# Chapter 2

## LIFE-CYCLE INVENTORY

A LCI is the identification and quantification of the material, resource, emission, waste, and product flows from the unit processes in the life-cycle of a product system (Figure 2-1). For the DfE LFSP, LCI inputs (a.k.a. resource flows) include materials used in the solders themselves, ancillary materials used in processing and manufacturing of the solders, and energy and other resources consumed in the manufacturing, use (application), or final disposition of the solders. LCI process output flows include primary and co-products, as well as releases to air, water, and land. A conceptual model of the specific unit processes for solders was represented previously by the boxes in Figure 1-3. Each unit process has flows particular to that process. Figures 2-2 through 2-5 show each unit process for the life-cycles of the paste solders, and Figures 2-6 through 2-8 show those for the bar solders. The figures graphically display how processes in the product life-cycle are linked to one another and what processes are evaluated within the scope of this LCA.

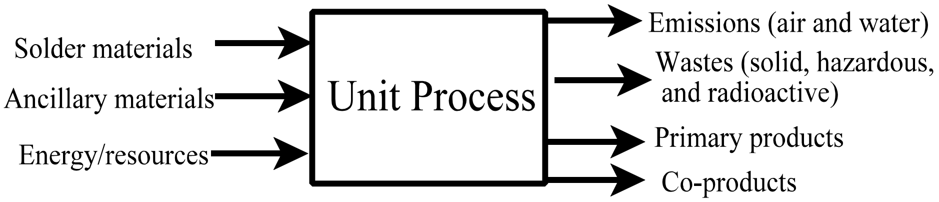


**Figure 2-1. Unit process inventory conceptual diagram**

Chapter 2 describes the approach taken for collecting and evaluating LCI data in the LFSP and summarizes the LCI results. Section 2.1 describes the general methodology for LCI data collection. Sections 2.2 through 2.5 present the specific methodologies, data sources, data quality, limitations and uncertainties for each life-cycle stage. Section 2.6 summarizes the baseline LCI data results for the paste and bar solder categories.

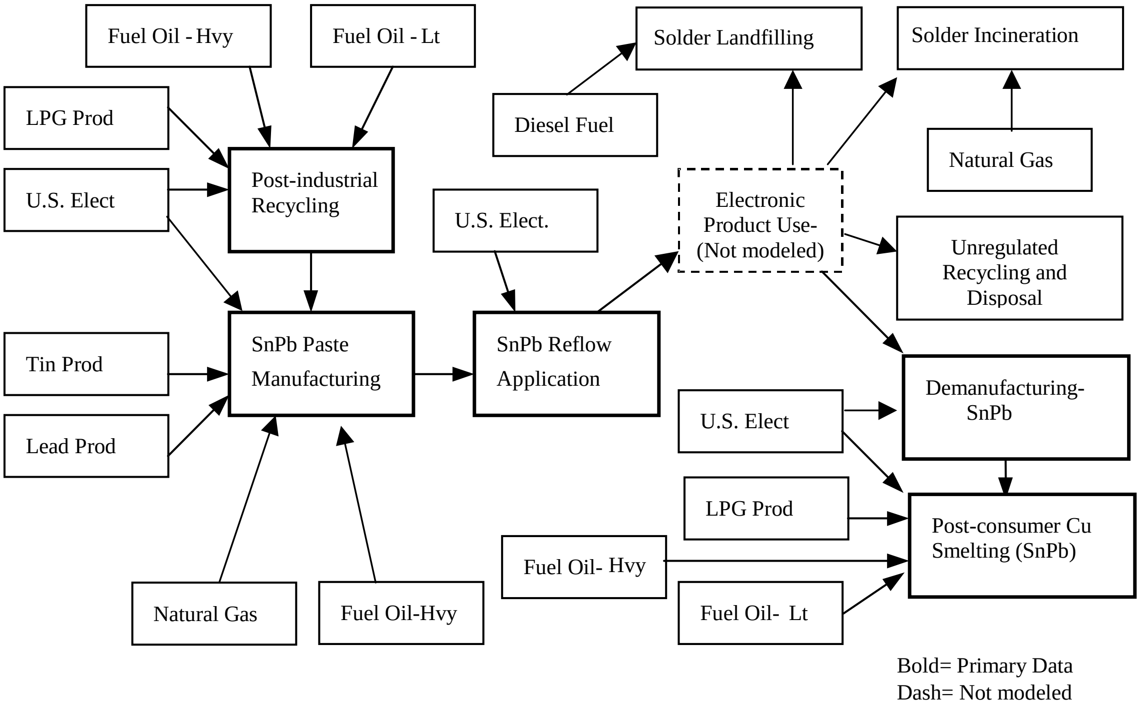


**Figure 2-2. SnPb Paste Solder Life-Cycle Processes**

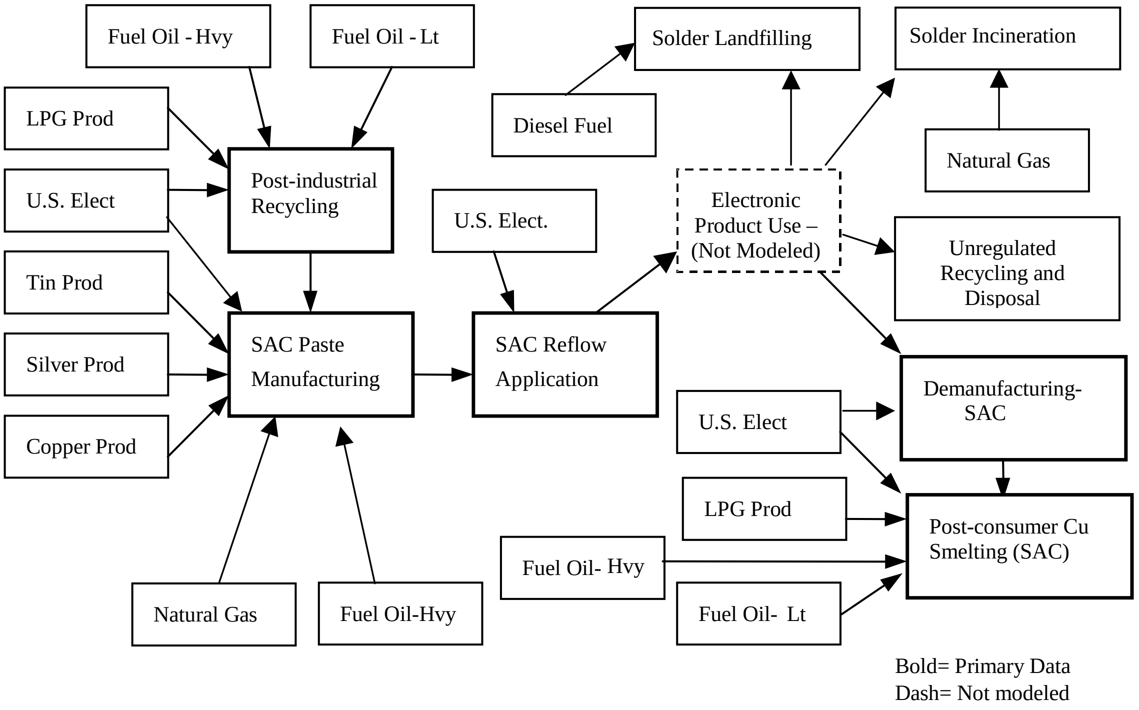
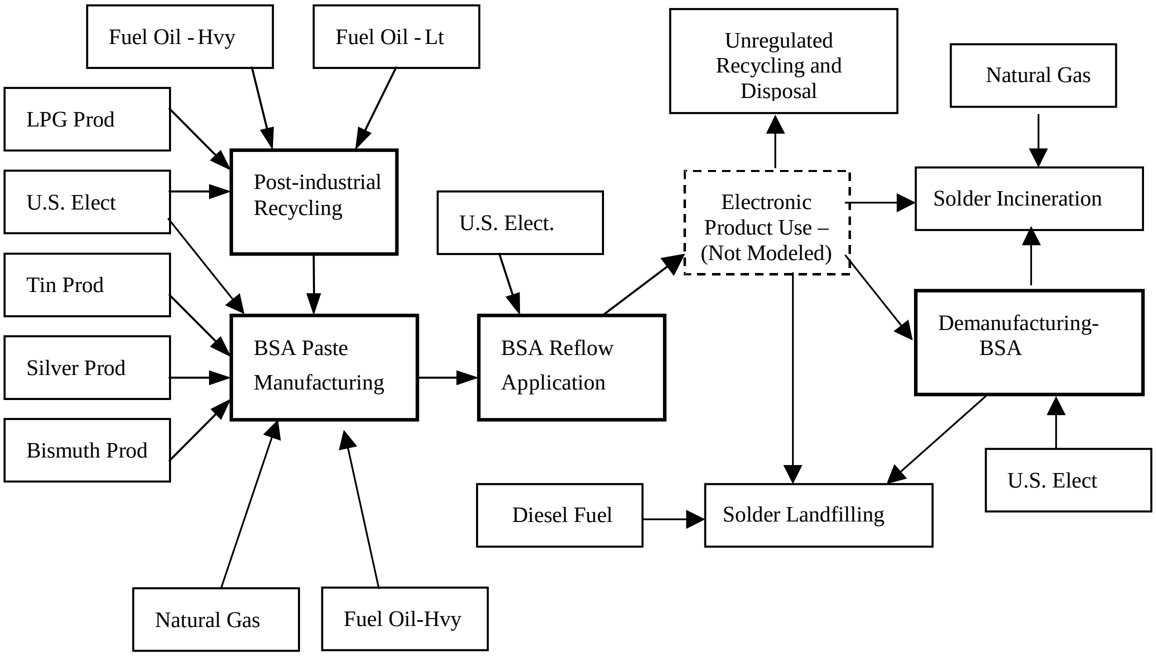
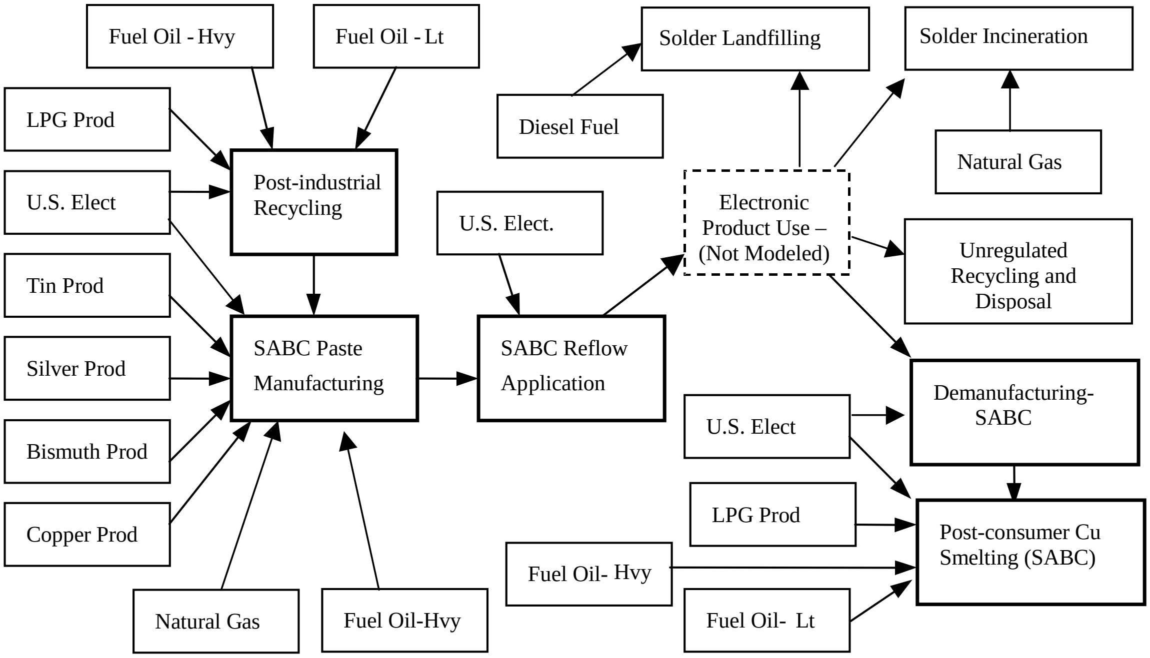


**Figure 2-3. SAC Paste Solder Life-Cycle Processes**



Bold= Primary Data
Dash= Not modeled

**Figure 2-4. BSA Paste Solder Life-Cycle Processes**



Bold= Primary Data
Dash= Not modeled

**Figure 2-5. SABC Paste Solder Life-Cycle Processes**

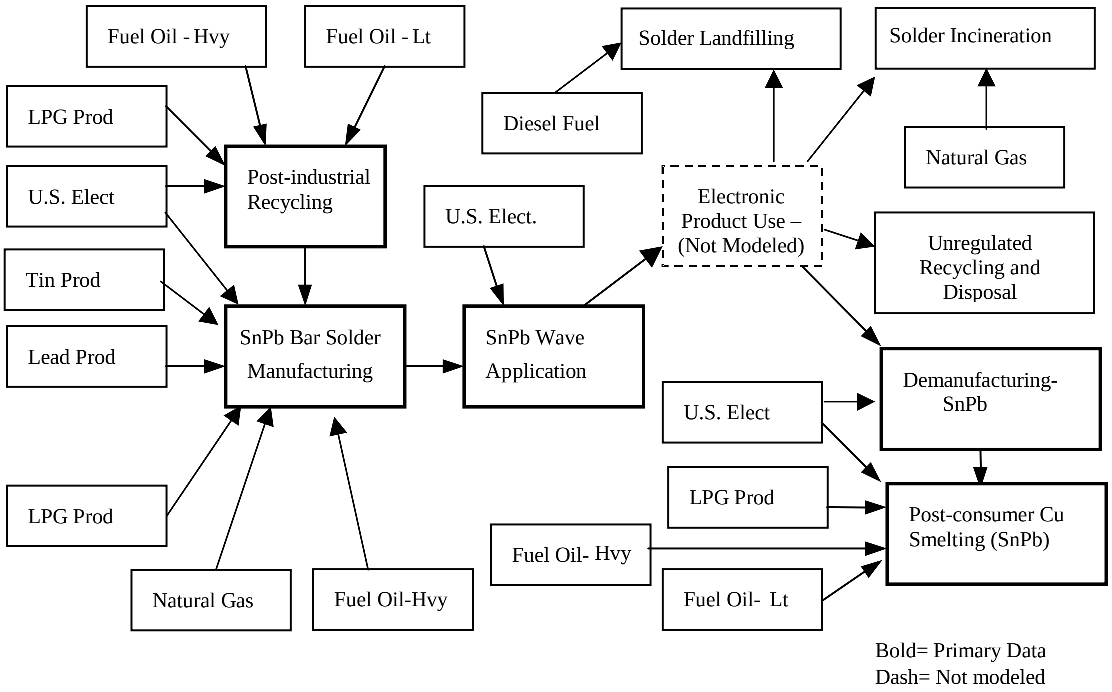


Figure 2-6. SnPb Bar Solder Life-Cycle Processes

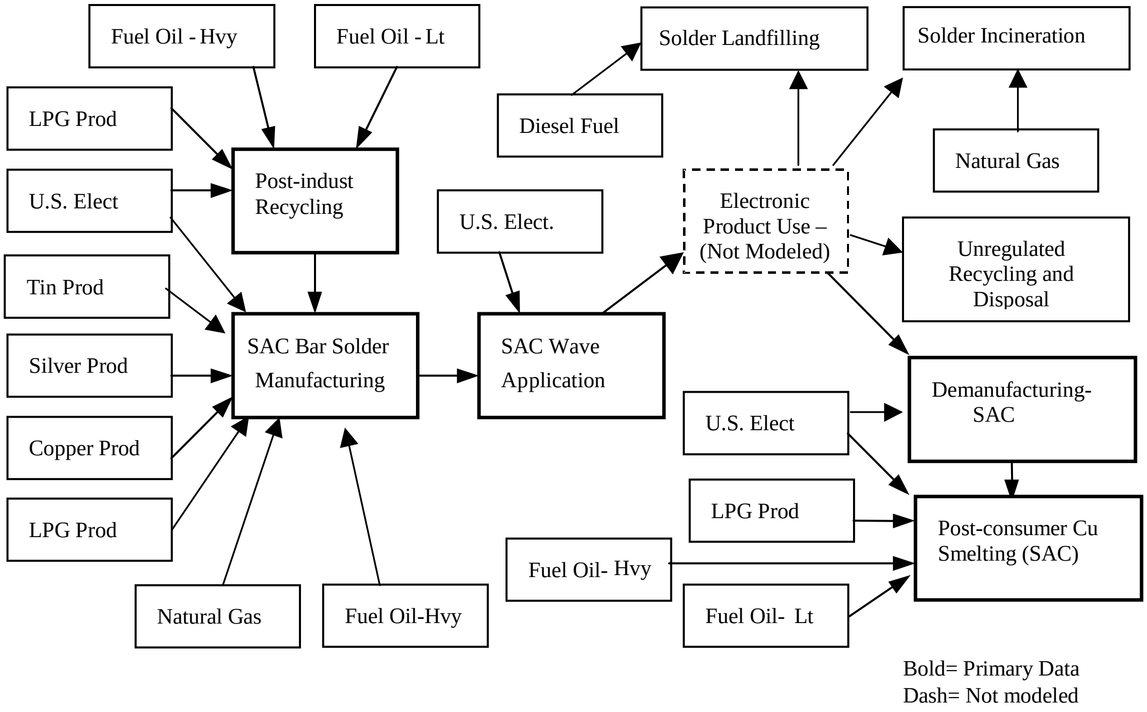


Figure 2-7. SAC Bar Solder Life-Cycle Processes

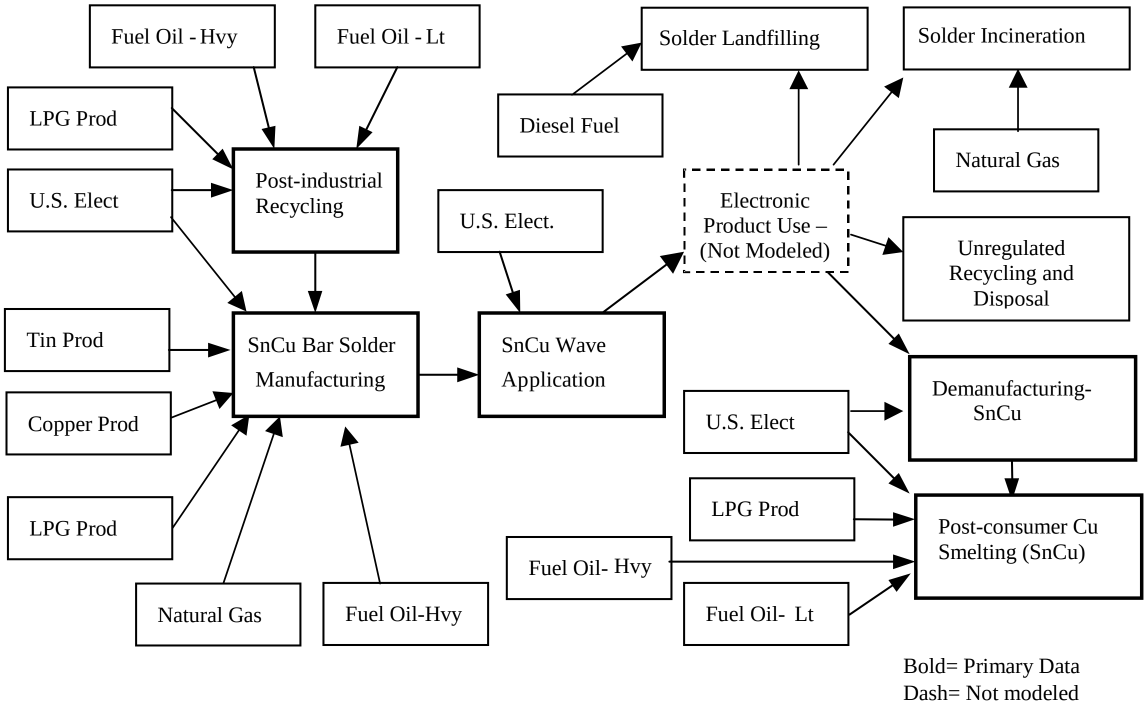


**Figure 2-8. SnCu Bar Solder Life-Cycle Processes**

## 2.1 GENERAL METHODOLOGY

This section describes the data categories evaluated in the LFSP LCI, decision rules used to determine which materials to evaluate in the study, and data collection methods. It also describes procedures for allocating inputs and outputs from a process to the product of interest (i.e., a solder) when the process is used in the manufacture, recycle, or disposal of more than one product type at the same facility. Finally, it describes the data management and analysis software used for the project, and methods for maintaining overall data quality and critical review.

### 2.1.1 Data Categories

Table 2-1 describes the data categories for which inventory data were collected, including material and resource flows (inputs), and emission, waste, and product flows (outputs). In general, inventory data were normalized to either (1) the mass of an input or output per functional unit, or (2) energy input (i.e., megajoules, [MJ]) per functional unit. As discussed in Chapter 1 (see Section 1.5.2), the functional unit is a unit volume of a particular solder equal to 1,000 cubic centimeters (cc) of solder. Solder density was used to convert the normalized data from mass to volume (see Table 1-1 for solder densities).

Data that reflect production for one year of continuous processes were scaled to distribute over time the excessive material or energy consumption associated with startups, shutdowns, and changeovers.  Consequently, any modeling associated with the impact assessment reflects continuous emissions when equilibrium concentrations may be assumed.  If data were reported over a period of less than one year for any inventory item, the analysis was adjusted as appropriate to the functional unit.  Data were collected on the final disposition of emissions and waste flows, such as whether these flows are recycled, treated, and disposed.  This information was used to determine which impacts will be calculated for each particular inventory item. Methods for calculating impacts are discussed in Chapter 3, Life-Cycle Impact Assessment.

**Table 2-1.  LCI data categories**

| **Data category** | **Description** |
|---|---|
| **Material and resource flows (inputs)** | |
| *Material flows (kilograms [kg] per functional unit)* | Actual materials that make up the final product for a particular process (primary materials) and materials that are used in the processing of a product for a particular process.  Process materials from solder application could include, for example, fluxes.  Materials may be non-renewable (i.e., materials extracted from the ground that are non-renewable or stock resources such as coal), renewable, or flow resources such as water and limestone. |
| *Energy flows (MJ per functional unit)* | Process energy and pre-combustion energy (i.e., energy expended to extract, process, refine, and deliver a usable fuel for combustion) consumed by any process in the life-cycle.  The energy flows modeled in this analysis are generally from non-renewable sources. |
| **Emissions, wastes, and product flows (outputs)** | |
| *Emissions to air (kg per functional unit)* | Mass of a product or material that is considered a pollutant within each life-cycle stage.  Air outputs represent actual or modeled gaseous or particulate releases to the environment from a point or diffuse source, after passing through emission control devices, if applicable. |
| *Emissions to water (kg per functional unit)* | Mass of a product or material that is considered a pollutant within each life-cycle stage. Water outputs represent actual or modeled discharges to either surface or groundwater from point or diffuse sources, after passing through any water treatment devices. |
| *Emissions to soil (kg per functional unit)* | Mass of chemical constituents that are considered pollutants and emitted to soil within each life-cycle stage.  Soil emissions represent actual or modeled discharges to soil from point or diffuse sources. |
| *Deposited goods (kg per functional unit)* | Mass of a product or material that is deposited as solid or hazardous waste in a landfill or deep well.  Represents actual disposal of either solids or liquids that are deposited either before or after treatment (e.g., incineration, composting), recovery, or recycling processes. |
| *Primary products (kg of material or number of components per functional unit)* | Material or component outputs from a process that are received as input by a subsequent unit process within the solder life-cycle. |
| *Co-products (kg per functional unit)* | Material outputs from a process that can be used, either with or without further processing, that are not used as part of the final functional unit product. |

### 2.1.2 Decision Rules

Given the enormous amount of data involved in inventorying all of the flows for a product system, decision rules are typically employed to make the data collection manageable and representative of the product system and its impacts. Decision rules are a set of criteria established by project participants used to determine if a given process or material flow is to be evaluated in the LCA.

In this project, decision rules as to which processes within the materials extraction and processing (i.e., "upstream") stage to include are based on the materials used to manufacture solders. In considering upstream materials, a combination of several factors, including availability of existing data, plus manufacturer's willingness to participate, were considered; including all of the upstream processes in the scope of the project can unnecessarily lengthen the project period and expend project resources on materials that are unlikely to be influential to the impact results. For example, while it is beneficial to include in the LCA scope the manufacture of the solder flux, it is not necessarily practical to include the manufacturing processes for each of the chemicals that comprise the flux material.

To help determine which upstream processes to include in the LFSP LCI, first the bill of materials of the primary solder materials (Table 1-1 in Section 1.5.1) was reviewed. Note that Table 1-1 does not include non-metallic components of solders, such as flux, which are considered to be ancillary materials. Because of the limited number of metals in the solders, each metal was included in the upstream inventories. Secondary inventory data exist for lead, tin, copper, and silver. As bismuth is a co-product of lead and copper mining, an inventory of materials associated with the extraction and processing of bismuth was developed from the lead and copper inventories. Material inventories for flux components were assessed once the flux formulations were obtained. Inclusion of the fluxes and other ancillary materials, as well as energy sources (e.g., fuels or electric power) associated with manufacturing the solders or applying the solders were determined based on decision rules.

The decision rule process begins by assessing the additional materials used in the various processes within the life-cycle of the solders for the following attributes:

1. *The quantity contribution of each material or energy source.* Materials or energy sources used in large quantities have the potential for even more materials and resources to be associated with their manufacture, and thus have a higher potential for having a significant environmental impact.

2. *Materials that are of known or suspected environmental significance (i.e., toxic).* In an environmental life-cycle assessment, consideration of materials or components that are known to or are suspected to exhibit an environmental hazard are to be included to the extent feasible.

3. *Materials that are known or suspected to have a large energy contribution to the systems energy requirements.* Significant environmental impacts are associated with the production of energy, therefore, priorities will be given to include materials or processes that are known to or suspected to consume large amounts of energy.

4. *Materials that are physically unique to one solder over another.* The physical uniqueness of a material or component has the potential to accentuate the environmental differences among solders and, thus, are included in the study, where possible.

5. *Materials that are functionally significant to the solder.* “Functionally significant” is defined as important to the technically successful use of the solder as it functions to allow the successful operation of a PWB. For example, each base metal is considered functionally significant.

In general, materials or energy sources that are greater than one percent of the total mass or energy required to manufacture the solder were included in the scope. Materials comprising between one and five percent, however, also were evaluated for whether or not upstream inventories were required. Inclusion of materials falling into the one to five percent range were then based on the other decision rule criteria, as well as availability of data. Materials of known or suspected environmental or energy significance were included, regardless of their mass contribution. Additionally, materials that were physically unique or functionally significant to a solder alternative were included if they would have been otherwise eliminated based on the mass cutoff. For example, copper production for SAC, SABC, and SnCu was included as an upstream process although it is less than one percent of the mass of the alloys, due to its technological importance and physical uniqueness (i.e., it is not found in the SnPb baseline alloy).

### 2.1.3 Data Collection and Data Sources

Data were collected from both primary and secondary sources. Primary data are directly accessible, plant-specific, measured, modeled, or estimated data generated for the particular project at hand. Secondary data are from literature sources or other LCAs, but are specific to either a product, material, or process used in the manufacture of the product of interest. Table 2-2 lists the types of data (primary or secondary) employed for each life-cycle stage in the LFSP LCI. Where both primary and secondary data were lacking, modeled data or assumptions served as defaults.

**Table 2-2. Data types by life-cycle stage**

| Life-cycle stage | Data types | Scope |
|---|---|---|
| Upstream<br>(materials extraction and processing) | Secondary data | Less emphasis |
| Product manufacturing | Primary data | Greater emphasis |
| Use (solder application) | Primary data | Greater emphasis |
| Final disposition<br>(leachability, recycling, and/or disposal) | Primary and secondary data.<br>Modeling for some processes | Greater emphasis |

### 2.1.4 Allocation Procedures

An allocation procedure is required when a process within a system shares a common management structure, or where multiple products or co-products are produced. In the LFSP LCI, allocation procedures were required when processes or services associated with the functional unit were used in more than one product line at the same facility. Flows are allocated among the product lines to avoid over-estimating the environmental burdens associated with the product under evaluation. For example, energy consumption data collected during the manufacture of solder must first be allocated by the quantity of each of the solder alloys produced, in order to accurately determine the energy consumption attributable to the manufacture of the solder in question.

The International Standards Organization (ISO, 1996) recommends that wherever possible, allocation should be avoided or minimized. This may be achieved by sub-dividing the unit process into two or more sub-processes, some of which can be excluded from the system under study. In the example above, if a manufacturer uses only one type of solder, no allocation would be necessary from that manufacturer. It is more likely that the manufacturer would produce multiple solders, however. This requires allocation of flows from the manufacturing using several solders to those associated only with the one solder alloy of interest. As suggested by ISO, if sub-processes within the facility can be identified that distinguish between solders used during application, the sub-processes using the solders that are not of interest can be eliminated from the analysis, thus reducing allocation procedures.

In this study allocation procedures were used as follows:

- *Inventory data for utilities and services common to several processes are allocated to reflect the relative use of the service.* For example, fuel inputs and emission outputs from electric utility generation are allocated to a solder according to the actual or estimated electricity consumed during the applicable process.

C *Where a unit process produces co-products, the burdens associated with the unit process are allocated to the co-product on a mass or volume basis, as appropriate.*

### 2.1.5 Data Management and Analysis Software

Data collected for the study were either obtained from site visits, telephone interviews, or electronic mail correspondences using a standardized data collection form developed for this project; from existing databases; or other secondary data collected by the UT Center for Clean Products and Clean Technologies. All these data were normalized to the study functional unit and then imported into GaBi3, a commercially available life-cycle assessment software program (GaBi, 2000). The GaBi3 software tool stores and organizes life-cycle inventory data and calculates life-cycle impacts for a product profile. It is designed to allow flexibility in conducting life-cycle design and life-cycle assessment functions, and to provide the means to organize inventory data, investigate alternative scenarios, evaluate impacts, and assess data quality.

### 2.1.6 Data Quality

LCI data quality can be evaluated based on the following data quality indicators (DQIs): (1) the source type (i.e., primary or secondary data sources); (2) the method in which the data were obtained (e.g., measured, calculated, estimated); and (3) the time period for which the data are representative. LCI DQIs are discussed further in *Life-Cycle Assessment Data Quality: A Conceptual Framework* (SETAC, 1994). LFSP data quality for each life-cycle stage is discussed in detail in Sections 2.2 through 2.5, and summarized below.

For the primary data collected in this project, participating companies reported the method in which their data were obtained and the time period for which the data are representative. Data from 2002 and 2003 were sought. The time period of secondary data and method in which the data were originally obtained were recorded, where available.

Anomalies and missing data are common hurdles in any data collection exercise. Anomalies are extreme values within a given data set. Any anomaly identified during the course of this project that was relevant to project results was highlighted for the project team and investigated to determine its source (i.e., mis-reported values). If an anomaly could be traced to an event inherently related to the process, it was left in the data set. If, however, an anomaly could not be accounted for, it was removed from the data set.

Missing data were replaced hierarchically. That is, if specific primary data were missing, secondary data were used. Where neither primary nor secondary data were available, assumptions were made. When assumptions or choices in data drove results, modified scenarios were applied to the analysis to help understand the sensitivity of the results to those assumptions or data. In the case where no data were found, or reasonable assumptions could not be made, these deficiencies are reported.

Any proprietary information required for the assessment was subject to confidentiality agreements between the Center for Clean Products and Clean Technologies and the participating company. Proprietary data are presented as aggregated data to avoid revealing the source of the data, or not reported at all if data aggregation is insufficient to protect the confidentiality of the data.

### 2.1.7 Critical Review

Critical review is a technique to verify whether an LCA has met the requirements of the study for methodology, data, and reporting, as defined in the goal definition and scoping phase. A critical review process was maintained in the LFSP LCA to help ensure that the following criteria were met:

- the methods used to carry out assessments were consistent with the EPA, SETAC, and ISO assessment guidelines;
- the methods used to carry out assessments were scientifically and technically valid within the LCA framework;
- the data used were appropriate and reasonable in relation to the goals of the study;
- any interpretations reflect the limitations identified, and the goals of the study; and
- the study results were transparent and consistent.

A project Core Group and Technical Work Group were identified, consisting of representatives from industry, academia, public interest groups, and EPA. Both groups provided critical reviews of the project assessments. The Core Group served as the project steering committee and was responsible for approving all major scoping assumptions and decisions. The Technical Work Group (which also includes the members of the Core Group) provided technical guidance and reviews of major project deliverables including the LCA report. In addition to the critical review process, primary data were double-checked with the original source to ensure accuracy.

## 2.2 MATERIALS EXTRACTION AND MATERIALS PROCESSING (UPSTREAM LIFE-CYCLE STAGES)

This section describes the extraction and processing inventories for the major primary materials (i.e., base metals) used in each solder alternative, as well as processes associated with fuel production and the generation of electricity. The fuel and electricity generation inventories are linked to processes in other life-cycle stages where fuels or electricity are used as process inputs. In the presentation of inventory results (Section 2.6) and impact results (Chapter 3), the fuel and electricity processes are presented as part of the life-cycle stage to which they are linked. Section 2.2.1 provides the methodologies, including discussions on data sources and data quality, for the major materials (Section 2.2.1.1), and for the major fuels and power sources (Section 2.2.1.2). Section 2.2.2 presents the limitations and uncertainties applicable to both materials and fuel/power sources.

### 2.2.1 Methodology

#### 2.2.1.1 Materials (metals)

The major primary materials being evaluated in the upstream life-cycle stage are the base metals in each solder alternative. These metals include lead, tin, copper, silver, and bismuth. Both the extraction and processing of these metals are included in the scope of this analysis. For each metal, this LCA combines the extraction and processing (e.g., smelting), along with associated transportation of each metal into one process inventory.

The inventories for lead, tin, copper and silver were available as secondary data. Where multiple data sets were available, data were selected based on reported data quality, timeliness of data, and consistency with other data sets used in the LFSP analyses. The lead, copper and silver inventories used for the LFSP were contained within GaBi3 software and databases (GaBi, 2000). The tin inventory was obtained from *Ecobilan* in their Database for Environmental Analysis and Management (Ecobilan, 1999).

No secondary data sets were available for bismuth. Worldwide, bismuth is primarily co-mined with other metals, including lead (35 percent), copper (35 percent), tungsten (15-20 percent, from China), and tin and other miscellaneous metals (10 to 15 percent) (Palmieri, 2002). As lead and copper co-mining consist of the majority (70 percent) of the worldwide bismuth supply, and because inventories for tungsten and the other metals were not readily available, the bismuth mining and processing inventory was developed from the inventories for lead and copper mining and processing, assuming they represent 100 percent of bismuth production. Thus, the resulting bismuth inventory assumes that 50 percent of bismuth is co-mined with lead and 50 percent with copper. In addition, research showed that the ratio of lead to bismuth production is approximately 14:1 (Miller, 2002). Lacking additional information for copper, both the lead and copper inventories were thus scaled by a 14:1 ratio to represent the bismuth inventory.[1] The uncertainties in this approach are discussed in Section 2.2.2.

Solder manufacturers reported data on the origin of virgin metals purchased for solder manufacturing. The data indicate that the majority of bismuth purchased for the manufacture of solder is derived from lead and copper mining processes. Judgments on the applicability and the level of confidence in the secondary mining and extraction data sets were based on the data collected. Table 2-3 lists the processes included and the basic assumptions used to develop the materials extraction and processing (ME&P) metals inventories.

The secondary inventories listed in the table include the primary production of the metals (e.g., production from virgin sources) and are provided as material and energy flows per kilogram of metal produced. In this analysis, these upstream inventories are linked to the associated solder manufacturing processes and scaled in two ways: (1) to the mass of each metal required as input to each solder manufacturing process, and (2) to the virgin content of each metal used in manufacturing. The percentages of base metals that are of virgin origin were estimated from primary data collected from five solder manufacturers and presented in Table 2-8 (see Section 2.3, *Product Manufacturing*). The mass of each metal input to the manufacturing process was estimated assuming a process in full production. These estimates are predictions, however, because most alternative solders are currently made only in batch processes to meet customer demand, rather than in full production.

The remainder of the solder not manufactured from virgin materials is made from recycled metal content. In this study, it is assumed that all the recycled content is from post-industrial recycling (as opposed to post-consumer recycling). Post-industrial recycling, in some form, is performed by most solder manufacturing facilities, and is included in this study as a separate unit process in the solder manufacturing life-cycle stage. Thus, if a metal has a high virgin content, more of the inventory will be represented in the upstream life-cycle stage than in the manufacturing stage; while, alternatively, if a metal has a high recycled content, more of the inventory will be represented in the manufacturing stage than in the upstream stage. While the LFSP does not model post-consumer waste recycled directly back into the product, the process of recycling solder from PWBs (via demanufacturing and copper smelting) is accounted for in the EOL life-cycle stage.

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[1] Estimation of a 14:1 lead to bismuth ration is based on data from one mine. Additional research produced an anecdotal, yet unconfirmed estimate that bismuth production might require ten times the materials as does lead mining and processing (CEFIC *et al.*, 2002). The more conservative 14:1 ratio was used, however, potentially causing the results of this study to overestimate the impacts from bismuth production if the 10:1 ratio is indeed more accurate.

## Table 2-3. Base metal inventories: summary of information from secondary data

| Base metal Inventory | Processes included |
|---|---|
| Lead (GaBi) | German-based primary lead production (99.995 percent lead), includes ore mining; ore beneficiation; production of concentrate; sintering (with sulfuric acid); processing via traditional shaft furnace (70 percent), QueneauSchuhmann-Lurgi (QSL) plants (20 percent),and imperial smelting (10 percent); and refinery. Breakdown of shaft, QSL and imperial smelting processes based on processing activities in Germany. Includes transportation and worldwide mix of electric power generation. |
| Tin (DEAM) | Open mining of Casserite ($SnO_2$), which is 55 percent tin. Otherwise, processes not specified. |
| Copper (GaBi) | German-based pyro-metallurgical primary copper production (from sulphidic ore); includes: mining (mixture of opencast and underground mining in Chile, Canada, Russia and the U.S.), beneficiation by flotation, transport, oxidation, and final electrolysis. Germany electric power grid inventory applied to electricity use. |
| Silver (GaBi) | Global mix of data (including Canadian- and Swedish-based data). Primarily a by-product of lead and copper (assumes 62.5 percent as a by-product from lead and 37.5 percent as a by-product from copper; this is based on scaling up percentages of 50 percent as a by-product from lead and 30 percent as a by-product of copper [GaBi, 2000]). Swedish silver production data are based on the Rönnskar production facility in Sweden where copper, lead, zinc, gold and silver are produced. The ores are mined in Laisvall (Zn, Pb), Litik (Cu) and Garpenberg (Zn/Pb/Cu/Ag/Au). The non-ferrous metals are produced from metal ores, while the precious metals are produced through recycling of secondary raw materials (i.e., scrap). Includes the mining and smelting. The inventory for silver from the Swedish data is based on the allocation of the market value of the pure silver produced from the overall production (from both mining and smelting). The silver process is linked to (1) ore mining, which includes both opencast mining and underground mining; (2) ore beneficiation, which involves extracting of valuable minerals, removal of unwanted impurities, and separation of several valuable minerals, and (3) sintering, which is a high temperature agglomeration process. The global mix silver production data also combines primary lead production data from Canada, which includes mining, concentrate production, sintering, and further processing at an acid plant, blast furnace and refinery. Country-specific energy and transportation are included. |
| Bismuth (derived from GaBi)[a] | Primarily a by-product of lead and copper (assumes 50 percent as a by-product of lead and 50 percent as a by-product of copper and a 14:1 ratio of lead or copper production to bismuth production). |

[a] The bismuth inventory developed for use in this analysis was derived from the GaBi inventories for lead and copper.

Table 2-4 summarizes sources of secondary data and data quality information (e.g., original source of data, year of data, and geographic boundaries) for the metals ME&P inventories used in this study.

## Table 2-4. Data sources and data quality for metals inventories in the ME&P life-cycle stage

| Materials | Year of data | Geographic boundaries | | Sources | Data quality description |
|---|---|---|---|---|---|
| | | Extraction | Processing | | |
| Lead | 1995[a] | Germany | Germany | GaBi, 2000 (which cites Wiley-VHS, 1997) | Average industry data. GaBi states, "the data describe the modeled process in a sufficient quality" (GaBi, 2000). |
| Tin | 1983-1989[b] | information not readily available | information not readily available | Ecobilan, 1999 (which cites IDEMAT, 1995; which cites the following primary sources: Chapman and Roberts, 1983 and U.S.BOM, 1989) | IDEMAT rates both data reliability and completeness as average. |
| Copper | 1994[a] | Chile, Canada, Russia, United States | Germany | GaBi, 2000 (which cites Wiley-VHS, 1997) | Average industry data. GaBi3 states that this is "a good estimation for the production of copper under consideration of the described conditions" (GaBi, 2000) |
| Silver | 1994[a] | Sweden, Canada | Sweden, Canada | Silver mix data was developed by GaBi based on co-mining with lead and copper. The global mix silver data is a combination of two inventories: silver production in Sweden and lead production in Canada (GaBi, 2000). | For the Swedish mine silver production data, GaBi3 states that the data quality "...is quite reasonable," although these data are only representative of conditions in Sweden, which only contributes a low percentage of the total world production. For the Canadian lead production process data quality is "relatively good" as reported by GaBi3; however, it should also be noted that the lead-based data does not include secondary raw materials (scrap) and, thus, is considered a worst case scenario for the lead available on the market (GaBi, 2000). |
| Bismuth | See lead and copper above. | See lead and copper above. | See lead and copper above. | Bismuth mix developed by UT, based on lead and copper inventories in GaBi3 (see above). | See lead and copper above. |

[a] Reference year of data
[b] Date of publication of primary data source; however, reference year of actual data expected to be slightly earlier, but actual year not known.
*Sources*: IDEMAT, 1995; Chapman and Roberts, 1983; U.S.BOM, 1989; GaBi, 2000; Ecobilan, 1999; and Wiley, 1997.

As shown in the table, the geographic boundaries of the data encompass mining operations worldwide spanning four continents. In addition, the temporal boundaries of the data range from 1983 to 1995. All of these factors create some inconsistencies among the data sets and reduce the data quality when used for the purposes of the LFSP; however, this difficulty is common with LCA, which typically uses data from secondary sources for upstream processes to limit the scope and budget of an LCA.

### 2.2.1.2 Fuels and power sources

Fuels and electricity are used in various processes in each life-cycle stage, as depicted in Figures 2-2 through 2-8. The inventories associated with the production of the major fuels and electricity (i.e., contributing greater than one percent of total energy sources per the decision rules outlined in Section 2.1.2) are included in the LCI of each solder. Flows from the production of the fuels and electricity in the ME&P life-cycle stages are already incorporated into the associated metals inventories provided from secondary data sources. In the other life-cycle stages (i.e., solder manufacturing, application, and EOL), the production processes for fuels and electricity are not incorporated into individual processes. Thus, separate processes (i.e., inventories of the flows from the fuel production or electricity generation) are included in the appropriate life-cycle stages.

The following inventories are included in the solder LCIs:

- natural gas
- light or distillate fuel oil (fuel oil #2)
- heavy fuel oil (fuel oil #6)
- liquified petroleum gas (LPG)
- diesel fuel
- electricity generation

Although the fuel and power inventories are presented in this section of the report under “materials extraction and processing,” they are presented in the inventory and impact results with the life-cycle stage of the process that uses that fuel or power source. For example, during the manufacture of solder, natural gas is used as a fuel; therefore, flows from the processing of natural gas, which is needed to fuel solder manufacturing activities, are included in the manufacturing stage LCI and impact results.

The fuel and power inventories were obtained from secondary data sources. The inventories of natural gas, fuel oils, diesel fuel, and electric power were contained within the GaBi3 databases. The LPG inventory was obtained from DEAM. The electric grid inventory used in this study was obtained from the GaBi database and is based on a 1995 reference year. This data set matched closely with the U.S. electric grid inventory developed by the UT in 1997 (see Socolof *et al*., 2001, Appendix E). Despite the fact that the UT data set was slightly more recent, the GaBi data set was used for the evaluation because it required fewer project resources to include in the analysis and the two data sets closely match. Table 2-5 describes the processes included in the fuel and power inventories.

**Table 2-5. Fuel and power inventories: summary of information from secondary data**

| Fuel Inventory | Processes included |
|---|---|
| Natural gas (GaBi) | Exploration, extraction, processing, and distribution (via pipeline or liquified natural gas [LNG] tanker) to the end customer. |
| Light fuel oil (#2) (GaBi) | Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, desulphurization (i.e., medium distillates to hydrofiner), medium distillates mix plant that produces light fuel oil. |
| Heavy fuel oil (#6) (GaBi) | Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, residue to fuel mix plant that produces heavy fuel oil. |
| LPG (DEAM) | Domestic and foreign crude oil production (onshore conventional, advanced recovery and offshore conventional recovery), transport (fluvial, pipeline, rail, sea, and road) to the refineries in the U.S., crude oil refining into LPG, and transport (pipeline and road) from refinery to end user. |
| Diesel fuel (GaBi) | Crude oil extraction, pipeline and tanker transport, crude oil desalinization, atmospheric distillation, desulphurization (i.e., medium distillates to hydrofiner), medium distillates mix plant that produces diesel fuel. |
| Electricity generation (GaBi) | Assumes a grid of 52.3 percent hard coal, 22.7 percent nuclear power, 12.4 percent natural gas, 4.2 percent crude oil, 3.5 percent lignite, 3.4 percent hydro, and 1.5 percent other.[2] |

Table 2-6 summarizes data sources and data quality information for the fuel and power source inventories used in this study. Like the metals inventories discussed previously, all of the fuel and power inventories are secondary data for the purposes of the LFSP.

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[2] The GaBi data are based on a 1995 reference year. In comparison, the U.S. Energy Information Alliance (EIA) reported in 1999 that the U.S. grid consisted of 57 percent coal (includes hard coal and lignite), 20 percent nuclear, 11 percent hydro, 9 percent natural gas, 3 percent petroleum (crude oil), and 1 percent other.

## Table 2-6 Data sources and data quality for fuel and power inventories used in various life-cycle stages

| Materials | Year of data | Geographic boundaries | | Sources | Data quality description |
|---|---|---|---|---|---|
| | | Extraction | Processing | | |
| Natural gas | 1995 | Canada, Mexico, United States, Algeria | United States | GaBi, 2000 (a) | GaBi3 states the data quality is: "...good. The important flows are considered. Natural gas supply is representative." |
| Light fuel oil (#2) | 1994 | Unclear (various country-based data sources cited) | Germany | GaBi, 2000 (b) | GaBi3 describes the data quality as "good." It is average industrial data from 1994. |
| Heavy fuel oil (#6) | 1994 | Unclear (various country-based data sources cited) | Germany | GaBi, 2000 (b) | GaBi3 describes the data quality as "good." It is average industrial data from 1994. |
| LPG | References range from 1983 to 1994 | "Domestic and foreign crude oil production" | United States refinery operations | Ecobilan, 1999 (c) | No data quality description provided by DEAM; data appear complete. |
| Diesel fuel | 1994 | Unclear (various country-based data sources cited) | Germany | GaBi, 2000 (b) | GaBi3 describes the data quality as "good." It is average industrial data from 1994. |
| Electricity generation | 1995 | Multiple countries, fuel dependent | United States | GaBi, 2000 (d) | GaBi describes the data quality as "good." They claim to use consistent statistics and a comparable information basis for every state. |

(a) GaBi, 2000: Natural Gas Production (sources are from secondary literature, see References at the end of this chapter).
(b) GaBi, 2000: Refinery data (light fuel oil, heavy fuel oil, diesel fuel production) (sources are from secondary literature, see References at the end of this chapter).
(c) Ecobilan, 1999: LPG production (sources are from secondary literature, see References at the end of this chapter).
(d) GaBi, 2000: U.S. electric power grid electricity generation (sources are from secondary literature, see References at the end of this chapter).

As discussed in Section 1.6.2, the geographic boundaries of this project are worldwide for most life-cycle stages, but most downstream processes using electricity were U.S.-based data; therefore, the inventory associated with electricity generation is based on the U.S. electric grid. Some of the other processes are represented by countries that might not be completely representative of operations applicable to this study; however, because the ME&P stage was given lower priority in terms of expending resources for primary data, already available and easily accessible data were often chosen.

### 2.2.2 Limitations and Uncertainties

The limitations and uncertainties associated with the ME&P stage inventories are primarily due to the fact that these inventories were derived from secondary sources and are not tailored to the specific goals and boundaries of the LFSP. Because the data are based on a limited number of facilities and have different geographic and temporal boundaries they are not necessarily representative of current industry practices in the geographic and temporal boundaries, defined for the LFSP (see Section 1.6.2). These limitations and uncertainties are common to LCA, which strives to evaluate the life-cycle environmental impacts of entire product systems and is, therefore, limited by resource constraints which do not allow the collection of original, measured data for every unit process within a product life-cycle. Recognizing the limited resources available for this LCA, project partners elected to rely on secondary data for the ME&P life-cycle stage to permit collection of primary data for other solder life-cycle stages for which data had not been previously compiled.

The potential inconsistent inclusion of transportation data in ME&P inventory data for some processes is another limitation. These data become particularly important when, for example, raw materials are uncommon and must be transported long distances for processing or when the particular transport mode used for a particular materials tends to have high environmental impacts. The lack of transportation data for ME&P processes is not unique to the secondary databases employed in this project or to the LFSP LCI, but a common limitation of other LCIs as well.

Specific to the metals ME&P inventories, uncertainties are associated with the methodology used for deriving the bismuth inventory from the lead and copper inventories as well as limitations in the resulting data set which may not account for flows from ME&P of bismuth when it is a co-product of other metals (e.g., tungsten, tin, and other miscellaneous metals). The uncertainty in the ratio of flows from bismuth production to those of lead and copper production could lead to an overestimate of bismuth impacts if a lower ratio (e.g., 10:1) of bismuth to lead is more accurate than the 14:1 ratio. Similarly, the results may be either over- or under-estimated should the bismuth to copper ratio be different from the 10:1 ratio assumed for the study.

The percentages of base metals that are of virgin origin were estimated from primary data collected from five solder manufacturers. For the alternative alloys, the estimates attempted to predict operations in full production; however, these are indeed predictions and may not represent what will actually occur in full production. The effects on the ME&P stage are caused by the virgin content, which dictates how much mining and extraction is done to process the virgin metal.

Specific to the electric grid inventory, uncertainties exist in the weighting values applied to the various fuel sources from which the power is generated for the U.S. electric grid. The factors were based on a reference year of 1995 and, thus, may vary given the volatility of the oil supply and the current U.S. energy policy.

## 2.3 PRODUCT MANUFACTURING

The solder product manufacturing life-cycle stage is made up of two distinct processes: solder manufacturing and post-industrial solder recycling. This section describes the details of the processes from which inventory data were collected for use in the LCA analyses of the solders. It also details the methods used to collect and validate the data.

As noted in Section 1.5.1, the solders investigated in this study were selected by the project participants based on a number of factors, including performance, likelihood of industry-wide adoption, and prioritized interest of project stakeholders. Solder manufacturers and other industry experts were consulted to accurately define the major manufacturing processes, in terms of resources used and potential importance to environmental impacts. These processes were then targeted and the collection of process data prioritized in our primary data collection effort.

Through consultation with our industry partners, and in collaboration with the Solder Products Value Council of IPC, solder manufacturers were identified and approached about supplying data on their individual solder manufacturing processes for both paste and bar solder.

### 2.3.1 Methodology

2.3.1.1 Data collection and allocation

Data were collected through site visits or through the distribution of data collection forms. Site visits were performed at several solder manufacturing facilities to capture data that reflect the varying methods of bar and paste solder manufacturing for each of the solder alloys being evaluated. Altogether, four solder manufacturing facilities were visited representing three solder manufacturers, one each in the countries of Mexico and Canada, and two in the U.S.

Data collection forms were developed by the UT research team and approved by the Technical Work Group to most efficiently collect and organize inventory data needed for the LCA. Appendix F provides a copy of the data collection form. Data forms were completed during site visits by project researchers or directly by companies when site visits were not possible. The data that were collected included brief process descriptions; primary and ancillary material inputs; utility inputs (e.g., electricity, fuels, water); air, water and waste outputs; product outputs; and associated transportation. Quantities of inputs and outputs provided by companies were converted to mass per unit of product. Transport of materials to and products or wastes from the manufacturing facility also were reported.

Site visits were conducted to observe and to collect inventory data for the post-industrial recycling process. Post-industrial recycling is the common practice among solder manufacturers of reclaiming base metal content from process wastes resulting from solder manufacture or from solder wastes generated during the solder use/application process. Reclaimed alloys are preferred to post-consumer recycled content as they only need to be refined to common alloy mixtures (e.g., 60 Sn/40 Pb) rather than refined to a pure alloy. The refined alloy is then modified to the desired alloy through further refinement and mixing. Altogether, data were collected during site visits to three post-industrial solder recycling facilities located in Mexico, Canada, and the U.S. Together, the data collected represent a variety of processes operated under a variety of conditions and environmental requirements.

During each site visit, UT staff completed a data collection form similar to those completed by facilities that were not visited. Each site visit took approximately a full day, and included an extensive tour of the processes, interviews with process personnel, and a period of time spent completing and reviewing the data on the collection form for accuracy. Data were either measured on the spot, obtained from previously measured or collected data by the facility, or estimated with the assistance of process personnel with appropriate experience and process knowledge. Data were collected, when possible, on a per mass of solder produced basis. Calculations to convert the data for the LCA based on data collected during the site visits were then verified through direct follow-up with the facility at a later date prior to use in the LCA.

Data collected from processes often had to be allocated to solder alloys based on the functional unit defined for this project: a volume equal to 1,000 cubic centimeters of solder. Since much of the process data collected was based on mass (i.e., per kg solder), these data were converted to the functional unit using the solder density. In cases where data collected covered the processing of two or more solder alloys (i.e., monthly energy consumption for a process producing multiple solder alloys), data were allocated to the various solder alloys based on the mass of solder produced, then converted to the functional unit using density. Other data were allocated to the solders using appropriate conversions, where applicable.

Multiple data sets collected for a single process (i.e., energy consumed during SnPb solder manufacture from five facilities) were aggregated before being used in the study. Data were aggregated to generate a single value for each inventory item, and to protect the confidentiality of individual data points.

#### 2.3.1.2 Solder manufacturing

Solder manufacturing data were collected through a series of site visits to solder manufacturing facilities or through the distribution of data collection forms. While the process of manufacturing solder varied by facility, the overall process of manufacturing followed a similar series of process steps for both bar and paste solder manufacturing. Figure 2-9 displays a flow diagram for both bar and paste solder manufacturing. The diagram depicts the primary process steps for which life-cycle inventory data were collected.

Bar solder manufacturing begins with the formation of the alloy from the base metals, which occurs in a large smelting pot. Metals are added in a metallurgically defined sequence to a gas-fired pot, melting the base alloy, and then adding each of the other alloys until the required composition is achieved. The time required to smelt the metals is dependent on a number of factors including temperature, number and type of metals, and the order in which the metals are added to the alloy.

The smelting is followed by a refining step during which undesired metals are removed from the alloy through the use of additives. Undesirable metals are precipitated, and then removed from the alloy typically through skimming or decanting the contaminant from the desired alloy. Finally, once the metal alloy has reached the desired purity and composition, the metal is poured into a series of molds in a casting step to form the solder bar product.

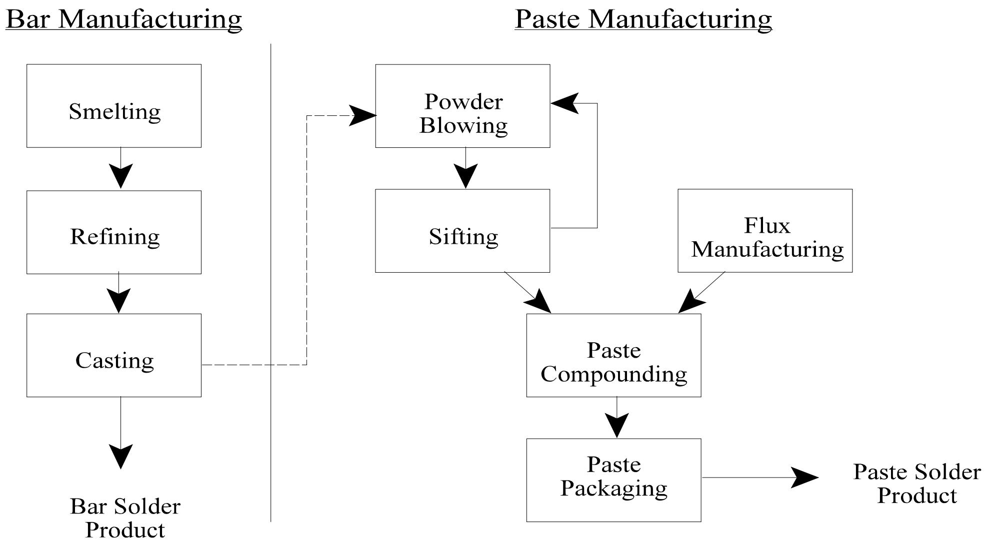

**Figure 2-9. Solder Manufacturing Process Diagrams for Bar and Paste Solders**

The early steps of solder paste manufacturing are similar to that of bar solder. Basic solder alloys are often prepared in advance and cast into bars for use at a later time, frequently as a feedstock for solder paste manufacture. Solder bars are re-melted in a smaller smelting pot and then fed into a process to generate solder powder. Powder is manufactured in one of three ways, by spinning disk, by ultrasonic dispersion, or by dispersion via air venturi. In all of these methods, the molten solder is introduced into the top of a column or tower, and ultimately dispersed into tiny particles, using one of the methods mentioned. The particles cool as they fall through the column forming small spheres. The spheres are sifted through a series of screens that ensure the size and spherical geometry of the powder. Out-of-specification solder spheres (fifty percent or more by volume) are reintroduced into the small smelting pot and the process repeated until the desired amount of solder powder is created.

Flux is blended in a separate process, combining chemicals in a formulation specific to each type of solder alloy and application. Flux chemistry is tailored to provide a variety of characteristics (e.g., no clean) to meet customer needs, and is considered quite confidential by solder manufacturers. As such, data were obtained for only one no-clean flux formulation during the project from a single manufacturer. This chemical formulation was used for all of the paste solder types.

The flux carrier is finally blended with the solder powder to create the solder paste. SnPb solder paste was considered to be a blend of ninety percent powder and ten percent flux when allocating inventory data. The lead-free alloys of SAC, SABC, and BSA were considered blended at eighty-nine percent solder and eleven percent flux, due to the differences in metal density. Solder paste is then packaged into various forms such as syringe tubes, squeezable tubes, or jars.

Table 2-7 displays the number of individual data sets collected for solder manufacturing by solder type for both paste and bar solders.

**Table 2-7 Inventory data sets for paste and bar solder manufacturing**

| Solder type | Paste data sets | Bar data sets |
|---|---|---|
| SnPb | 3 | 4 |
| SAC | 3 | 3 |
| BSA | 2 | N/A |
| SABC | 3 | N/A |
| SnCu | N/A | 3 |

N/A=Not applicable

Being the predominant solder technology for a number of decades, SnPb solder manufacturing is a mature technology performed using full-scale production processes. Although the methods for manufacturing the solder alternatives are similar to those for SnPb, involving smelting and refining processes, these solders are only produced in small-scale, batch operations. Data are not yet available for full-scale production, therefore, product manufacturing inventories for the solder alternatives were scaled from batch production data or from SnPb production data combined with factors to account for the different melting points of the solder constituents. This is a limitation and uncertainty of this study, discussed further in Section 2.3.2.

### 2.3.1.3 Post-industrial recycling

Process wastes from the use/application process (i.e., solder dross from wave soldering) are often returned to the solder manufacturer for reclamation and reuse. These wastes are considered to be of high value because they seldom contain other hard to separate metals or compounds, and are already in a composition that requires minimal effort to recycle into new solder. Other similar materials, such as solder manufacturing wastes (e.g., out of spec solder paste) and even high purity non-solder related wastes (e.g., lead-based wiring), are often accepted as material for recycling, depending on the manufacturer and the capabilities of the reclamation process.

Figure 2-10 presents a typical flow diagram for a post-industrial recycling process operated by a solder manufacturer. The process depicted is representative of the processes from which inventory data were collected, though process steps differ between facilities.

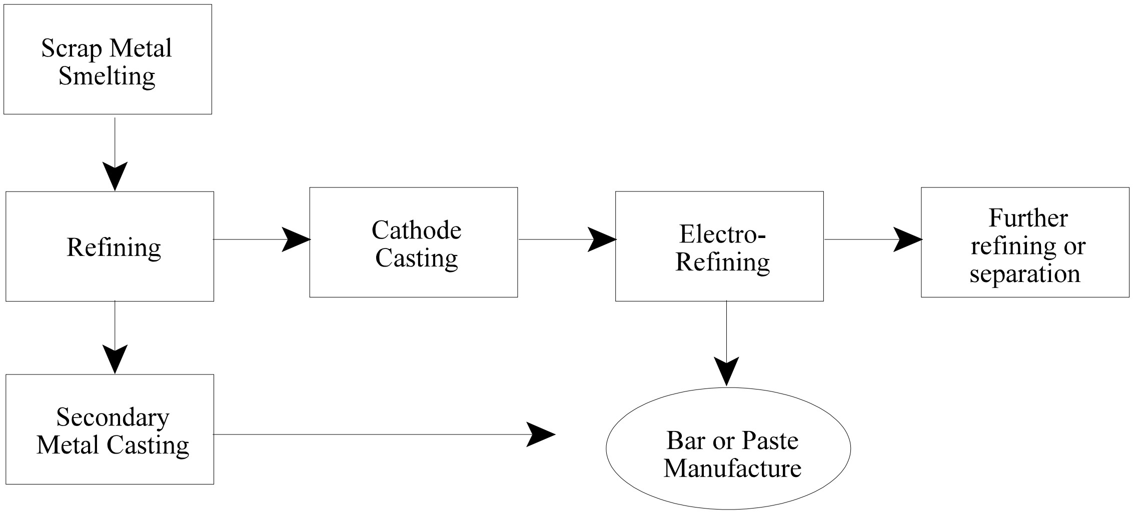

**Figure 2-10 Typical Post-Industrial Recycling Process Flow Diagram**

Scrap metal is first smelted to melt the alloy and to combust any organic content contained within the scrap. The molten metal is poured into ingots, and tested to identify any contaminants. The ingots are then sent to refining, where the metal is reheated in pots and the undesirable metal content is separated through the use of additives. Metals are not refined back to pure elements, but rather into combinations of metals similar to those required for future solder manufacturing (e.g., SnPb). Desirable metal combinations are sent to casting where they are cast into large ingots of secondary metals that are later used as a feedstock for the paste or bar solder manufacturing process. Metals or combinations of metals that cannot be separated during the refining process are cooled and cast into cathodes in preparation for electro-refining.

Electrorefining uses an electrochemical cell to plate out the pure copper content while simultaneously depositing the other metal content onto the cathode. The high purity metal anodes are sent to bar and paste manufacturing as a feedstock, while the remaining metal content is deposited as a sludge that is scraped off the cathode into a bin. The sludge is later sold to an appropriate refiner or is sold as is to a customer using the remaining metal content. The sludge sometimes will undergo further refining using methods suited for the particular metal content.

Inventory from three facilities performing post-industrial recycling were collected through site-visits by project personnel. Data were collected on input and output materials, natural resource consumption (e.g., natural gas), energy consumption, and basic process parameters such as process throughput. Inventory data were allocated to solders based on the composition of the alloys produced.

The solder alloys generated from the post-industrial recycling process are primarily used as secondary metal feedstock to the solder manufacturing process. The percentages of base metals that are primary, or virgin, materials were estimated from data collected from solder manufacturers, and are displayed in Table 2-8 below. For each solder, the majority of each metal comes from virgin content, with the remaining secondary content coming primarily from the post- industrial recycling content. Since all the secondary metal content was assumed to have been generated through the post-industrial recycling process, the inventory data were weighted to reflect the ratio of virgin content to secondary, recycled content. For example, sixty-eight percent of the metals for SnPb came from virgin content, therefore, sixty-eight percent of the inventory data representing metals production came from the upstream materials extraction and processing data set. Similarly, thirty-two percent of both the Sn and Pb content of SnPb is recycled, thus thirty-two percent of the metals inventory data came from the post-industrial solder recycling data. As a result, if a metal has a high virgin content, more of the inventory will be represented in the upstream life-cycle stage than in the manufacturing stage; while, alternatively, if a metal has a high recycled content, more of the inventory will be represented in the manufacturing stage than in the upstream stage.

**Table 2-8. Average virgin content of base metals used in solder manufacturing**

| Solder Type | Sn | Pb | Ag | Cu | Bi |
|---|---|---|---|---|---|
| SnPb | 68 percent | 68 percent | — | — | — |
| SAC | 74 percent | — | 68 percent | 93 percent | — |
| BSA | 74 percent | — | 68 percent | — | 99 percent |
| SABC | 74 percent | — | 68 percent | 68 percent | 99 percent |
| SnCu | 74 percent | — | — | 81 percent | — |

*Note*: No data were provided for SnCu, therefore, the content was assumed to be the average virgin content of Sn from Sn-bearing alternatives (i.e., SAC, BSA, and SABC); and the average virgin content of Cu from Cu-bearing alternatives (i.e., SAC and SACB)

For the alternative alloys, the estimates attempted to predict operations in full production; however, these are indeed *predictions* and may not represent what will occur in full production. The estimates are difficult to determine at this time because the limited production of these alternative solders are currently made in batch processes as required, rather than in full production. Post-industrial recycling is performed at some solder manufacturing facilities and, in this study, is included as a separate unit process in the solder manufacturing life-cycle stage. While the LFSP does not model post-consumer waste recycled directly back into the product, the process of recycling solder from PWBs (via demanufacturing and copper smelting) is accounted for in the EOL life-cycle stage.

### 2.3.2 Limitations and Uncertainties

The limitations and uncertainties associated with the manufacturing stage are related to the following categories:

- the product system boundaries (scope),
- the data collection process, and
- the data.

Specific limitations/uncertainties for each of these categories are briefly described below.

#### 2.3.2.1 Product system boundary uncertainties

In this LCA, all secondary metal content was assumed to have been generated through post-industrial recycling, rather than through post-consumer recycling. This may lead to an over estimate of impacts in post-industrial recycling. In practice, secondary material is obtained first from post-industrial recycling, and then from outside, post-consumer sources when additional material is required. Post-industrial content is more cost-effective as it requires less energy to refine into a common alloy, rather than to create the alloy from material of a composition significantly different from the desired alloy, or with unpredicted contaminants. This assumption leads to uncertainty in the project results.

#### 2.3.2.2 Data collection process uncertainties

Limitations and uncertainties related to the data collection process include the fact that companies were self-selected, which could lead to selection bias (i.e., those companies that are more advanced in terms of environmental protection might be more willing to supply data than those that are less progressive). Companies providing data also may have a vested interest in the project outcome, which could result in biased data being provided. Much of the data collected for the solder manufacturing life-cycle stage was obtained through site-visits by project personnel, however, limiting the opportunity for bias through reporting by the manufacturer. Where possible, multiple sets of data were obtained for this project to develop life-cycle processes. The peer review process and employment of the Core and Technical Work Groups as reviewers in this project is intended to help identify and reduce any such bias.

#### 2.3.2.3 Data uncertainties

Additional limitations to the manufacturing stage inventory are related to the data themselves. Specific data with the greatest uncertainty include the scaling of full production data for lead free alternatives from data collected for batch processes and from manufacturers' professional experience. In some cases, solder manufacturing inventory for lead-free alloys was developed from the batch process data adjusted to account for scaled-up production, and for required process changes estimated through the experience of process engineers.

Due to the confidentiality of flux chemistries and the variability in chemistries manufactured by companies for use with the various solders, data for flux manufacturing was based only on flux formulation. Variability in chemical constituents used for fluxes and any associated process changes required to manufacture other fluxes results in uncertainty in the study results.

## 2.4 SOLDER USE/APPLICATION

Solder is primarily used to attach electronic components to PWBs during the assembly process. In addition, the selection of the type of solder has no effect on the energy consumed over the lifetime of the product the assembly becomes a part of; thus, for the purposes of the LCA, the use stage is defined as the solder application process, and does not include the period of time during which the electronics assembly is used for its intended application.

The process of solder application differs for paste and bar solders. Paste solders are applied through a reflow soldering process that uses a heated oven to melt, or reflow the solder paste. Paste solder is used to attach surface mount components to the surface of the PWB. Bar solder is applied using a wave soldering process that requires passing the populated PWB over a defined wave of molten solder. Wave soldering is used to attach through-hole components and other hardware, such as connectors to the surface of a PWB. Some boards require assembly using both methods to attach all of the boards components.

The electricity consumed during application is directly dependent on the melting point of the individual solder alloys, which vary significantly. Because these energy differences were suspected to be important within the solder life-cycle, collection of primary, measured data from the solder application/use stage was given priority. Testing of electricity consumption was performed at two facilities, and the data were linked to the electricity generation process in the use stage LCI. This section presents the methodology and results of testing, and compares results to other studies of electricity consumption. In the test results, it also discusses data quality, and limitations and uncertainties.

### 2.4.1 Methodology

#### 2.4.1.1 Paste solder

Solder paste is applied to a PWB using a reflow soldering process, which is shown in Figure 2-11. A screen is first prepared with a stencil defining the pattern of solder application for a specific PWB design. Solder paste is then introduced to the screen, and applied to the PWBs using a squeegee to control the amount of solder paste applied. After the boards are populated with components using a pick and place machine, applying surface mount components to the pads covered with solder paste. Components are held in place by the paste and prevented from moving throughout the remainder of the assembly process.

Populated boards are passed through an oven comprised of six to twelve temperature controlled zones, configured to create a temperature-time reflow profile to control the manner in which the solder paste is melted to form the solder joints. PWBs are then passed through a chiller (optional) or allowed to cool in air. Depending on the type of flux, PWBs may need to pass through a cleaning step to remove any flux residue prior to assembly.

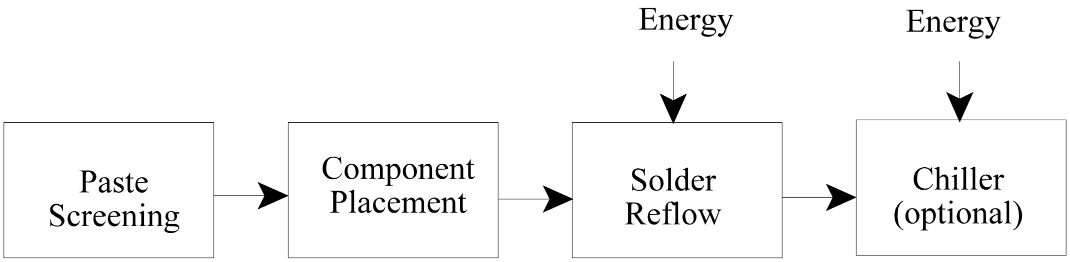

**Figure 2-11. Solder Paste Reflow Process Diagram**

Life-cycle inventory data for the solder paste reflow process were collected through the execution of a detailed testing protocol developed in consultation with industry experts knowledgeable about reflow assembly and the overall goals of the LCA project. The developed protocol balanced the need to collect data in a timely and cost-efficient manner with the desire to measure the primary factors of power consumption during assembly; namely, the shape of the oven temperature profile, conveyor speed, oven loading, and the overall mass of the PWB assembly. In order to evaluate the power consumption under typical operating conditions, it was assumed that the ovens would be operating continuously throughout the day or that work would be scheduled to minimize the cost of operation. Therefore, testing was confined to the measurement of power consumption during periods of steady-state operation, neglecting the preheat cycle.

As a result of prior testing performed by Intel, assembly profiles describing the rate and duration of the incremental temperature changes the assembly must undergo to obtain a functioning solder joint were already available for all but BSA. A suggested profile for BSA was obtained from Hewlett Packard and used by Intel to develop an appropriate reflow profile. The suggested profile was adjusted using a set of thermocouples attached to the surface of the panel. The panel was then passed repeatedly through the temperature zones of the reflow oven while the profile was adjusted until the surface temperature of the panel met the minimum peak melting temperature of the solder. The resulting profile for each solder is depicted in Figure 2-12.

The profiles presented in the figure represent ramp-soak-spike (RSS) assembly profiles, so named for their quick ramp up to melting temperature, followed by a period of slow temperature increase to promote the proper flow characteristics, before a final spike up to the target peak temperature. Other assembly approaches (i.e., ramp to spike) may also be valid and might result in slightly different energy consumption data. The time domain has been removed from the profiles in Figure 2-12 to protect the confidentiality of the research conducted by Intel.

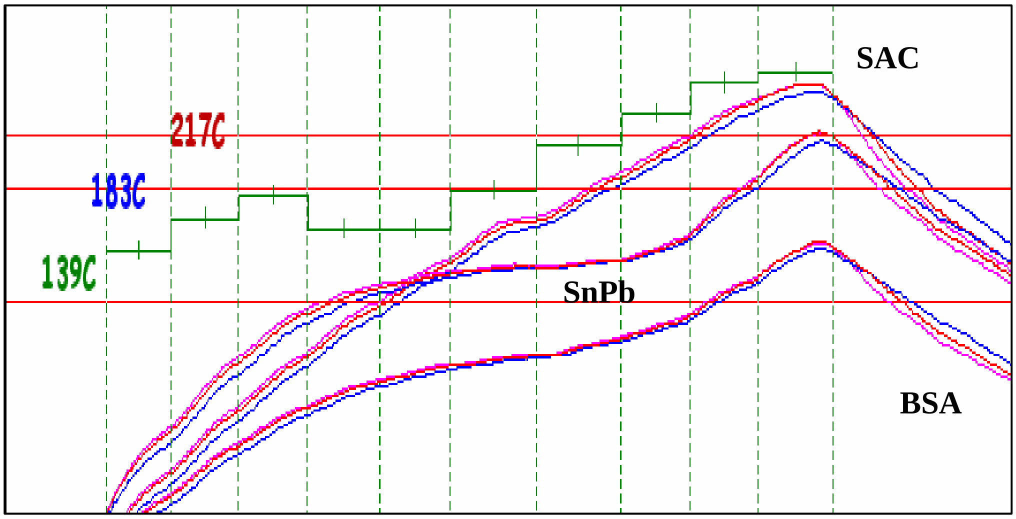

Figure 2-12. Reflow Profiles for Solder Pastes

For comparison purposes, each profile was developed using a constant conveyor speed across profiles to ensure a constant and comparable oven loading during periods of energy measurement. Characteristics of the solder profiles are presented in Table 2-9.

**Table 2-9. Reflow profile specifications**

| Solder | Peak temperature (ºC) [a] | Average TAL (seconds) [b] | Change in temperature (ºC) |
|---|---|---|---|
| SnPb | 204.4-219.1 | 51 | 14.7 |
| SAC | 235.2-248.8 | 65 | 13.6 |
| BSA | 160.2-170.1 | 65 | 9.9 |
| SABC | 235.2-248.8 | 65 | 13.6 |

[a] Peak temperature represents the peak temperatures taken at different points on the PWB surface, reported as a range.

[b] Time above liquidous (TAL) is the period of time a board is heated above the liquidous temperature of the solder.

*Note:* The same reflow profile was used for both SABC and SAC

Because solder reflow occurs once the joint reaches the minimus temperature required for the particular solder, and because the scope of the testing was limited to energy consumption and not joint testing, preassembled Intel micro ATX motherboards were used to limit the cost of the testing. The Intel motherboard was selected because it is at the upper end of applications typical for the consumer electronics market in terms of size, mass, and complexity. A photo of the test board is shown in Figure 2-13. Specifications for the test assembly are presented in Table 2-10.

**Figure 2-13. Reflow Test PWB Assembly**

**Table 2-10. Reflow test vehicle specifications**

| Category | Specification |
|---|---|
| PWB type | Intel Micro ATX Motherboard |
| Length | 9.6 inches |
| Width | 9.6 inches |
| Assembly mass | 225 grams |
| Solder mass | 2.5 grams/board |

Initial testing was conducted at Intel using a ten zone forced convection reflow oven with an attached water-cooled chiller unit to cool the assemblies following reflow. A second phase of testing was conducted at Vitronics-Soltec using an eight heating zone forced convection oven with two cooling zones. Power consumption was measured at both facilities using a data logger connected to the main power. Assemblies were fed into the oven at a controlled rate of 35.5 inches per minute until the oven achieved a fully loaded condition under the design profile. Electricity consumption data were collected from the time the first assembly entered the oven until the final assembly exited. Assemblies exiting the oven were allowed to reach room temperature before being reintroduced to the oven for the next test run.

Results of the reflow testing are presented in Table 2-11. Measured power consumption data from the testing were converted to energy consumed using the time of the individual test run, then normalized based on the amount of solder applied to the PWBs. Mass of solder applied to the board was estimated by Intel and compared to measured data for a similar Intel ATX mother board. Energy consumption data for each of the test runs were averaged and converted to megajoules per kilogram of solder for entry into the LCA.

**Table 2-11. Paste solder reflow test data**

| **Solder Alloy** | **Power Consumption (kW)** | | **Average energy consumption (MJ/kg)** |
|---|---|---|---|
| | **Vitronics- Soltec** | **Intel** | |
| SnPb | 8.3 | 23.3 | 412 |
| SAC | 9.1 | 25.2 | 447 |
| BSA | 6.8 | 15.7 | 297 |
| SABC | 9.1 | 25.2 | 447 |

*Note*: power consumption data were converted to an average energy consumption using the following method: [power (kilowatt [kW]) * 3.6 (MJ/kW-h)]/ time of test run (h)

### 2.4.1.2 Bar Solder

Bar solder is applied during PWB assembly in a soldering process known as wave soldering. Basic process steps associated with wave soldering are displayed in Figure 2-14. PWBs already populated with through-hole components and hardware (e.g., connectors) are first coated with flux to facilitate the proper solder flow across the surface of the circuit pads. PWBs are then loaded onto a conveyor and passed over a pot of molten solder that is pumped through a nozzle with a defined flow profile, or wave. The solder, which is allowed only to contact the bottom surface of the board, wicks up into the through-holes, forming a solder joint. Boards are then allowed to cool in air and are inspected for defects before going on to further processing, if required.

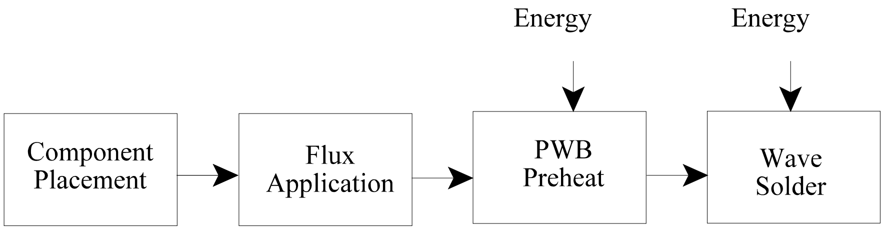

**Figure 2-14. Process Flow Diagram for Wave Solder**

Wave solder data was collected through the development of a detailed test protocol in conjunction with industry experts. The protocol balanced the need to collect data in a timely and cost efficient manner with the desire to measure the key parameters of wave assembly; namely, the pot temperature, conveyor speed, flux usage, and the overall mass of solder applied to the PWB assembly.

Wave solder testing was conducted at Vitronics-Soltec using a PWB assembly measuring 7 inches wide x 10 inches long, designed specifically for wave solder application. In order to evaluate the power consumption under typical operating conditions, it was assumed that the solder pot would be operating continuously throughout the day; therefore, power consumption measurements were confined to periods of steady-state operation, neglecting the solder pot preheat cycle.

Testing was conducted using both water-based and alcohol-based flux. Energy data were measured using a continuous data logger connected to the main power feed of the wave solder machine. PWBs were fed into the wave solder machine with a board length spacing between assemblies. Energy data were collected from the time the first board was placed on the conveyor until the time of the exit of the final board from the machine. Flux use was measured by diverting the flow of flux into a collection jar over the span of the test period. Assemblies were weighed both before and after soldering to determine the mass of solder applied to the assemblies.

Table 2-12 presents the results of the wave solder testing described above. Energy use data for both alcohol and water-based flux were averaged and then normalized for the amount of solder applied to each PWB. The amount of solder applied was measured by comparing the mass of the board after assembly with the initial mass of the board measured just before wave soldering. Flux use also was normalized for the mass of solder applied.

Table 2-12. Wave solder test data

| Solder Type | Flux Type | Energy Use (MJ/kg solder) | Flux Use (kg flux/kg solder) |
|---|---|---|---|
| SnPb | Alcohol-based | 56.4 | 0.733 |
| | Water-based | 60.9 | 1.133 |
| SAC | Alcohol-based | 65.4 | 0.838 |
| | Water-based | 70.3 | 1.294 |
| SnCu | Alcohol-based | 65.9 | 0.843 |
| | Water-based | 70.8 | 1.073 |

## 2.4.2 Limitations and Uncertainties

### 2.4.2.1 Paste solder

Due to the limited number of PWBs available for assembly testing, unpopulated motherboards without solder were used to measure the energy consumption during reflow testing. This allowed for the reuse of the boards, after they were allowed to cool, for testing of the remaining alternatives. The measurement of energy data will likely underestimate the overall energy load measured in the testing resulting in uncertainty. In addition, the mass of solder used to normalize the energy test data was developed based on data already measured for another similar Intel test vehicle. Data were compared for validation to an estimate of solder applied per surface area of PWB developed from a series of similar PWB designs.

### 2.4.2.2 Bar solder

Wave testing was performed at a single facility using the test protocol described. The resulting data represent that process, but may not be reflective of all wave soldering. The single set of data presents uncertainty in the overall results.

## 2.5 END-OF-LIFE

### 2.5.1 Methodology

The functional unit in this analysis is a unit volume of solder used on an arbitrary PWB design. At EOL, the solder is inextricably linked to a PWB which, in turn, becomes part of some electronic product. To the extent possible, this project follows the solder itself to its final disposition. Where EOL activities involve processing the entire product or the PWB on which the solder lies, the flows from those activities are allocated by the mass of product or PWB being processed. For example, if the mass of the solder accounted for a third of the total mass of material processed, only one third of the process flows are attributed to the solder. The allocation prevents the results from being unduly influenced from processing that is unrelated to the amount of solder.

Allocation is not an issue in earlier life-cycle stages including the upstream, manufacturing, and use/application stages. At this point the solder has not yet been incorporated into another product. In order to remain as consistent as possible with the functional unit, the EOL *outputs* are limited to the metals in the solders. For example, while incineration energy inputs are allocated to the mass of the waste going in (which contains the solder), only the metal outputs from the solder are characterized as outputs (and not outputs such as dioxins from incinerating the boards). Further details are provided in subsections that follow.

For the EOL analysis, a PWB is assumed to have reached EOL status when:

- it has served its useful life;
- it is no longer functional; and
- it is rendered unusable due to technological obsolescence.

The major EOL dispositions considered in this analysis are as follows:

- landfilling - includes hazardous and non-hazardous waste landfills;
- incineration - waste to energy incineration; and
- post-consumer recycling[3]
  - regulated demanufacturing followed by copper smelting, and
  - unregulated recycling and disposal.

The various EOL dispositions were allocated as the probability of a PWB going to a certain EOL disposition. The U.S. EPA estimated that 9 percent of electronic waste is recycled (EPA, 2002). No direct estimates on the amount of electronic waste landfilled or incinerated were identified. The EPA reported, however, that of the municipal solid waste (MSW) generated in the United States in 2000, 55.3 percent was landfilled and 14.5 percent was incinerated. The remaining was either recovered for recycling or composted. Based upon the proportions of the

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[3] Post-industrial recycling is included in the solder manufacturing stage (see Section 2.3).

MSW being landfilled or incinerated, it was assumed the fate of the remaining 91 percent of electronic waste is 72 percent to landfilling and 19 percent to incineration. An independent verification on these estimates was conducted by UT researchers. Individual states were contacted, and the percentages estimated above were consistent with what was found in many states.

Among electronics waste that is recycled, two possible scenarios were included: (1) regulated demanufacturing followed by copper smelting for materials recovery and, (2) unregulated recycling and disposal. The latter was included in response to reports of recycling overseas under uncontrolled or unregulated conditions (BAN & SVTC, 2002). Half of the electronic waste being sent for recycling was assumed to be processed under controlled conditions and the other half under uncontrolled conditions. Table 2-13 presents the assumptions used for the EOL life-cycle stage dispositions for most of the alloys.

The distribution of BSA at EOL differs somewhat from what is represented in Table 2-13. The flow charts showing how each alloy is modeled (refer to Figures 2-2 through 2-8) show which processes are included in the life-cycles of each alloy. For BSA (see Figure 2-4), which has a 57 percent bismuth content, the PWBs with BSA are assumed to be demanufactured under the first recycling scenario, but are assumed *not* to be sent to a copper smelter. This is due to the high bismuth content that makes cost-effective metals recovery difficult. Therefore, in the BSA life-cycle model, we assume that once the electronic waste has been demanufactured (i.e., disassembled and/or shredded), it is then sent to a landfill or an incinerator, in the same proportions assumed for the non-recycled waste (as described earlier). As a result, there is no copper smelting process for BSA, and more landfilling and incineration than modeled for the other alloys.

**Table 2-13. General distribution of EOL electronics by disposition**

| **Disposition** | **Distribution** |
|---|---|
| Landfilling | 72 percent |
| Incineration | 19 percent |
| Recycling: demanufacturing and copper smelting* | 4.5 percent |
| Recycling: unregulated recycling and disposal | 4.5 percent |

**Note:* The BSA life-cycle does not include the copper smelting process. After demanufacturing, the waste PWBs with BSA are sent to either a landfill or an incinerator.

The methodologies for each disposition are presented in subsections 2.5.1.1 through 2.5.1.4. Included in each methodology section is also a discussion of data sources and data quality. Table 2-14 lists the general data collection approaches for each disposition. Limitations and uncertainties for all dispositions are presented in Section 2.5.2.

**Table 2-14. Data collection approach for EOL dispositions**

| Disposition | Data source |
|---|---|
| Landfilling | Literature and<br>leachability analysis |
| Incineration | Literature |
| Recycling: demanufacturing and copper smelting | Primary data |
| Recycling: unregulated recycling and disposal | Primary data and assumptions |

### 2.5.1.1 Landfilling

The inputs to the landfilling process modeled in this study include the fuels required to run the landfill equipment (i.e., diesel fuel) and the PWBs or electronic waste assumed to be sent to the landfill. Outputs include the solder metals, which were quantitatively measured based on a leachability analysis commissioned for the LFSP (Appendix C). The transport and collection of waste is not included since these activities would be similar for any of the solder types being analyzed. While this will not affect solder to solder comparisons, it can affect comparisons across life-cycle stages. The exclusion of transportation results in less total overall landfill impacts.

A literature search was conducted to estimate the fuel requirements needed for operating landfill equipment. Data were not available on landfilling of PWBs or electronics alone as there are not dedicated electronics landfills. Energy requirements for landfilling MSW was used as a surrogate for processing electronics waste, as it is expected that electronics waste will be combined with all types of waste. Further, the operation of landfill equipment is not expected to vary greatly depending on the type of waste. Denison (1996) reported that 230,800 BTU of energy per ton of MSW (equivalent to 0.288 MJ/kg MSW) are used for landfill equipment. Diesel fuel was assumed to be used to operate the heavy equipment. The diesel fuel production process from the GaBi3 databases was included in the landfill inventory for each solder type and allocated to the amount of fuel consumed.

The outputs from the landfilling process were based on a leachability study conducted by the University of Florida (UF) in support of the LFSP. The study conducted the EPA-approved toxicity characteristic leachate procedure (TCLP) test on each of the solder types included in the LFSP. In addition to the TCLP test, a less aggressive test method called the synthetic precipitation leaching procedure (SPLP) also was conducted. The TCLP test uses acetic acid and sodium hydroxide in the leaching fluid, and is expected to represent conditions in a landfill. The SPLP uses sulfuric acid and nitric acid, which is intended to be more representative of rainwater. Appendix C presents the draft report describing the methodology and results. The leachate output data are used to represent potential releases to water from landfilling. No further fate and transport modeling is done in the context of this LCA, since the LCA does not address specific locations for impacts and does not have the ability to incorporate site specific fate and transport parameters. The output data used in the LFSP are derived from the TCLP study;

however, the acetic acid contained in the TCLP leachate is known to more aggressively leach lead than other metals. In response to concerns about whether the TCLP will over-estimate the leaching from SnPb solder, an alternate analysis also was conducted using the detection limits as a lower bound (Section 3.3.3).

From the leachability study results, which were provided in concentrations of metal per liter of leachate, the data were converted to kilograms of metal outputs per kilogram of solder (see Appendix C). Table 2-15 presents the data used as the landfilling process outputs based on the leachability study. The table shows that lead in the SnPb alloy leached to the greatest extent, followed by bismuth in BSA. In addition, other outputs from the landfilling process group include outputs from the diesel fuel production process.

**Table 2-15. TCLP-based leachate data used to predict outputs from landfilling**

| Solder Alloy | Solder type | Metal | Fraction leached (kg metal/kg solder) |
|---|---|---|---|
| SnPb | Paste and bar | Lead | 1.88E-01 |
| SnPb | Paste and bar | Tin | 2.93E-05 |
| SAC | Paste and bar | Silver | 1.86E-05 |
| SAC | Paste and bar | Tin | 1.86E-05 |
| SAC | Paste and bar | Copper | 1.34E-05 |
| BSA | Paste | Bismuth | 2.39E-02 |
| BSA | Paste | Tin | 5.18E-04 |
| BSA | Paste | Silver | 2.03E-05 |
| SABC | Paste | Bismuth | 9.09E-04 |
| SABC | Paste | Copper | 3.59E-05 |
| SABC | Paste | Silver | 2.39E-05 |
| SABC | Paste | Tin | 2.39E-05 |
| SnCu | Bar | Copper | 2.72E-05 |
| SnCu | Bar | Tin | 2.39E-05 |

The inputs to landfilling include only the fuel inputs from landfill equipment and PWB waste entering the landfill. Other inputs such as fill materials were not included. Thus, the inputs to this data set are considered incomplete; however, the fuel is expected to be a major input and the production associated with the diesel fuel used in the landfilling process is included in this process. The energy data used for landfilling was estimated from data on MSW and, thus, does not exactly match the waste being considered in this study. It is expected that activities for processing electronic waste at a landfill would be similar to processing MSW, however. With differences in the density of the wastes, there would likely be differences in the fuel consumption during processing. The quality of the output data is considered to be much higher. The leachability tests were done directly to support this project, and measured the fraction of each metal that leached from each solder type.

### 2.5.1.2 Incineration

Direct data for the flows associated with incinerating electronic waste were unavailable; therefore, literature reviews were conducted to estimate incineration flows. Energy inputs are based on a waste to energy combustion facility that can process 500 metric tonnes per day of MSW as presented by Harrison *et al.* (2000). The total energy *recovered* during MSW combustion was reported as being equivalent to 6.36 MJ/kg of MSW. This value was mathematically derived from a series of calculations according to Harrison *et al.* that determined that the heat generated from combustion of the waste more than offset the energy consumed to fire the incinerator. For the purposes of modeling the solder life-cycles, natural gas was assumed to be used as the fuel for the combustion facility. Incineration of electronics would likely result in an even higher net energy gain because the BTU content for a PWB exceeds that for a similar mass of MSW. The energy gain was applied to the system as an offset, acting as a credit to natural gas production (shown as a negative number in the LCI) and the associated process flows for its' production.

The metal outputs were estimated by predicting the percent distribution of outputs to three dispositions: bottom ash, fly ash, and fumes. Table 2-16 presents the percentages that are applied to the mass of metal outputs. Metals in the bottom ash were assumed to be landfilled, and the leachability results presented in Section 2.5.1.1. were used to predict the resulting landfill outputs to water.

**Table 2-16. Percent distribution of incinerator outputs**

| **Species** | **Bottom ash** | **Fly ash** | **Fumes** | **Total** |
|---|---|---|---|---|
| Copper (a) | 94.8 | 4.75 | 0.5 | 100 |
| Lead (a)(b) | 64 | 34.5 | 1.5 | 100 |
| Silver (c) | 82 | 17 | 1 | 100 |
| Tin (b)(d) | 65 | 34 | 1 | 100 |
| Bismuth (b) | 81 | 18 | 1 | 100 |

(a) Average of four data points from Chang-Hwan (no date) and Abanades (2002).
(b) At 800ºC.
(c) At 1100ºC. Disposition based upon EPA reference for MACT technology and metal volatility states. *Note*: Listed as hazardous constituent under RCRA Appendix VIII of Section 261; however not a Hazardous Air Pollutant (HAP) under Clean Air Act, therefore not categorized under maximum achievable control technology (MACT) metals volatility groups directly. Listed disposition based on cement kiln burning Hazardous wastes.
(d) Chang-Hwan (no date).

The data for the incineration inputs include data obtained through secondary literature for energy saved and from the GaBi3 database for the natural gas inventory. The data quality description for the natural gas inventory is provided in Table 2-6. The outputs were estimated from literature describing the fate of metals from incineration. Overall, the incineration data quality for the purposes of the LFSP is moderate, as it is from secondary data and required estimates from data on general thermal treatment.

2.5.1.3 Post-consumer recycling: demanufacturing and copper smelting

Primary data were collected from three demanufacturing facilities and copper smelting data were obtained from two copper smelters, Noranda and Boliden. Data for each process were averaged from each data set collected using an EOL data collection form (see Appendix F). See Section 2.3.1 for more information on primary data collection conducted for the LFSP.

PWBs sent to demanufacturing are dismantled and shredded and then sent to a copper smelter for materials recovery. The demanufacturing process simply includes electric power used to operate dismantling and shredding equipment and the waste PWBs as inputs The generation of electricity from the U.S. electric grid, as described in Section 2.2, is linked to the demanufacturing process in proportion to the amount of electricity required to process waste PWBs. The mass of solder is assumed to remain constant throughout the demanufacturing process, thus the mass of waste PWB (and associated solder) as an input is equal to the mass of the shredded PWB (and associated solder) as an output. The shredded PWBs are the only direct outputs from the demanufacturing process. Indirect outputs are emissions associated with electricity generation.

The shredded PWBs containing each alloy (except BSA) are assumed to be sent to a copper smelter. BSA is assumed to be sent to incineration or landfilling after demanufacturing (discussed above). Based on averaged data, the copper smelting process is fueled by electricity, LPG, light fuel oil, heavy fuel oil, and kerosene. Only kerosene did not meet the mass cut off based on the decision rules as described in Section 2.1.2 and, thus, upstream inventories of all the fuels, except kerosene, were linked to the copper smelting process (as depicted in Figures 2-2 through 2-8).

Estimates of outputs from copper smelting were obtained from interviews and site visits. Process outputs for solder metals were allocated according to the smelting process distributions presented in Table 2-17.

Data for regulated recycling (i.e., demanufacturing and copper smelting) were from primary data sources and are considered of good quality. The demanufacturing process data are expected to be of greater quality than the copper smelting data, as there were more data sets which were used to average the primary data received.

**Table 2-17. Fraction distribution of copper smelting outputs.**

| Species | Air | Slag/tailings impoundment | Product | Lead to recovery | Total |
|---|---|---|---|---|---|
| Tin | 0.0023 | 0.9977 | Negligible | N/A | 1 |
| Lead | 0.0023 | 0.05 | Negligible | 0.9477 | 1 |
| Silver | 0 | 0.05 | 0.95 | N/A | 1 |
| Copper | 0 | 0.05 | 0.95 | N/A | 1 |
| Bismuth | 0.00092 | 0.79908 | 0.2 | N/A | 1 |

N/A=not applicable

#### 2.5.1.4 Post-consumer recycling: unregulated recycling and disposal

The unregulated PWB recycling and disposal process evaluated in the LFSP is modeled after descriptions of processes in various Asian cities in a recent report (hereafter referred to as the BAN report) by a coalition of environmental groups (BAN & SVTC, 2002). These processes involve heat application to remove valuable components and recover solder from PWBs followed by open burning or dumping of the stripped PWBs. Unregulated recycling and disposal processes are expected to result in uncontrolled air emissions, water discharges, and soil releases of solder metals. Although some air emissions may occur during the heating process to recover valuable components and solder metals, the vast majority of environmental releases are expected to occur from open dumping or burning of stripped PWBs. Figure 2-15 presents a process flow diagram and describes the unregulated recycling and disposal processes in the BAN report in more detail.

Descriptions of unregulated recycling and disposal processes for a few locations are presented in the BAN report, but it should be noted that the processes may not be representative of unregulated disposal processes at other locations.

The LFSP did not attempt to determine precise environmental releases at various steps in the unregulated recycling and disposal process. Rather, our approach was to estimate: (1) the amount of solder entering these facilities on PWBs; (2) the amount recovered for resale; and (3) the distribution of the remainder among releases to air, soil, and water. The environmental outputs and associated impacts from combustion of the plastics and flame retardants contained in PWBs are not included in the analysis.

The amount of solder entering unregulated facilities was calculated assuming the amount per functional unit (e.g., per 1000 cc of solder as applied to an arbitrary PWB design) is directly proportional to the percent of waste electronics being exported for recycling and disposal. Therefore, assuming 4.5 percent of EOL electronics is being exported to unregulated facilities, 4.5 percent of the functional unit (45 cc solder) also is being exported.

The amount of solder recovered from PWBs was estimated based on the amount theoretically available for recovery adjusted to account for inefficiencies in the solder recovery process. The amount theoretically available for recovery was defined as the mass of solder used in connections, not including solder used in surface finishing. Based on data for SnPb solder collected by the LFSP**,** approximately 65 percent of the solder on a PWB can be recovered; however, since the solder recovery process employed by unregulated facilities is not likely to be 100 percent efficient, 50 percent recovery of the solder was assumed.

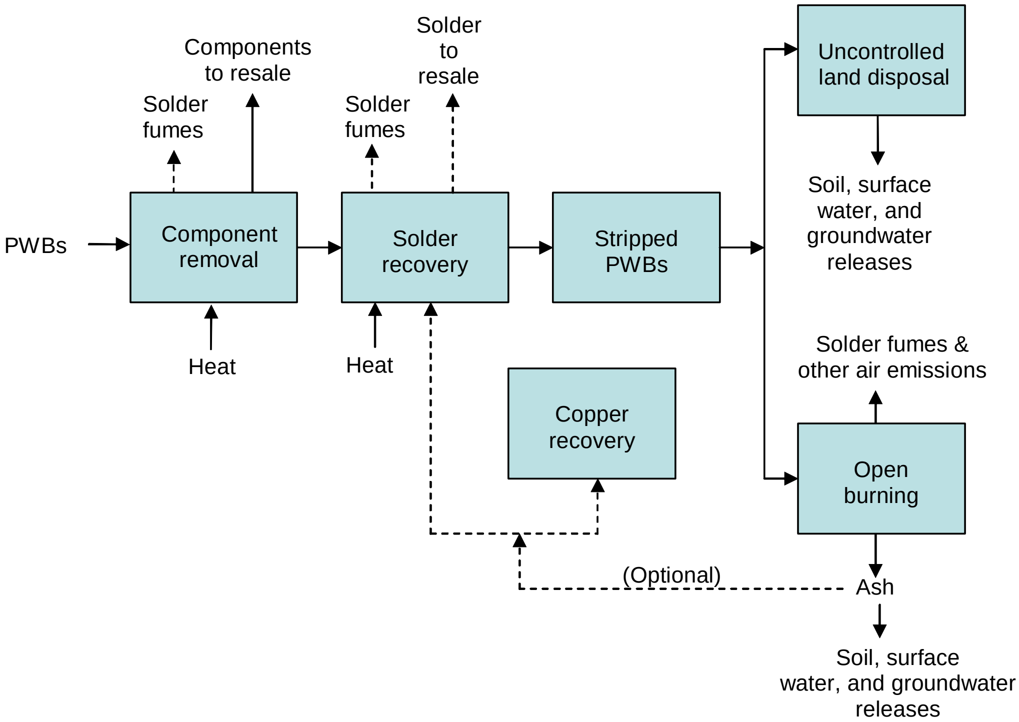

**Figure 2-15. Unregulated Recycling and Disposal Process Flow Diagram**

Estimating the distribution of the remainder among releases to air, soil, and water is more problematic. The BAN report presents metals concentrations found in a limited number of soil, sediment, and water samples from locations along a river in China where PWBs and wires are treated and burned. These data cannot be related to the LFSP functional unit since there is no record of the number of PWBs treated and disposed at these sites. Furthermore, the BAN data do not include air emissions. EPA is currently conducting research to measure air emissions from the open burning of electronics waste.

Pending release of EPA's data on air emissions from open burning of electronics waste, the LFSP assumed 75 percent of the solder not recovered for resale is released to air and soil with the remaining 25 percent released to water via surface water runoff and leaching to groundwater. It should be noted that, in this instance, the relative distribution between soil and water does not affect LCIA results for public toxicity impacts because releases to soil are uncontained, unlike disposal in a controlled landfill. This means that there is potential for exposure to all of the soil releases just as there is potential for exposure to all air releases. The LCIA method for public toxicity impacts uses release amounts as a surrogate for exposure together with a toxicity value. More information on the LCIA methodology for public toxicity impacts can be found in
Section 3.2.12.

Table 2-18 summarizes the assumptions used to calculate the unregulated solder inventory. The overall quality of the data for the unregulated recycling and disposal process is considered low. Assumptions were made based on limited available data; however, the project Core Group agreed that it was important to recognize this scenario by including it even with general assumptions about the fate of the solder metals.

**Table 2-18. Unregulated recycling and disposal assumptions**

| **Parameter** | **Assumption (volume solder per functional unit)** | **Basis** |
|---|---|---|
| Volume solder entering unregulated facilities on PWBs | 45 cc | 4.5 percent of the solder functional unit. Assumes the volume of solder entering unregulated facilities is directly proportional to the percent of waste electronics being exported. |
| Volume recovered for resale | 22.5 cc | 50 percent of the volume of solder entering unregulated facilities on PWBs. Based on the percent of solder that can theoretically be recovered from a typical PWB (e.g., used in connections instead of as a surface finish) minus losses in the recovery process |
| Volume released to air and soil | 16.9 cc | 37.5 percent of the volume of solder entering unregulated facilities on PWBs. Assumes 75 percent of solder remaining after solder recovery has a final disposition in air or soil. This value is subject to change pending results of open burning trials being conducted by EPA. |
| Volume released to water | 5.6 cc | 12.5 percent of the volume of solder entering unregulated facilities on PWBs. Assumes 25 percent of solder remaining after solder recovery is released to water either through leachate or surface water runoff from dumps and burn piles. This value is subject to change pending results of open burning trials being conducted by EPA. |

### 2.5.2 Limitations and Uncertainties

Assumptions about the disposition percentages may not truly represent the actual dispositions. Sensitivity analyses, which vary these assumptions, can be conducted if results show enough impacts at EOL to warrant further analysis. For incineration and landfilling inventories, predictions about process flows were often based on processing MSW rather than specifically on processing solder or PWBs. For regulated post-consumer recycling, fewer limitations exist as primary data were collected for demanufacturing and copper smelting.

## 2.6 BASELINE LIFE-CYCLE INVENTORY RESULTS

Figures 2-16 and 2-17 present the total mass quantity of inputs and outputs, respectively, for each paste alloy. Figures 2-18 and 2-19 present the inputs and outputs, respectively, for each of the bar alloys. These LCI results are only intended to be used as an interim step to conducting the LCIA; therefore, only a brief discussion is provided here. The reflow solders show similar total mass input quantities for SnPb, SAC and SABC, with SAC having the greatest mass inventory inputs (Figure 2-16). BSA has the fewest mass inputs. The greatest contributor to these mass inputs is water as a resource. The outputs from the paste solder life-cycles (Figure 2-17) show SnPb, SAC, and SABC to be almost equivalent to one another and BSA to have a lower mass output. The outputs are also dominated by water emissions.

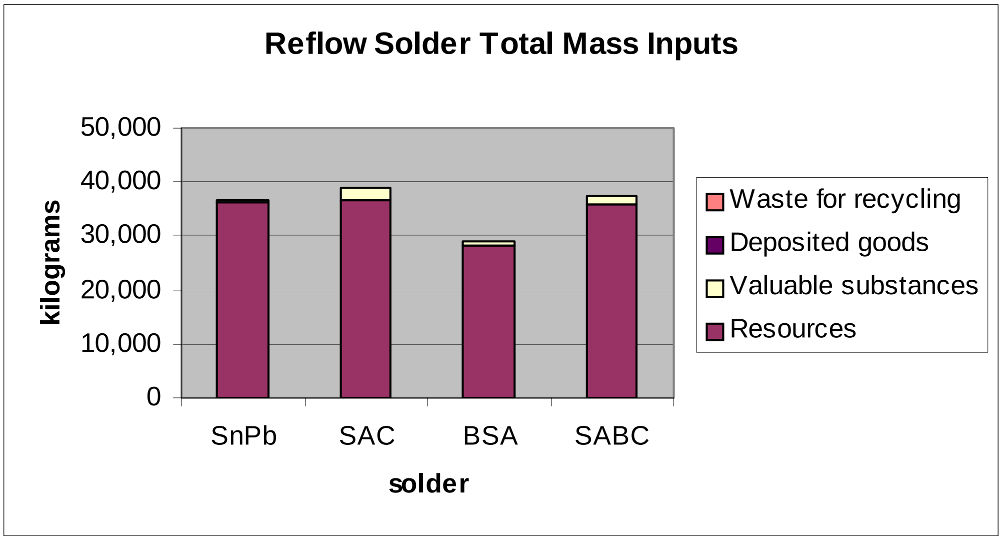

**Figure 2-16. Paste Solder Total Mass Inputs**

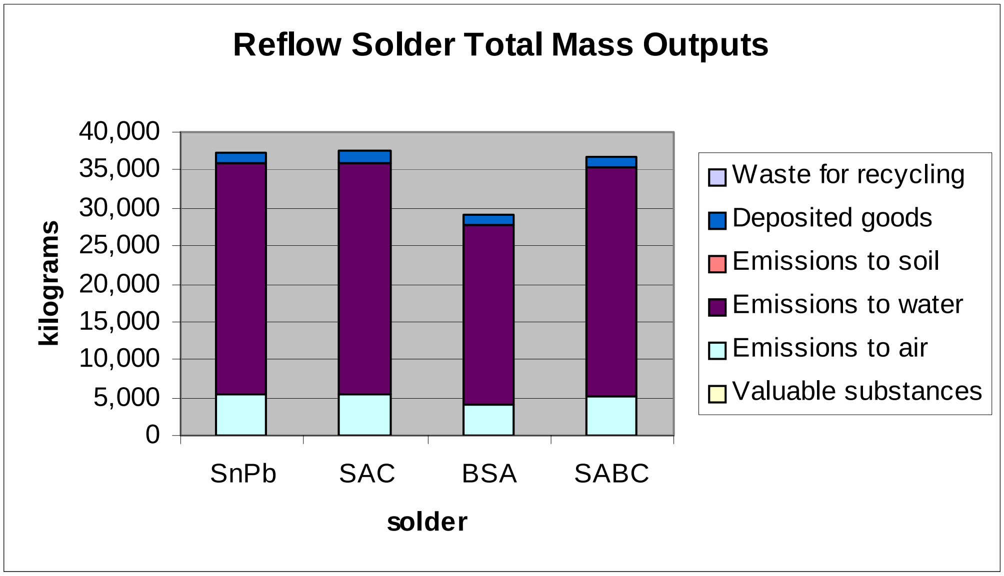

**Figure 2-17. Paste Solder Total Mass Outputs**

For the bar solder inventories, SAC has the greatest mass quantity of inputs, and SnPb and SnCu mass inputs are nearly equivalent. The outputs follow the same pattern. Similar to the paste solder, most of the inputs are from water resources. The outputs are also dominated by emissions to water.

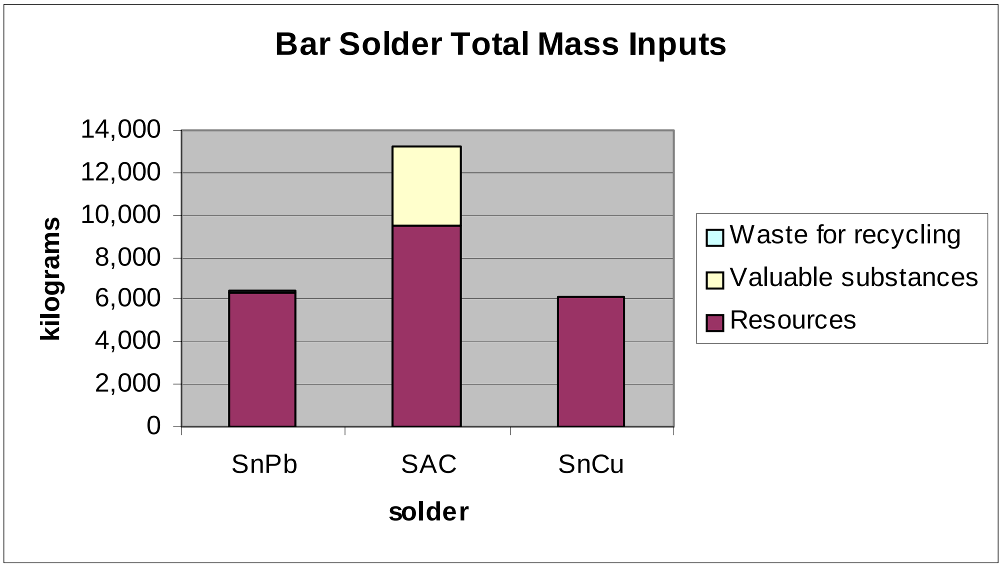

**Figure 2-18. Bar Solder Total Mass Inputs**

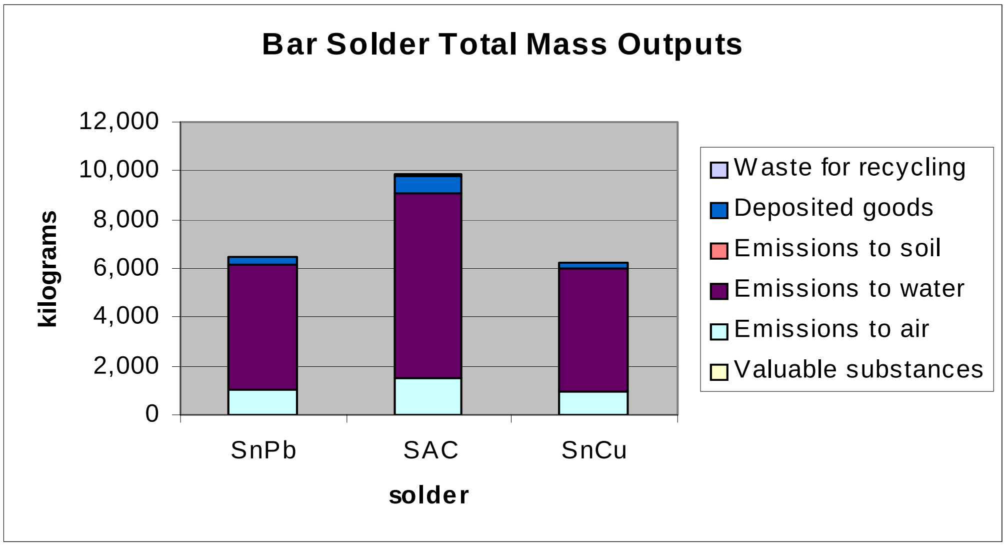

**Figure 2-19. Bar Solder Total Mass Outputs**

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