E-08	1.1E-04	9.0E-05
Perchloroethylene	2.2E-06	8.5E-07	4.5E-06	3.5E-06
Methylene Chloride	1.9E-05	8.3E-06	4.6E-05	3.6E-05
Carbon Tetrachloride*	3.0E-05	2.4E-08	1.4E-07	1.1E-07
Phenols	4.1E-06	2.2E-06	1.4E-05	1.1E-05
Fluorides	1.5E-04	1.7E-06	0.0021	0.0016
Polyaromatic Hydrocarbons (total)	2.5E-06	1.2E-06	4.4E-05	3.4E-05
Biphenyl	8.3E-08	3.2E-08	1.7E-07	1.3E-07
Acenaphthene	2.5E-08	9.6E-09	5.1E-08	4.0E-08
Acenaphthylene	1.2E-08	4.7E-09	2.5E-08	1.9E-08
Anthracene	1.0E-08	4.0E-09	2.1E-08	1.6E-08
Benzo(a)anthracene	3.9E-09	1.5E-09	8.0E-09	6.2E-09
Benzo(a)pyrene	1.9E-09	7.2E-10	3.8E-09	3.0E-09
Benzo(e)pyrene	0	0	0	0
Benzo(b,j,k)fluroanthene	5.4E-09	2.1E-09	1.1E-08	8.6E-09
Benzo(g,h,i) perylene	1.3E-09	5.1E-10	2.7E-09	2.1E-09
Chrysene	4.9E-09	1.9E-09	1.0E-08	7.8E-09
Fluoranthene	3.5E-08	1.3E-08	7.1E-08	5.5E-08
Fluorene	4.4E-08	1.7E-08	9.1E-08	7.1E-08
Indeno(1,2,3-cd)pyrene	3.0E-09	1.2E-09	6.1E-09	4.8E-09
Naphthanlene	6.3E-07	2.5E-07	1.3E-06	1.0E-06
Phenanthrene	1.3E-07	5.1E-08	2.7E-07	2.1E-07
Pyrene	1.6E-08	6.2E-09	3.3E-08	2.6E-08
5-methyl Chrysene	1.1E-09	4.2E-10	2.2E-09	1.7E-09
Dioxins (unspecified)	6.8E-09	8.9E-10	5.2E-09	4.0E-09
Furans(unspecified)	2.1E-10	8.6E-11	2.4E-10	1.9E-10
CFC12*	2.0E-09	1.0E-09	7.6E-09	6.0E-09
CFCs (unspecified)*	4.9E-09	6.5E-09	6.0E-11	4.7E-11
HCFC/HFCs*	3.2E-04	1.1E-04	0	0
BTEX	0.041	0.048	4.5E-05	3.5E-05
Hydrogen	1.5E-04	2.3E-04	0	0
Vinyl Chloride	0.011	0	0	0
Methanol	7.1E-08	0	0	0
TOC	3.9E-06	0	0	0
Methyl Acetate	1.9E-06	0	0	0
Radionuclides (unspecified)	0.0035	0.0015	0.0042	0.0033
			0	0
TOTAL GHG (lb CO2 equivalents)	751	316	1985	1553
% from fossil CO2	86%	78%	93%	93%

---

* Indicates substances that contribute to global warming potential.

Table 3-13
ATMOSPHERIC EMISSIONS FOR 1000 FEET OF 3/4" HCWD PIPE
(page 1 of 2)

Pounds/1000 ft of Pipe	**CPVC**	**PEX**	**Copper K**	**Copper L**	**Copper M**
Particulates (unspecified)	0.15	0.11	4.77	3.39	2.45
Particulates (PM2.5)	0.0018	0.0023	0	0	0
Particulates (PM10)	0.038	0.036	1.73	1.23	0.88
Nitrogen Oxides	0.95	1.04	3.48	2.48	1.79
Hydrocarbons (unspecified)	0.032	0.051	0.10	0.074	0.054
VOC (unspecified)	0.11	0.15	0.28	0.20	0.14
TNMOC (unspecified)	0.044	0.15	0.026	0.022	0.019
Sulfur Dioxide	2.73	1.81	7.83	5.57	4.02
Sulfur Oxides	1.13	2.85	4.72	3.35	2.42
Carbon Monoxide	0.63	1.15	1.82	1.29	0.94
Fossil CO2*	395	312	1,415	1,006	726
Non-Fossil CO2	0.17	0.15	0.45	0.32	0.23
Formaldehyde	1.8E-04	1.3E-04	9.7E-04	6.9E-04	5.0E-04
Acetaldehyde	7.2E-06	5.3E-06	1.7E-04	1.2E-04	8.9E-05
Propionaldehyde	6.0E-07	4.8E-09	1.3E-05	9.5E-06	6.8E-06
Aldehydes (unspecified)	0.0015	0.0030	0.0022	0.0016	0.0011
Organics (unspecified)	0.0060	0.0022	2.5E-04	1.8E-04	1.3E-04
Ammonia	6.2E-04	0.0014	0.0011	7.9E-04	5.8E-04
Ammonia Chloride	2.7E-05	2.0E-05	3.2E-05	2.3E-05	1.6E-05
Methane*	1.93	2.43	3.98	2.83	2.04
Kerosene	4.8E-05	3.6E-05	5.7E-05	4.1E-05	2.9E-05
Chlorine	0.0016	2.5E-04	1.8E-06	1.3E-06	9.5E-07
HCl	0.043	0.032	0.073	0.052	0.037
HF	0.0053	0.0039	0.0099	0.0070	0.0051
Metals (unspecified)	3.6E-05	3.3E-05	1.0E-04	7.1E-05	5.1E-05
Mercaptan	3.4E-04	2.5E-06	0.0076	0.0054	0.0039
Antimony	6.6E-07	4.7E-07	1.4E-06	9.9E-07	7.2E-07
Arsenic	1.6E-05	1.2E-05	3.2E-05	2.3E-05	1.6E-05
Beryllium	8.9E-07	6.0E-07	1.7E-06	1.2E-06	8.7E-07
Cadmium	3.8E-06	2.5E-06	1.1E-05	8.2E-06	5.9E-06
Chromium (VI)	2.8E-06	2.0E-06	6.0E-06	4.3E-06	3.1E-06
Chromium	1.2E-05	8.5E-06	2.6E-05	1.9E-05	1.4E-05
Cobalt	7.3E-06	5.7E-06	2.1E-05	1.5E-05	1.1E-05
Copper	2.1E-07	7.0E-08	3.5E-07	2.5E-07	1.8E-07
Lead	2.2E-05	1.2E-05	0.014	0.010	0.0072
Magnesium	4.0E-04	2.9E-04	8.4E-04	6.0E-04	4.3E-04
Manganese	2.1E-05	1.6E-05	4.5E-05	3.2E-05	2.3E-05
Mercury	1.4E-05	2.5E-06	5.1E-05	3.6E-05	2.6E-05
Nickel	6.4E-05	5.2E-05	2.1E-04	1.5E-04	1.1E-04
Selenium	4.8E-05	3.4E-05	1.0E-04	7.2E-05	5.2E-05
Zinc	2.6E-07	4.7E-08	3.3E-07	2.6E-07	2.1E-07
Acetophenone	2.4E-08	1.9E-10	5.3E-07	3.7E-07	2.7E-07
Acrolein	1.4E-05	1.1E-05	4.5E-05	3.2E-05	2.3E-05
Nitrous Oxide*	0.010	0.0071	0.044	0.032	0.023
Benzene	0.0068	0.0042	0.025	0.018	0.013
Benzyl Chloride	1.1E-06	8.8E-09	2.5E-05	1.7E-05	1.3E-05
Bis(2-ethylhexyl) Phthalate (DEHI	1.2E-07	9.1E-10	2.6E-06	1.8E-06	1.3E-06
1,3 Butadiene	2.2E-07	1.5E-07	7.4E-06	5.3E-06	3.9E-06
2-Chloroacetophenone	1.1E-08	8.8E-11	2.5E-07	1.7E-07	1.3E-07
Chlorobenzene	3.5E-08	2.8E-10	7.7E-07	5.5E-07	4.0E-07
2,4-Dinitrotoluene	4.4E-10	3.5E-12	9.8E-09	7.0E-09	5.0E-09
Ethyl Chloride	6.7E-08	5.3E-10	1.5E-06	1.0E-06	7.6E-07
Ethylbenzene	7.9E-04	5.0E-04	0.0026	0.0018	0.0013
Ethylene Dibromide	1.9E-09	1.5E-11	4.2E-08	3.0E-08	2.2E-08
Ethylene Dichloride	6.3E-08	5.0E-10	1.4E-06	1.0E-06	7.2E-07
Ethylene Oxide	0	0	0	0	0
Hexane	1.1E-07	8.4E-10	2.4E-06	1.7E-06	1.2E-06
C9H14O Isophorone	9.2E-07	7.3E-09	2.0E-05	1.4E-05	1.0E-05
Methyl Bromide*	2.5E-07	2.0E-09	5.6E-06	4.0E-06	2.9E-06
Methyl Chloride*	8.4E-07	6.6E-09	1.9E-05	1.3E-05	9.5E-06
Methyl Ethyl Ketone	6.2E-07	4.9E-09	1.4E-05	9.7E-06	7.0E-06

Table 3-13
ATMOSPHERIC EMISSIONS FOR 1000 FEET OF 3/4" HCWD PIPE
(page 2 of 2)

Pounds/1000 ft of Pipe	**CPVC**	**PEX**	**Copper K**	**Copper L**	**Copper M**
Methyl Hydrazine	2.7E-07	2.1E-09	6.0E-06	4.2E-06	3.1E-06
Methyl Methacrylate	3.2E-08	2.5E-10	7.0E-07	5.0E-07	3.6E-07
Methyl Tert Butyl Ether (MTBE)	5.5E-08	4.4E-10	1.2E-06	8.7E-07	6.3E-07
Naphthalene	1.7E-06	1.3E-06	5.6E-06	4.0E-06	2.9E-06
Propylene	1.5E-05	1.0E-05	4.9E-04	3.5E-04	2.6E-04
Styrene	4.0E-08	3.1E-10	8.8E-07	6.2E-07	4.5E-07
Toluene	0.010	0.0064	0.033	0.024	0.017
Trichloroethane*	3.4E-08	6.7E-09	7.1E-07	5.0E-07	3.6E-07
Vinyl Acetate	1.2E-08	9.5E-11	2.7E-07	1.9E-07	1.4E-07
Xylenes	0.0059	0.0037	0.020	0.014	0.010
Acid (unknown)	0	0	0	0	0
Sulfuric Acid	0	0	1.15	0.82	0.59
Acetic Acid	0	0	0	0	0
Bromine	0	0	0	0	0
Bromoform	6.2E-08	4.9E-10	1.4E-06	9.7E-07	7.0E-07
Chloroform*	9.3E-08	7.4E-10	2.1E-06	1.5E-06	1.1E-06
Carbon Disulfide	2.1E-07	1.6E-09	4.6E-06	3.2E-06	2.3E-06
Dimethyl Sulfate	7.6E-08	6.0E-10	1.7E-06	1.2E-06	8.6E-07
Cumene	8.4E-09	6.6E-11	1.9E-07	1.3E-07	9.5E-08
Cyanide	4.0E-06	3.1E-08	8.8E-05	6.2E-05	4.5E-05
Perchloroethylene	1.6E-06	1.2E-06	3.5E-06	2.5E-06	1.8E-06
Methylene Chloride	1.5E-05	1.1E-05	3.5E-05	2.5E-05	1.8E-05
Carbon Tetrachloride*	9.3E-06	3.6E-08	1.1E-07	7.5E-08	5.4E-08
Phenols	3.6E-06	2.6E-06	1.0E-05	7.4E-06	5.3E-06
Fluorides	7.3E-05	2.2E-06	0.0016	0.0011	8.0E-04
Polyaromatic Hydrocarbons (total)	1.7E-06	1.2E-06	3.4E-05	2.4E-05	1.8E-05
Biphenyl	6.1E-08	4.4E-08	1.3E-07	9.2E-08	6.7E-08
Acenaphthene	1.8E-08	1.3E-08	3.9E-08	2.8E-08	2.0E-08
Acenaphthylene	9.0E-09	6.5E-09	1.9E-08	1.4E-08	9.8E-09
Anthracene	7.6E-09	5.4E-09	1.6E-08	1.1E-08	8.2E-09
Benzo(a)anthracene	2.9E-09	2.1E-09	6.1E-09	4.3E-09	3.1E-09
Benzo(a)pyrene	1.4E-09	9.8E-10	2.9E-09	2.1E-09	1.5E-09
Benzo(e)pyrene	0	0	0	0	0
Benzo(b,j,k)fluroanthene	4.0E-09	2.9E-09	8.4E-09	6.0E-09	4.3E-09
Benzo(g,h,i) perylene	9.7E-10	7.0E-10	2.1E-09	1.5E-09	1.1E-09
Chrysene	3.6E-09	2.6E-09	7.6E-09	5.4E-09	3.9E-09
Fluoranthene	2.6E-08	1.8E-08	5.4E-08	3.9E-08	2.8E-08
Fluorene	3.3E-08	2.4E-08	6.9E-08	4.9E-08	3.6E-08
Indeno(1,2,3-cd)pyrene	2.2E-09	1.6E-09	4.7E-09	3.3E-09	2.4E-09
Naphthanlene	4.7E-07	3.4E-07	9.9E-07	7.1E-07	5.1E-07
Phenanthrene	9.7E-08	7.0E-08	2.1E-07	1.5E-07	1.1E-07
Pyrene	1.2E-08	8.6E-09	2.5E-08	1.8E-08	1.3E-08
5-methyl Chrysene	7.9E-10	5.7E-10	1.7E-09	1.2E-09	8.6E-10
Dioxins (unspecified)	2.9E-09	1.3E-09	4.0E-09	2.8E-09	2.0E-09
Furans(unspecified)	1.6E-10	1.2E-10	1.9E-10	1.3E-10	9.7E-11
CFC12*	1.8E-09	2.9E-09	5.8E-09	4.2E-09	3.0E-09
CFCs (unspecified)*	1.5E-09	5.0E-09	4.6E-11	3.2E-11	2.3E-11
HCFC/HFCs*	6.0E-04	2.4E-04	0	0	0
BTEX	0.014	0.037	3.4E-05	2.4E-05	1.8E-05
Hydrogen	3.2E-04	2.6E-04	0	0	0
Vinyl Chloride	0.0035	0	0	0	0
Methanol	0	1.5E-05	0	0	0
TOC	0	0	0	0	0
Methyl Acetate	0	0	0	0	0
Radionuclides (unspecified)	0.0027	0.0020	0.0032	0.0023	0.0017
TOTAL GHG (lb CO2 equivalen	444	371	1,520	1,080	780
% from fossil CO2	89%	84%	93%	93%	93%

---

* Indicates substances that contribute to global warming potential.

Table 3-14
WATERBORNE EMISSIONS FOR 1000 FEET OF 4" DWV PIPE
(page 1 of 2)

Pounds/1000 ft of Pipe	**PVC Solid**	**PVC Solid 50% PCR**	**PVC Cell Core**	**ABS Solid**	**ABS Cell Core**
Acid (unspecified)	0.0049	0.0027	0.0030	0.0044	0.0029
Acid (benzoic)	0.0087	0.0046	0.0053	0.012	0.0082
Acid (hexanoic)	0.0018	9.5E-04	0.0011	0.0025	0.0017
Metal (unspecified)	59.0	30.7	35.9	55.2	36.4
Dissolved Solids	426	225	258	540	361
Suspended Solids	8.79	4.96	5.43	18.5	12.4
BOD	1.74	0.90	1.05	2.49	1.66
COD	2.58	1.35	1.56	8.66	5.79
Phenol/Phenolic Compounds	0.0042	0.0022	0.0025	0.0058	0.0038
Sulfur	0.023	0.012	0.014	0.032	0.021
Sulfates	0.90	0.50	0.55	1.21	0.78
Sulfides	1.2E-04	9.4E-05	7.5E-05	0.0010	6.8E-04
Oil	0.17	0.092	0.10	0.43	0.29
Hydrocarbons	8.5E-04	4.6E-04	5.2E-04	8.9E-04	5.9E-04
Ammonia	0.064	0.035	0.040	0.070	0.046
Ammonium	1.7E-04	1.1E-04	0.0051	2.0E-04	1.2E-04
Aluminum	0.26	0.15	0.16	0.53	0.35
Antimony	1.6E-04	8.9E-05	9.7E-05	3.2E-04	2.2E-04
Arsenic	0.0020	0.0010	0.0012	0.0029	0.0019
Barium	3.70	2.08	2.29	7.42	4.97
Beryllium	9.3E-05	5.0E-05	5.7E-05	1.4E-04	9.6E-05
Cadmium	2.9E-04	1.5E-04	1.8E-04	4.3E-04	2.9E-04
Chromium (unspecified)	0.0073	0.0041	0.0045	0.015	0.0099
Chromium (hexavalent)	9.6E-06	5.3E-06	5.8E-06	3.4E-05	2.2E-05
Cobalt	1.9E-04	1.0E-04	1.1E-04	2.7E-04	1.8E-04
Copper	0.0015	8.1E-04	9.0E-04	0.0024	0.0016
Iron	0.67	0.37	0.41	1.22	0.82
Lead	0.0031	0.0017	0.0019	0.0050	0.0033
Lead 210	4.5E-13	2.3E-13	2.7E-13	7.9E-13	5.3E-13
Lithium	7.72	3.95	4.64	8.45	5.62
Magnesium	5.37	2.85	3.26	7.60	5.07
Manganese	0.012	0.0070	0.0077	0.017	0.011
Mercury	3.1E-06	1.7E-06	1.9E-06	5.8E-06	3.9E-06
Molybdenum	2.0E-04	1.0E-04	1.2E-04	2.8E-04	1.9E-04
Nickel	0.0016	8.8E-04	0.0010	0.0025	0.0017
Selenium	8.8E-05	5.4E-05	5.6E-05	1.3E-04	8.3E-05
Silver	0.018	0.0095	0.011	0.025	0.017
Sodium	87.1	46.2	52.9	123	82.3
Strontium	0.47	0.25	0.28	0.66	0.44
Thallium	3.3E-05	1.9E-05	2.0E-05	6.9E-05	4.6E-05
Tin	0.0011	5.9E-04	6.7E-04	0.0018	0.0012
Titanium	0.0024	0.0014	0.0015	0.0050	0.0033
Vanadium	2.3E-04	1.2E-04	1.4E-04	3.3E-04	2.2E-04
Yttrium	5.8E-05	3.0E-05	3.5E-05	8.1E-05	5.4E-05
Zinc	0.0067	0.0038	0.0041	0.013	0.0086
Chlorides (unspecified)	309	164	188	437	292
Chlorides (methyl chloride)	3.4E-07	1.8E-07	2.1E-07	4.9E-07	3.2E-07
Vinyl Chloride	0.0019	9.3E-04	0.0011	0	0
Calcium	27.5	14.6	16.7	38.9	25.9
Fluorine/Fluorides	0.0038	0.0028	0.0028	0.0048	0.0031
Nitrates	0.019	0.0096	0.011	0.016	0.010
Nitrogen (ammonia)	0.062	0.032	0.037	0.28	0.19
Bromide	1.83	0.97	1.11	2.59	1.73
Boron	0.027	0.014	0.016	0.038	0.025
OrganicCarbon	0.020	0.010	0.012	0.018	0.012
Aldehydes (unspecified)	2.2E-05	2.2E-05	2.2E-05	2.9E-05	4.7E-05

Table 3-14
WATERBORNE EMISSIONS FOR 1000 FEET OF 4" DWV PIPE
(page 2 of 2)

Pounds/1000 ft of Pipe	PVC Solid	PVC Solid 50% PCR	PVC Cell Core	ABS Solid	ABS Cell Core
Other Organics	0	0	0.0029	0	0
Cyanide	1.1E-05	9.4E-06	9.0E-06	4.9E-06	8.2E-07
Hardness	84.5	44.7	51.3	120	79.9
Total Alkalinity	0.68	0.36	0.42	0.97	0.65
Surfactants	0.0083	0.0044	0.0050	0.011	0.0076
Acetone	8.5E-05	4.5E-05	5.2E-05	1.2E-04	8.1E-05
Isopropyl alcohol	7.5E-05	7.5E-05	4.1E-05	0	0
Methanol	3.4E-05	3.4E-05	4.6E-05	4.8E-05	3.8E-05
Process solvents	0	0	0.0015	0	0
Alkylated Benzenes	1.4E-04	7.8E-05	8.5E-05	2.8E-04	1.9E-04
Alkylated Fluorenes	7.9E-06	4.5E-06	4.9E-06	1.7E-05	1.1E-05
Alkylated Naphthalenes	2.2E-06	1.3E-06	1.4E-06	4.7E-06	3.1E-06
Alkylated Phenanthrenes	9.3E-07	5.3E-07	5.8E-07	1.9E-06	1.3E-06
Benzene	0.014	0.0076	0.0087	0.020	0.014
Cresols	5.0E-04	2.7E-04	3.1E-04	7.2E-04	4.8E-04
Cymene	8.5E-07	4.5E-07	5.2E-07	1.2E-06	8.1E-07
Dibenzofuran	1.6E-06	8.6E-07	9.9E-07	2.3E-06	1.5E-06
Dibenzothiophene	1.3E-06	7.0E-07	8.0E-07	1.9E-06	1.2E-06
2,4 dimethylphenol	2.4E-04	1.3E-04	1.5E-04	3.4E-04	2.3E-04
Ethylbenzene	8.1E-04	4.3E-04	4.9E-04	0.0022	0.0014
Styrene	8.5E-08	4.3E-08	5.0E-08	0.0010	6.8E-04
2-Hexanone	5.6E-05	3.0E-05	3.4E-05	7.9E-05	5.3E-05
Methyl ethyl Ketone (MEK)	6.9E-07	3.6E-07	4.2E-07	9.7E-07	6.5E-07
1-methylfluorene	9.7E-07	5.1E-07	5.9E-07	1.4E-06	9.2E-07
2-methyl naphthalene	1.4E-04	7.2E-05	8.2E-05	1.9E-04	1.3E-04
4-methyl- 2-pentanone	3.6E-05	1.9E-05	2.2E-05	5.1E-05	3.4E-05
Naphthalene	1.6E-04	8.2E-05	9.4E-05	2.2E-04	1.5E-04
Pentamethylbenzene	6.4E-07	3.4E-07	3.9E-07	9.1E-07	6.1E-07
Phenanthrene	1.3E-06	7.1E-07	8.0E-07	2.2E-06	1.5E-06
Toluene	0.014	0.0072	0.0083	0.019	0.013
Total Biphenyls	8.9E-06	5.0E-06	5.5E-06	1.8E-05	1.2E-05
Total dibenzothiophenes	2.7E-08	1.6E-08	1.7E-08	5.7E-08	3.8E-08
Xylenes	0.0081	0.0043	0.0049	0.010	0.0069
Phosphates	8.4E-04	8.4E-04	8.2E-04	0.016	0.011
Phosphorus	2.5E-07	2.5E-07	2.5E-07	0	0
Nitrogen	4.8E-04	4.8E-04	3.6E-04	0	0
Other Chem.	6.7E-10	6.7E-10	3.7E-10	0	0
Herbicides	1.8E-06	1.8E-06	1.0E-06	0	0
n-Decane	1.3E-04	6.5E-05	7.5E-05	2.2E-04	1.5E-04
n-Docosane	4.6E-06	2.4E-06	2.8E-06	8.2E-06	5.5E-06
n-Dodecane	2.4E-04	1.2E-04	1.4E-04	4.2E-04	2.8E-04
n-Eicosane	6.6E-05	3.4E-05	3.9E-05	1.2E-04	7.8E-05
n-Hexacosane	2.9E-06	1.5E-06	1.7E-06	5.1E-06	3.4E-06
n-Hexadecane	2.6E-04	1.3E-04	1.6E-04	4.6E-04	3.1E-04
n-Octadecane	6.5E-05	3.3E-05	3.9E-05	1.1E-04	7.6E-05
n-Tetradecane	1.1E-04	5.4E-05	6.3E-05	1.9E-04	1.2E-04
CFC-11	2.5E-07	2.5E-07	2.5E-07	0	0
CFCs	0	0	2.1E-04	0	0
HCFC/HFCs	0	0	3.7E-04	0	0
Dioxins	2.6E-04	2.6E-04	1.4E-04	0	0
Furans	0	0	5.0E-05	0	0
Radium 226	1.6E-10	8.1E-11	9.3E-11	2.8E-10	1.9E-10
Radium 228	8.0E-13	4.1E-13	4.8E-13	1.4E-12	9.5E-13
Radionuclides (unspecified)	2.9E-07	1.9E-07	1.9E-07	3.5E-07	2.0E-07

Table 3-15
WATERBORNE EMISSIONS FOR 1000 FEET OF 1" WATER SUPPLY PIPE
(page 1 of 2)

Pounds/1000 ft of Pipe	**PVC**	**PE**	**Copper K**	**Copper L**
Acid (unspecified)	8.0E-04	2.7E-04	0.0020	0.0016
Acid (benzoic)	0.0014	0.0010	0.0016	0.0012
Acid (hexanoic)	2.8E-04	2.1E-04	3.2E-04	2.5E-04
Metal (unspecified)	9.32	3.43	20.1	15.7
Dissolved Solids	67.1	43.6	87.4	68.3
Suspended Solids	1.39	1.03	1.56	1.22
BOD	0.27	0.17	0.23	0.18
COD	0.41	0.29	0.39	0.30
Phenol/Phenolic Compounds	6.6E-04	5.8E-04	7.1E-04	5.5E-04
Sulfur	0.0036	0.0026	0.0041	0.0032
Sulfates	0.14	0.091	0.17	0.13
Sulfides	2.0E-05	1.2E-05	1.2E-05	9.7E-06
Oil	0.027	0.020	0.12	0.097
Hydrocarbons	1.3E-04	2.0E-04	3.1E-04	2.4E-04
Ammonia	0.010	0.0039	0.024	0.019
Ammonium	0.0014	1.2E-05	3.3E-05	2.6E-05
Aluminum	0.041	0.032	0.046	0.036
Antimony	2.5E-05	1.9E-05	2.8E-05	2.2E-05
Arsenic	3.1E-04	2.3E-04	3.5E-04	2.8E-04
Barium	0.58	0.46	0.67	0.52
Beryllium	1.5E-05	1.1E-05	1.7E-05	1.3E-05
Cadmium	4.6E-05	3.3E-05	5.2E-05	4.1E-05
Chromium (unspecified)	0.0012	8.9E-04	0.0013	0.0010
Chromium (hexavalent)	1.5E-06	2.0E-06	0	0
Cobalt	3.0E-05	2.2E-05	3.4E-05	2.7E-05
Copper	2.4E-04	1.7E-04	2.6E-04	2.1E-04
Iron	0.11	0.080	0.12	0.095
Lead	4.9E-04	3.6E-04	5.6E-04	4.4E-04
Lead 210	7.1E-14	7.5E-14	2.5E-16	1.9E-16
Lithium	1.22	0.85	1.39	1.09
Magnesium	0.85	0.61	0.97	0.76
Manganese	0.0020	0.0012	0.0028	0.0022
Mercury	4.8E-07	3.4E-07	5.1E-07	4.0E-07
Molybdenum	3.1E-05	2.2E-05	3.5E-05	2.8E-05
Nickel	2.6E-04	1.9E-04	2.9E-04	2.3E-04
Selenium	1.5E-05	7.9E-06	1.7E-05	1.3E-05
Silver	0.0028	0.0020	0.0032	0.0025
Sodium	13.7	9.96	15.7	12.3
Strontium	0.073	0.053	0.084	0.066
Thallium	5.2E-06	4.1E-06	6.0E-06	4.7E-06
Tin	1.7E-04	1.3E-04	2.0E-04	1.5E-04
Titanium	3.8E-04	3.0E-04	4.3E-04	3.4E-04
Vanadium	3.7E-05	2.7E-05	4.2E-05	3.3E-05
Yttrium	9.1E-06	6.6E-06	1.0E-05	8.1E-06
Zinc	0.0011	8.5E-04	0.0012	9.1E-04
Chlorides (unspecified)	48.7	35.3	55.6	43.5
Chlorides (methyl chloride)	5.4E-08	3.9E-08	6.2E-08	4.8E-08
Vinyl Chloride	2.9E-04	0	0	0
Calcium	4.33	3.14	4.95	3.87
Fluorine/Fluorides	7.2E-04	1.9E-04	0.0012	0.0011
Nitrates	0.0030	2.9E-05	8.3E-05	6.5E-05
Nitrogen (ammonia)	0.0097	0.010	7.1E-05	5.5E-05
Bromide	0.29	0.21	0.33	0.26
Boron	0.0042	0.0031	0.0048	0.0038
OrganicCarbon	0.0032	0.0013	0.0065	0.0051
Aldehydes (unspecified)	6.0E-06	0	1.2E-05	1.2E-05

Table 3-15
WATERBORNE EMISSIONS FOR 1000 FEET OF 1" WATER SUPPLY PIPE
(page 2 of 2)

Pounds/1000 ft of Pipe	**PVC**	**PE**	**Copper K**	**Copper L**
Other Organics	7.6E-04	0	0	0
Cyanide	8.5E-07	1.6E-06	1.1E-07	8.7E-08
Hardness	13.3	9.68	15.2	11.9
Total Alkalinity	0.11	0.078	0.12	0.097
Surfactants	0.0013	9.4E-04	0.0015	0.0012
Acetone	1.3E-05	6.6E-05	1.5E-05	1.2E-05
Isopropyl alcohol	1.2E-05	5.6E-05	0	0
Methanol	1.1E-05	0	2.0E-05	2.0E-05
Process solvents	3.9E-04	1.6E-05	0	0
Alkylated Benzenes	2.2E-05	1.7E-05	2.5E-05	1.9E-05
Alkylated Fluorenes	1.3E-06	9.8E-07	1.4E-06	1.1E-06
Alkylated Naphthalenes	3.5E-07	2.8E-07	4.1E-07	3.2E-07
Alkylated Phenanthrenes	1.5E-07	1.2E-07	1.7E-07	1.3E-07
Benzene	0.0023	0.0017	0.0026	0.0020
Cresols	7.9E-05	5.8E-05	9.0E-05	7.0E-05
Cymene	1.3E-07	9.8E-08	1.5E-07	1.2E-07
Dibenzofuran	2.6E-07	1.9E-07	2.9E-07	2.3E-07
Dibenzothiophene	2.1E-07	1.5E-07	2.4E-07	1.9E-07
2,4 dimethylphenol	3.8E-05	2.7E-05	4.3E-05	3.4E-05
Ethylbenzene	1.3E-04	1.5E-04	1.5E-04	1.1E-04
Styrene	1.3E-08	5.6E-05	0	0
2-Hexanone	8.8E-06	6.4E-06	1.0E-05	7.9E-06
Methyl ethyl Ketone (MEK)	1.1E-07	7.9E-08	1.2E-07	9.7E-08
1-methylfluorene	1.5E-07	1.1E-07	1.8E-07	1.4E-07
2-methyl naphthalene	2.1E-05	1.5E-05	2.4E-05	1.9E-05
4-methyl- 2-pentanone	5.7E-06	4.1E-06	6.5E-06	5.1E-06
Naphthalene	2.4E-05	7.4E-05	2.8E-05	2.2E-05
Pentamethylbenzene	1.0E-07	7.3E-08	1.2E-07	9.0E-08
Phenanthrene	2.1E-07	1.5E-07	2.4E-07	1.8E-07
Toluene	0.0021	0.0016	0.0024	0.0019
Total Biphenyls	1.4E-06	1.1E-06	1.6E-06	1.3E-06
Total dibenzothiophenes	4.3E-09	3.4E-09	4.9E-09	3.9E-09
Xylenes	0.0013	8.9E-04	0.0013	0.0010
Phosphates	2.0E-04	0	4.9E-04	4.9E-04
Phosphorus	3.9E-08	7.2E-05	0	0
Nitrogen	1.1E-04	0	0	0
Other Chem.	1.1E-10	0	0	0
Herbicides	3.0E-07	0	0	0
n-Decane	2.0E-05	2.1E-05	7.0E-08	5.5E-08
n-Docosane	7.3E-07	7.7E-07	2.6E-09	2.0E-09
n-Dodecane	3.8E-05	4.0E-05	1.3E-07	1.0E-07
n-Eicosane	1.0E-05	1.1E-05	3.7E-08	2.9E-08
n-Hexacosane	4.5E-07	4.8E-07	1.6E-09	1.3E-09
n-Hexadecane	4.1E-05	4.4E-05	1.5E-07	1.1E-07
n-Octadecane	1.0E-05	1.1E-05	3.6E-08	2.8E-08
n-Tetradecane	1.6E-05	1.8E-05	5.8E-08	4.6E-08
CFC-11	3.9E-08	0	0	0
CFCs	5.5E-05	5.6E-05	0	0
HCFC/HFCs	9.5E-05	0	0	0
Dioxins	4.3E-05	0	0	0
Furans	1.3E-05	9.8E-07	0	0
Radium 226	2.5E-11	2.6E-11	8.7E-14	6.8E-14
Radium 228	1.3E-13	1.3E-13	4.5E-16	3.5E-16
Radionuclides (unspecified)	4.9E-08	2.1E-08	5.9E-08	4.6E-08

Table 3-16
WATERBORNE EMISSIONS FOR 1000 FEET OF 3/4" HCWD PIPE
(page 1 of 2)

Pounds/1000 ft of Pipe	**CPVC**	**PEX**	**Copper K**	**Copper L**	**Copper M**
Acid (unspecified)	3.7E-04	2.3E-04	0.0016	0.0011	8.0E-04
Acid (benzoic)	5.9E-04	8.5E-04	0.0012	8.5E-04	6.1E-04
Acid (hexanoic)	1.2E-04	1.8E-04	2.5E-04	1.8E-04	1.3E-04
Metal (unspecified)	4.68	2.95	15.4	10.9	7.89
Dissolved Solids	29.2	37.2	66.9	47.5	34.3
Suspended Solids	0.62	0.99	1.19	0.85	0.61
BOD	0.12	0.13	0.18	0.13	0.092
COD	0.17	0.23	0.30	0.21	0.15
Phenol/Phenolic Compounds	7.8E-04	6.4E-04	5.4E-04	3.8E-04	2.8E-04
Sulfur	0.0015	0.0022	0.0031	0.0022	0.0016
Sulfates	0.077	0.087	0.13	0.091	0.066
Sulfides	1.1E-05	1.3E-05	9.5E-06	6.8E-06	4.9E-06
Oil	0.012	0.018	0.095	0.067	0.049
Hydrocarbons	7.2E-05	1.8E-04	2.4E-04	1.7E-04	1.2E-04
Ammonia	0.0056	0.0045	0.018	0.013	0.0094
Ammonium	4.3E-04	1.6E-05	2.5E-05	1.8E-05	1.3E-05
Aluminum	0.019	0.031	0.035	0.025	0.018
Antimony	1.1E-05	1.9E-05	2.2E-05	1.5E-05	1.1E-05
Arsenic	1.4E-04	2.0E-04	2.7E-04	1.9E-04	1.4E-04
Barium	0.26	0.44	0.51	0.36	0.26
Beryllium	6.4E-06	9.5E-06	1.3E-05	9.1E-06	6.6E-06
Cadmium	2.0E-05	2.9E-05	4.0E-05	2.8E-05	2.1E-05
Chromium (unspecified)	5.1E-04	8.6E-04	9.8E-04	7.0E-04	5.0E-04
Chromium (hexavalent)	4.5E-07	1.5E-06	0	0	0
Cobalt	1.3E-05	1.9E-05	2.6E-05	1.9E-05	1.3E-05
Copper	1.2E-04	1.5E-04	2.0E-04	1.4E-04	1.0E-04
Iron	0.048	0.075	0.093	0.066	0.048
Lead	2.1E-04	3.2E-04	4.3E-04	3.0E-04	2.2E-04
Lead 210	2.3E-14	5.7E-14	1.9E-16	1.4E-16	9.7E-17
Lithium	0.52	0.67	1.06	0.76	0.55
Magnesium	0.37	0.52	0.74	0.53	0.38
Manganese	0.0011	0.0012	0.0021	0.0015	0.0011
Mercury	2.4E-07	3.4E-07	3.9E-07	2.8E-07	2.0E-07
Molybdenum	1.3E-05	1.9E-05	2.7E-05	1.9E-05	1.4E-05
Nickel	1.1E-04	1.7E-04	2.2E-04	1.6E-04	1.2E-04
Selenium	9.6E-06	9.3E-06	1.3E-05	9.4E-06	6.8E-06
Silver	0.0012	0.0018	0.0025	0.0018	0.0013
Sodium	5.95	8.51	12.0	8.53	6.16
Strontium	0.032	0.046	0.064	0.046	0.033
Thallium	2.3E-06	4.0E-06	4.6E-06	3.2E-06	2.4E-06
Tin	7.6E-05	1.2E-04	1.5E-04	1.1E-04	7.8E-05
Titanium	1.7E-04	2.9E-04	3.3E-04	2.4E-04	1.7E-04
Vanadium	1.6E-05	2.3E-05	3.2E-05	2.3E-05	1.6E-05
Yttrium	3.9E-06	5.6E-06	7.9E-06	5.6E-06	4.1E-06
Zinc	7.5E-04	8.8E-04	8.9E-04	6.3E-04	4.6E-04
Chlorides (unspecified)	21.1	30.2	42.6	30.2	21.8
Chlorides (methyl chloride)	2.3E-08	3.4E-08	4.7E-08	3.4E-08	2.4E-08
Vinyl Chloride	9.1E-05	0	0	0	0
Calcium	1.88	2.68	3.79	2.69	1.94
Fluorine/Fluorides	7.8E-04	2.6E-04	0.0011	9.5E-04	8.7E-04
Nitrates	9.6E-04	4.0E-05	6.3E-05	4.5E-05	3.3E-05
Nitrogen (ammonia)	0.0032	0.0078	5.4E-05	3.8E-05	2.8E-05
Bromide	0.12	0.18	0.25	0.18	0.13
Boron	0.0018	0.0026	0.0037	0.0026	0.0019
OrganicCarbon	0.0018	0.0012	0.0050	0.0036	0.0026
Aldehydes (unspecified)	7.8E-06	0	1.2E-05	1.2E-05	1.2E-05

Table 3-16
WATERBORNE EMISSIONS FOR 1000 FEET OF 3/4" HCWD PIPE
(page 2 of 2)

Pounds/1000 ft of Pipe	**CPVC**	**PEX**	**Copper K**	**Copper L**	**Copper M**
Other Organics	3.0E-04	0	0	0	0
Cyanide	7.6E-07	6.0E-08	8.5E-08	6.0E-08	4.4E-08
Hardness	5.77	8.27	11.7	8.29	5.99
Total Alkalinity	0.047	0.067	0.095	0.067	0.049
Surfactants	5.6E-04	8.0E-04	0.0011	8.1E-04	5.9E-04
Acetone	2.5E-04	1.3E-04	1.2E-05	8.4E-06	6.0E-06
Isopropyl alcohol	2.5E-04	1.2E-04	0	0	0
Methanol	1.5E-05	2.6E-06	2.0E-05	2.0E-05	2.0E-05
Process solvents	1.5E-04	1.2E-05	0	0	0
Alkylated Benzenes	9.7E-06	1.6E-05	1.9E-05	1.3E-05	9.8E-06
Alkylated Fluorenes	5.6E-07	9.6E-07	1.1E-06	7.8E-07	5.7E-07
Alkylated Naphthalenes	1.6E-07	2.7E-07	3.1E-07	2.2E-07	1.6E-07
Alkylated Phenanthrenes	6.6E-08	1.1E-07	1.3E-07	9.2E-08	6.6E-08
Benzene	0.0012	0.0015	0.0020	0.0014	0.0010
Cresols	3.4E-05	5.0E-05	6.9E-05	4.9E-05	3.5E-05
Cymene	5.8E-08	8.3E-08	1.2E-07	8.4E-08	6.0E-08
Dibenzofuran	1.1E-07	1.6E-07	2.2E-07	1.6E-07	1.1E-07
Dibenzothiophene	9.0E-08	1.3E-07	1.8E-07	1.3E-07	9.3E-08
2,4 dimethylphenol	1.6E-05	2.3E-05	3.3E-05	2.3E-05	1.7E-05
Ethylbenzene	3.0E-04	2.0E-04	1.1E-04	7.9E-05	5.7E-05
Styrene	2.5E-04	1.2E-04	0	0	0
2-Hexanone	3.8E-06	5.5E-06	7.7E-06	5.5E-06	3.9E-06
Methyl ethyl Ketone (MEK)	4.7E-08	6.7E-08	9.5E-08	6.7E-08	4.9E-08
1-methylfluorene	6.6E-08	9.5E-08	1.3E-07	9.5E-08	6.9E-08
2-methyl naphthalene	9.2E-06	1.3E-05	1.9E-05	1.3E-05	9.6E-06
4-methyl- 2-pentanone	2.4E-06	3.5E-06	5.0E-06	3.5E-06	2.5E-06
Naphthalene	2.6E-04	1.4E-04	2.1E-05	1.5E-05	1.1E-05
Pentamethylbenzene	4.4E-08	6.3E-08	8.8E-08	6.3E-08	4.5E-08
Phenanthrene	9.1E-08	1.4E-07	1.8E-07	1.3E-07	9.3E-08
Toluene	0.0012	0.0015	0.0019	0.0013	9.6E-04
Total Biphenyls	6.3E-07	1.1E-06	1.2E-06	8.7E-07	6.3E-07
Total dibenzothiophenes	1.9E-09	3.3E-09	3.8E-09	2.7E-09	1.9E-09
Xylenes	7.9E-04	8.3E-04	0.0010	7.1E-04	5.1E-04
Phosphates	3.2E-04	0	4.9E-04	4.9E-04	4.9E-04
Phosphorus	2.5E-04	1.3E-04	0	0	0
Nitrogen	0	0	0	0	0
Other Chem.	5.1E-11	0	0	0	0
Herbicides	1.4E-07	0	0	0	0
n-Decane	6.6E-06	1.6E-05	5.4E-08	3.8E-08	2.8E-08
n-Docosane	2.4E-07	5.9E-07	2.0E-09	1.4E-09	1.0E-09
n-Dodecane	1.2E-05	3.1E-05	1.0E-07	7.2E-08	5.2E-08
n-Eicosane	3.4E-06	8.4E-06	2.8E-08	2.0E-08	1.4E-08
n-Hexacosane	1.5E-07	3.7E-07	1.2E-09	8.7E-10	6.3E-10
n-Hexadecane	1.4E-05	3.3E-05	1.1E-07	7.9E-08	5.7E-08
n-Octadecane	3.4E-06	8.2E-06	2.8E-08	2.0E-08	1.4E-08
n-Tetradecane	5.5E-06	1.3E-05	4.5E-08	3.2E-08	2.3E-08
CFC-11	1.4E-07	0	0	0	0
CFCs	2.7E-04	1.2E-04	0	0	0
HCFC/HFCs	5.8E-05	0	0	0	0
Dioxins	2.0E-05	0	0	0	0
Furans	5.1E-06	1.2E-07	0	0	0
Radium 226	8.1E-12	2.0E-11	6.7E-14	4.7E-14	3.4E-14
Radium 228	4.2E-14	1.0E-13	3.4E-16	2.4E-16	1.7E-16
Radionuclides (unspecified)	3.8E-08	2.8E-08	4.5E-08	3.2E-08	2.3E-08

APPENDIX A
CONSIDERATIONS FOR INTERPRETATION OF DATA AND RESULTS

INTRODUCTION

An important issue with LCI results is whether two numbers are really different from one another. For example, if one product has a total system requirement of 100 energy units, is it really different from another product system that requires 110 energy units? If the error or variability in the data is sufficiently large, it cannot be concluded that the two numbers are actually different.

STATISTICAL CONSIDERATIONS

A statistical analysis that yields clear numerical answers would be ideal, but unfortunately LCI data are not amenable to this. The data are not (1) random samples from (2) large populations that result in (3) "normal curve" distributions. LCI data meet none of these requirements for statistical analysis. LCI data for a given sub-process (such as potato production, roundwood harvesting, or caustic soda manufacture, for example) are generally selected to be representative of a process or industry, and are typically calculated as an average of two to five data points. In statistical terminology, these are not random samples, but "judgment samples," selected so as to reduce the possible errors incurred by limited sampling or limited population sizes. Formal statistics cannot be applied to judgment samples; however, a hypothetical data framework can be constructed to help assess in a general sense the reliability of LCI results.

The first step in this assessment is reporting standard deviation values from LCI data, calculated by:

$$\mathrm{s} = \sqrt{\frac{\sum (x_1 - x_{mean})^2}{n-1}},$$

where x_i is a measured value in the data set and x_{mean} is the average of n values. An analysis of sub-process data from Franklin Associates, Ltd. files shows that, for a typical sub-process with two to five different companies supplying information, the standard deviation of the sample is about 30 percent of the sample average.

In a typical LCI study, the total energy of a product system consists of the sum of many sub-processes. For the moment, consider an example of adding only two numbers. If both numbers are independent of each other and are an average of measurements which have a sample standard deviation, s, of 30, the standard deviation of the sum is obtained by adding the variances of each term to form the sum of the variances, then taking the square root. Variances are calculated by squaring the standard deviation, s^2, so the sum of the variances is $30^2 + 30^2 = 900 + 900 = 1800$. The new standard deviation of the sum is the square root of the sum of the variances, or $\sqrt{1800} = 42.4$. In this example, suppose both average values are 100, with a sum of 200. If reported as a percent of the sum, the new standard deviation is 42.4/200 = 21.3% of the sum. Another way of obtaining this value is to use the formula $s_{\%} = \frac{s/x_{mean}}{\sqrt{n}}$, where the term $s_{\%}$ is defined as the standard deviation of n data points, expressed as a % of the average, where each entry has approximately the same standard deviation, s. For the example, then, $s_{\%} = \frac{30\%}{\sqrt{2}} = 21.3\%$.

Going back to a hypothetical LCI example, consider a common product system consisting of a sum of approximately 40 subsystems. First, a special hypothetical case is examined where *all of the values are approximately the same size, and all have a standard deviation of 30%*. The standard deviation in the result is $s_{\%} = \frac{30\%}{\sqrt{40}} = 4.7\%$. The act of summing reduces the standard deviation of the result with respect to the standard deviation of each entry because of the assumption that errors are randomly distributed, and by combining values there is some cancellation of total error because some data values in each component system are higher than the true values and some are lower.

The point of this analysis, however, is to compare two results, e.g., the energy totals for two different product systems, and decide if the difference between them is significant or not. To test a hypothetical data set it will be assumed that two product systems consist of a sum of 40 values, and that the standard deviation, $s_{\%}$, is 4.7% for each product system.

If there is statistical knowledge of the sample only, and not of the populations from which they were drawn, “t” statistics can be used to find if the two product totals are different or not. The expression selected is:
$\mu 1 - \mu 2 = x1 - x2 +/- t_{.025}\, s' \sqrt{\frac{1}{n1} + \frac{1}{n2}}$, where $\mu 1 - \mu 2$. is the difference in population means, x_1-x_2 is the difference in sample means, and s' is a pooled standard deviation of the two samples. For the hypothetical case, where it is assumed that the standard deviation of the two samples is the same, the pooled value is simply replaced with the standard deviation of the samples.

The goal is to find an expression that compares our sample means to “true,” or population, means. A new quantity is defined:
$\Delta = (\mu 1 - \mu 2) - (x1 - x2)$, and the sample sizes are assumed to be the same (i.e., n_1=n_2). The result is $\Delta = t_{.025} s' \sqrt{\frac{2}{n}}$, where Δ is the minimum difference corresponding to a 95% confidence level, s' is the standard deviation of the sum of n values, and $t_{.025}$ is a t

statistic for 95% confidence levels. The values for t are a function of n and are found in tables. This expression can be converted to percent notation by dividing both sides by the average of the sample means, which results in $\Delta\% = t_{.025} s'\% \sqrt{\frac{2}{n}}$, where $\Delta\%$ is now the percent difference corresponding to a 95% confidence level, and s'% is the standard deviation expressed as a percent of the average of the sample means. This formula can be simplified for the example calculation by remembering that $s'\% = \frac{s\%}{\sqrt{n}}$, where s% is the standard deviation of each energy entry for a product system. Now the equation becomes $\Delta\% = t_{.025} s\% \frac{\sqrt{2}}{n}$. For the example, t = 2.0, s = 30%, and n = 40, so that $\Delta\%$ = 2.1%. This means that if the two product system energy totals differ by more than 2.1%, there is a 95% confidence level that the difference is significant. That is, if 100 independent studies were conducted (in which new data samples were drawn from the same population and the study was conducted in the identical manner), then 95 of these studies would find the energy values for the two product systems to differ by more than 2.1%.

The previous discussion applies only to a hypothetical and highly idealized framework to which statistical mathematics apply. LCI data differ from this in some important ways. One is that the 40 or so numbers that are added together for a final energy value of a product system are of widely varying size and have different variances. The importance of this is that large numbers contribute more to the total variance of the result. For example, if 20 energy units and 2,000 energy units are added, the sum is 2,020 energy units. If the standard deviation of the smaller value is 30% (or 6 units), the variance is 6^2 = 36. If the standard deviation of the larger number is 10% (or 200), the variance is 200^2 = 40,000. The total variance of the sum is 36 + 40,000 = 40,036, leading to a standard deviation in the sum of $\frac{\sqrt{(40036)}}{2020}$ = 9.9%. Clearly, the variance in the result is much more greatly influenced by larger numbers. In a set of LCI energy data, standard deviations may range from 10% to 60%. If a large number has a large percentage standard deviation, then the sum will also be more uncertain. If the variance of the large number is small, the answer will be more certain. To offset the potential problem of a large variance, Franklin Associates goes to great lengths to increase the reliability of the larger numbers, but there may simply be inherent variability in some numbers which is beyond the researchers' control.

If only a few numbers contribute most of the total energy in a system, the value of $\Delta\%$ goes up. This can be illustrated by going back to the formula for $\Delta\%$ and calculating examples for n = 5 and 10. From statistical tables, the values for $t_{.025}$ are 2.78 for n = 5, and 2.26 for n = 10. Referring back to the hypothetical two-product data set with s% = 30% *for each entry*, the corresponding values for $\Delta\%$ are 24% for n = 5 and 9.6% for n = 10. Thus, if only 5 numbers out of 40 contribute most of the energy, the percent *difference* in the two product system energy values must increase to 24% to achieve the 95% confidence level that the two values are different. The minimum difference decreases to 9.6% if there are 10 major contributors out of the 40 energy numbers in a product system.

CONCLUSIONS

The discussion above highlights the importance of sample size, and of the variability of the sample. However, once again it must be emphasized that the statistical analysis does not apply to LCI data. It only serves to illustrate the important issues. Valid standard deviations cannot be calculated because of the failure of the data to meet the required statistical formula assumptions. Nevertheless, it is important to achieve a maximum sample size with minimum variability in the data. Franklin Associates examines the data, identifies the large values contributing to a sum, then conducts more intensive analysis of those values. This has the effect of increasing the number of data points, and therefore decreasing the "standard deviation." Even though a calculated standard deviation of 30% may be typical for Franklin Associates' LCI data, the actual confidence level is much higher for the large values that control the variability of the data than for the small values. However, none of this can be quantified to the satisfaction of a statistician who draws conclusions based upon random sampling. In the case of LCI data, it comes down to a matter of professional judgment and experience. The increase in confidence level resulting from judgment and experience is not measurable.

It is the professional judgment of Franklin Associates, based upon over 25 years of experience in analyzing LCI data, that a 10% rule is a reasonable value for $\Delta\%$ for stating results of product system energy totals. That is, if the energy of one system is 10% different from another, it can be concluded that the difference is significant. It is clear that this convention is a matter of judgment. This is not claimed to be a highly accurate statement; however, the statistical arguments with hypothetical, but similar, data lend plausibility to this convention.

We also conclude that the weight of postconsumer solid waste data can be analyzed in a similar way. These data are at least as accurate as the energy data, perhaps with even less uncertainty in the results. Therefore, the 10% rule applies to postconsumer solid waste weight. However, we apply a 25% rule to the solid waste volume data because of greater potential variability in the volume conversion factors.

Air and water pollution and industrial solid waste data are not included in the 10% rule. Their variability is much higher. Data reported by similar plants may differ by a factor of two, or even a factor of ten or higher in some cases. Standard deviations may be as high as 150%, although 75% is typical. This translates to a hypothetical standard deviation in a final result of 12%, or a difference of at least 25% being required for a 95% confidence of two totals being different if 10 subsystems are major contributors to the final results. However, this rule applies only to single emission categories, and cannot be extended to general statements about environmental emissions resulting from a single product system. The interpretation of environmental emission data is further complicated by the fact that not all plants report the same emission categories, and that there is not an accepted method of evaluating the relative importance of various emissions.

It is the intent of this appendix to convey an explanation of Franklin Associates' 10% and 25% rules and establish their plausibility. **Franklin Associates' policy is to consider product system totals for energy and weight of postconsumer solid waste weight to be different if there is at least a 10% difference in the totals. Otherwise, the difference is considered to be insignificant. In the detailed tables of this report there are many specific pollutant categories that are variable between systems. For the air and waterborne emissions, industrial solid waste, and postconsumer solid waste volume, the 25% rule should be applied.** The formula used to calculate the difference between two systems is:

$$\% \text{ Diff} = \left(\frac{x-y}{\frac{x+y}{2}} \right) \text{ X } 100,$$

where x and y are the summed totals of energy or waste for two product systems. The denominator of this expression is the average of the two values.