EXECUTIVE SUMMARY

This report presents the results of a voluntary, cooperative project among the Design for the Environment (DfE) Program in the Economics, Exposure, and Technology Division of the U.S. Environmental Protection Agency's (EPA) Office of Pollution Prevention and Toxics, the University of Tennessee (UT) Center for Clean Products and Clean Technologies, the electronics industry, and other interested parties to develop a life-cycle model and to assess the life-cycle environmental impacts of lead-based and lead-free solders. Analyses are presented for both bar and paste soldering applications used in electronics manufacturing.

The DfE Lead-Free Solder Project (LFSP) used life-cycle assessment (LCA) as an environmental evaluation tool that looked at the full life cycle of the product from materials acquisition to manufacturing, use, and final disposition. As defined by the Society of Environmental Toxicology and Chemistry (SETAC), there are four major components of an LCA study: goal definition and scoping, in which the goals of the study and boundaries of the assessment are determined; life-cycle inventory (LCI), in which data on material and energy inputs and outputs for each process in each life-cycle stage are gathered; life-cycle impact assessment (LCIA), in which the LCI data are entered into a tool-kit, and impact scores are generated for each impact category in each life-cycle stage; and improvement assessment. The more recent International Standards Organizations (ISO) definition of LCA includes the same first three components, but replaces the improvement assessment component of LCA with a life-cycle interpretation component. During the interpretation component, the user weighs the impact scores from the different categories and determines how to improve a product, or decides which product poses an environmentally preferable profile. As is the case with this study, this last step of the LCA process is often left to the user of the results, because it involves weighting the results toward the impact categories that are of most concern to the user. However, there are many accepted methods for performing this step including the eco-indicator '99 method, or the analytical hierarchy process, which is a technique for multi-attribute decision making. Commercially available software packages are available for conducting such analyses.

LCAs are generally global and non-site specific in scope. The LFSP uses the LCA methodology developed and refined in a previous DfE LCA of desktop computer displays (EPA 2003a) and published in Socolof *et al*., 2003. LCAs evaluate the potential environmental impacts from each of the following major life-cycle stages: raw materials extraction and processing, product manufacturing, product use/application, and final disposition at end-of-life (EOL). The inputs (e.g., resources and energy) and outputs (e.g., products, emissions, and waste) within each life-cycle stage are evaluated to determine the environmental impacts.

In this study and project report, the goal and scope of the LFSP are the subject of Chapter 1. The life-cycle inventory (LCI), which describes the method of quantification of raw material and fuel inputs, along with solid, liquid, and gaseous emissions and effluents, is the subject of Chapter 2. The life-cycle impact assessment (LCIA) involves the translation of the environmental burdens identified in the LCI into environmental impacts and is described in detail in Chapter 3. The improvement assessment or life-cycle interpretation is left to the electronics industry or any other interested party given the results of this study.

I. GOAL DEFINITION AND SCOPE

Purpose and Need

The purpose of this study is three-fold: (1) to establish a scientific baseline that evaluates the potential life-cycle environmental impacts of selected lead-based and lead-free solder alternatives using LCA methodologies; (2) to evaluate the effects of lead-free solders on leachability, recycling, and reclamation at end-of-life; and (3) to identify data gaps or other potential areas of analysis for future investigation by EPA or industry. This study is designed to provide the electronics industry with the information needed to improve the environmental attributes of electronics and electronic equipment containing solder. The evaluation considers impacts related to material consumption, energy, air resources, water resources, landfills, human toxicity, and ecological toxicity, as well as leachability and recycling. It is intended to provide valuable data not previously published, and an opportunity to use the model developed for this project in future improvement evaluations that consider life-cycle impacts. It also will provide the industry and regulating authorities with valuable information to make environmentally informed decisions regarding solders and electronics, and enable them to consider the relative environmental merits of an alternative solder along with its performance and cost.

Solder is the chief method for attaching components to a printed wiring board (PWB) during the manufacturing of electronic assemblies. Eutectic tin-lead (SnPb) solder has long been the primary choice for assembling electronics due to its reflow properties, low melting point, and the relative ductility of the solder joints formed. Lead, however, has come under increasing regulatory scrutiny due to its relatively high toxicity to human health and the environment. In 2001, the European Union (EU) proposed the Waste Electronics and Electronic Equipment (WEEE), and the associated Restriction of Hazardous Substances (ROHS) directives, that bans the use of lead in electronics devices sold in the EU beginning in July 2006. The directives have since been finalized. In Japan, subsequent to takeback (recycling) legislation that took effect in that country in 2001, the Japanese EPA and Ministry of International Trade and Industry (MITI) suggested a voluntary phase-out of lead, with lead levels reduced to half by 2000, and by two-thirds by 2005, along with increased EOL product recycling. In response, electronics industry members have undertaken the development and evaluation of alternative lead-free alloys as potential replacements for the SnPb solder. Thus far, the focus of industry research has been on performance-based issues. While there have been some screening-level assessments of the life-cycle environmental impacts of paste solder, there has not to-date been a comprehensive quantitative study of the leading lead-free paste solder alternatives, nor has there been any study of bar solders. Given the importance of solder during the manufacture of electronics, the likelihood of the impending EU ban, and the unknown environmental profiles of the leading solder alternatives, there is a need for an independently conducted, science-based evaluation of the potential life-cycle environmental impacts of the SnPb solder and the leading alternative solder alloys.

Targeted Audience and Use of the Study

The electronics industry is expected to be one of the primary users of the LFSP study results. The project aims to provide the industry with an objective analysis of the life-cycle environmental impacts of selected lead-free solders. Scientific verification of these relative impacts will allow industry to consider environmental concerns equitably along with traditionally evaluated parameters of cost and performance, and to potentially redirect efforts towards products and processes that reduce solder's environmental footprint, including energy consumption, releases of toxic chemicals, and risks to health and the environment. Based on the study results, the industry can perform an improvement assessment of solder alternatives.

This study was designed to provide the electronics industry with information needed to identify impacts throughout the life-cycle of various solder alternatives that can lead to improving the environmental attributes of solders. The LFSP study also allows the electronics industry to make environmentally informed choices about solder alternatives when assessing and implementing improvements such as changes in product, process, and activity design; raw material use; industrial processing; consumer use; and waste management.

Identification of impacts from the life-cycle of lead-free solders also can encourage industry to implement pollution prevention options such as the development and demonstration projects, and to foster technical assistance and training. The electronics industry can use the tools and data provided by this study to evaluate the health, environmental, and energy implications of the solder alternatives. Using this evaluation, the U.S. electronics industry may be better prepared to meet the growing demand for extended product responsibility; to help guide public policy towards informed, scientifically based solutions that are environmentally preferable; and to be better able to meet the competitive challenges of the world market. Potentially, the LCA model and results presented by this study provide a baseline upon which solder alternatives not included in the study can be evaluated. This will allow for further, expedited LCA studies, whose growing popularity within the industry puts them in demand by original equipment manufacturers (OEMs) and international organizations.

The information generated in this study also can be used by the electronics industry to select the lead-free solders that work well for a given application and that pose the fewest risks to public health and the environment over their entire life cycles. The study results should inform the activities of community action groups and help governmental organizations to better manage their electronics purchasing and EOL disposition activities.

Product System

The product system was divided into two groups—bar solders and paste solders—based on the manner that they are applied to the circuit assembly. Bar solders are melted in a solder pot and then pumped through a nozzle that forms a defined wave over which the assembly is passed. Wave soldering is used to attach large surface devices and through-hole components. Paste solders are screened onto the boards to facilitate placement of components, then reflowed by passing the assembly though a high-temperature oven. Reflow soldering is used to attach surface mount components and other micro-componentry to a circuit board during assembly.

The solders evaluated in the study are listed in Table ES-1. Solders were selected for evaluation by project participants based on the results of initial industry research on solder performance, the likelihood of industry-wide adoption of the solder, and the prioritized interests of project stakeholders. Eutectic SnPb solder (bar and paste) was selected as the baseline for both wave and reflow applications. Tin/silver/copper (SAC) was selected because of its ability to function in both the wave and reflow solder environment, and because it has emerged as a leading candidate for adoption as an alternative solder during industry testing (NEMI, 2002). Other solder pastes included two bismuth containing solders, selected for their low melting temperatures and to evaluate their impacts at end-of-life. For bar solders, in addition to SnPb and SAC, tin-copper (SnCu) was included as a potential low-cost alternative that is currently in limited use.

Product systems in an LCA are evaluated on a functionally equivalent basis to provide a reference for relating process inputs and outputs to the inventory and impact assessment across alternatives. For this project, the functional unit is a unit volume of solder required to form a viable surface mount or through-hole connection between the PWB and the component, or multiples thereof. The selection of the functional unit was based on the knowledge that a similar volume of solder is required to fill the space in a solder joint regardless of the type of solder used. A volume of one thousand cubic centimeters (cc) of solder was selected for use as the functional unit in the LCA. The selection of this functional unit is independent of PWB design or configuration because the number and types of connections formed by the solder would be the same for each alternative.

Table ES-1. Solders selected for evaluation

Solder alloys	Composition	Density (g/cc)	Melting Point (^{o}c)	Application type
Tin-Lead (SnPb) (baseline)	63 Sn /37 Pb	8.4	183	Paste and Bar
Tin-Copper (SnCu)	99.2 Sn /0.8 Cu	7.3	227	Bar
Tin-Silver-Copper (SAC)	95.5 Sn /3.9 Ag /0.6 Cu	7.35	218	Paste and Bar
Bismuth-Tin-Silver (BSA)	57 Bi /42 Sn/1.0 Ag/	8.56	138	Paste
Tin-Silver-Bismuth-Copper (SABC)	96 Sn /2.5 Ag /1.0 Bi /0.5 Cu	7.38	215	Paste

Assessment Boundaries

In a comprehensive cradle-to-grave analysis, the solder system includes five life-cycle stages: (1) raw materials extraction/acquisition; (2) materials processing; (3) product manufacture; (4) product use/application; and (5) final disposition/EOL.

The geographic boundaries of this assessment depend on the life-cycle stage. For example, the raw materials acquisition and processing of the metals comprising the solder alloys is done throughout the world and is represented by worldwide data sets. Product manufacturing also occurs worldwide; however, all of the solders selected for evaluation in this project are manufactured in the U.S. Although a worldwide geographic boundary was considered for the manufacturing stage, ultimately the data were obtained primarily from the U.S. Similarly, solder application in the use stage is done worldwide; but, given the geographic location of the project researchers, data were only collected from manufacturers in the U.S. The EOL evaluation focuses on solders and electronic products containing solder that reach the end of their lives in the U.S. Due to limited availability of U.S. EOL data (e.g., on recycling), however, EOL data from other countries also were used. For purposes of this study, the geographic boundaries for all life-cycle stages are worldwide; however, several stages are primarily represented by data collected in the U.S.

Temporal boundaries of the LFSP are defined from 2001 to 2003, the period representing the majority of data collected. Data for manufacturing and use/application life-cycle stages reflect the period stated. Unlike most products, solder does not have a use life-cycle that extends over a large time frame, instead it occurs over the relatively short period of time required to assemble a printed wiring board. While EOL disposition for electronics can be temporarily displaced for many years, data used to assess EOL impacts were based during the time period mentioned.

Impacts from the transportation and distribution of materials, products, and wastes throughout the life-cycle of a solder are included in most of the upstream processes where secondary data are used that already include transportation. For the primary data collected from solder manufacturers, PWB assemblers, and recyclers, transportation was not included in the scope, mostly due to limited project resources. The *differences* in transportation among the different solder alloys in the associated life-cycle stages (i.e., manufacturing, use, and EOL) are not expected to be significant. Therefore, excluding transportation from primary data collection is not expected to adversely affect the study results.

II. LIFE-CYCLE INVENTORY (LCI)

General Methodology

A LCI is the identification and quantification of the material and resource inputs and emission and product outputs from the unit processes in the life cycle of a product system. For the LFSP, LCI inputs include materials used in the solder products; ancillary materials used in processing and manufacturing the solders; and energy and other resources consumed in the manufacturing, use, or final disposition of the solders. Outputs include products, air emissions, water effluents, and releases to land. Figure ES-1 shows the unit processes that are included in the scope of this project for the SnPb solder paste life cycle. While process diagrams for solder alternatives may vary somewhat from solder to solder, and from paste to bar, a scope for each alternative is similar to that shown for the SnPb paste solder alloy. The differences include the following: (1) the upstream production of lead will be replaced with the appropriate alternate metals found in each alloy; (2) liquified petroleum gas (LPG) also is used as a fuel input in *bar* manufacturing, in addition to the fuels used in *paste* manufacturing (i.e., natural gas, heavy fuel oil); and (3) for the BSA alloy, due to the high bismuth content and the potentially prohibitive cost of copper smelting due to the bismuth content, flows from demanufacturing are assumed to be sent to landfilling or incineration instead of copper smelting.

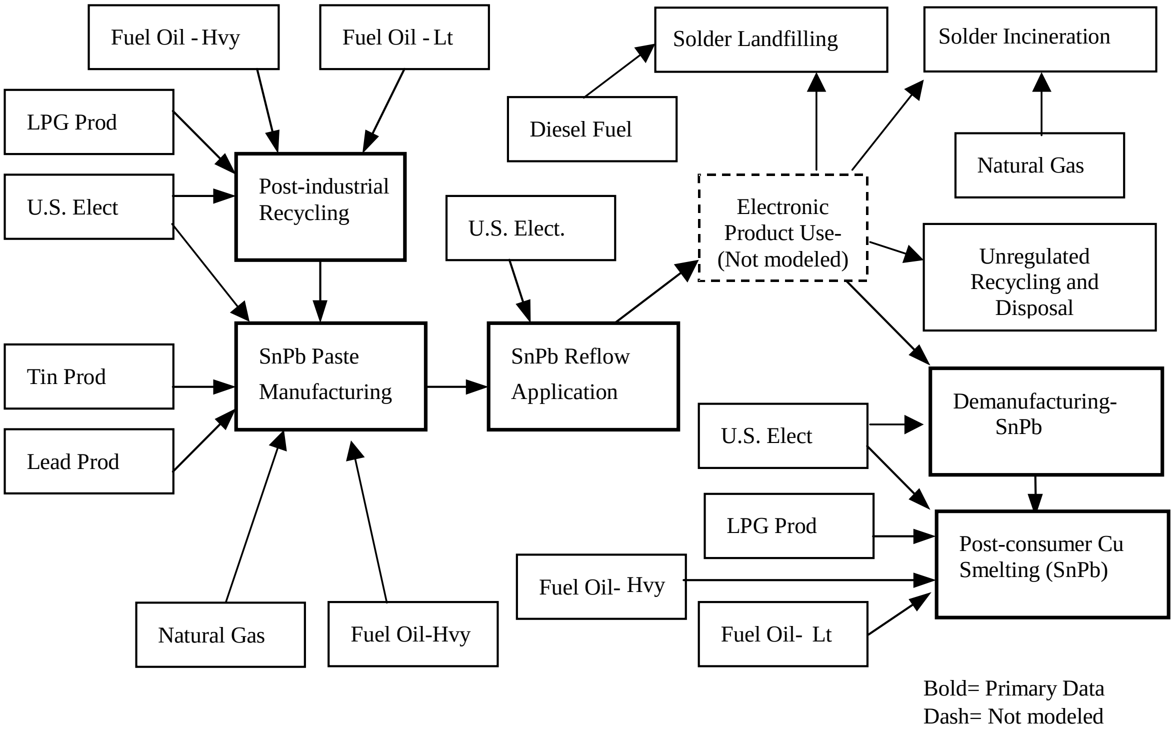

Figure ES-1. SnPb Paste Solder Life-Cycle Processes

Data also were collected on the final disposition of emissions outputs, such as whether outputs are released directly to the environment, recycled, treated, or disposed. This information was used to determine which impacts will be calculated for a particular inventory item. Methods for calculating impacts are discussed in Chapter 3, Life-Cycle Impact Assessment.

Given the enormous amount of data involved in inventorying all of the inputs and outputs for a product system, decision rules were used to determine which materials or unit processes to include in the LCI. Decision rules are designed to make data collection manageable while still representative of the product system and its impacts; they were based on mass, environmental, energy, and functional significance. Data were collected from both primary and secondary sources. Table ES-2 lists the types of data (primary or secondary) used for each life-cycle stage. In general, greater emphasis was placed on collecting data and developing models for the product manufacturing, use, and EOL life-cycle stages.

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

Life-cycle stage	**Data types**
Upstream (materials extraction and processing)	Secondary data
Solder manufacturing	Primary data
Use (Solder Application)	Primary data
Final disposition (Leachability, recycling and/or disposal)	Primary and secondary data

In the LFSP, LCI data were allocated to the functional unit (i.e., 1,000 cubic centimeters of solder) as appropriate. The data that were collected for this study were either obtained using questionnaires developed for this project, site visits, and performance testing (i.e., primary data), or from existing databases (i.e., secondary data). LCI data were imported into GaBi, a publicly available life-cycle assessment tool in which customized life-cycle process profiles were developed for each of the solder alloys.

LCI data quality was 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 (i.e., measured, calculated, estimated); and (3) the time period for which the data are representative. Any proprietary information required for the assessment was aggregated to protect confidentiality.

A critical review process was maintained in the LFSP LCA to help ensure that appropriate methods were employed and study goals were met. A project Core Group and Technical Work Group, both consisting of representatives from industry, academia, government, and other interested parties provided critical reviews of the assessment. The Core Group served as the project steering committee and was responsible for approving all major scoping assumptions and decisions, as well as for providing guidance on technical issues. The Technical Work Group also provided technical guidance and were given the opportunity to review all major project deliverables, including the final LCA report.

Upstream Life-Cycle Stage Methodology

The materials extraction and processing inventories for lead, tin, copper, and silver were available as secondary data. The lead, copper, and silver inventories were contained within the GaBi 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 publicly available for bismuth, so a bismuth data set was constructed from the lead and copper inventories weighted to represent the percentage of bismuth co-mined with each metal.

In the upstream processes for metals production, fuel and energy data are included within the secondary inventory data sets. For the primary data collected in the other life-cycle stages of this analysis, fuel and energy production inventory data are included as separate processes. Although these processes are described in the "Upstream Life-Cycle Stage Methodology" section of this report, the inventory and impact results associated with fuel/energy production are presented with the appropriate life-cycle stage in which the fuel or energy is used. For example, SnPb solder manufacturing requires natural gas as an input, therefore, the impacts associated with the production of natural gas (needed during solder manufacturing) are presented within the *manufacturing* life-cycle stage results. Fuel inventories were obtained from secondary data sources. The natural gas, fuel oils, and diesel fuel inventories were contained within the GaBi databases, while the LPG inventory was obtained from DEAM. Electricity generation inventory data was obtained from a GaBi data set based on the U.S. electric grid.

Manufacturing Stage Methodology

The inventories for the product manufacturing life-cycle stage were developed from primary data collected from manufacturers in North America and Japan. Five companies provided primary data for the analyses. For the paste alloys, data were obtained from three manufacturers, and for the bar alloys, data were collected from all five manufacturers. All told, these five solder manufacturers account for approximately eighty percent of the U.S. market demand. Data were collected through site-visits to three of the manufacturing facilities throughout North America and through questionnaires forwarded to the remaining participating companies. Manufacturers provided inventory data for the manufacture of both lead-based and lead-free solders, as well as for the processes used to reclaim or recycle post-industrial solder waste returned by customers. Allocation of data to the functional unit was conducted as necessary. Processes for which more than one company's data were collected were averaged together.

The quality of the manufacturing stage data is dependent on how the data were obtained, measured, calculated, or estimated. Because solder manufacturers have been producing SnPb in volume for many years, the majority of SnPb solder manufacturing data were measured or calculated based on known process parameters and experience. Demand for the lead-free solders, though increasing, had not yet been enough to require them to be made in anything other than batch mode. Data for the lead-free solders, therefore, was often estimated based on batch production data and on required process parameters for lead-free solder manufacture.

Product Use/Application Life-Cycle Stage Methodology

The use stage for solder was defined as the process of applying solder to the PWB during the assembly process. LCI data were collected for the use/application stage through performance testing conducted at two manufacturing facilities. Data measured during testing were then compared to published data for verification and validation of testing protocols.

Protocols for testing were developed in conjunction with industry experts. Testing was conducted for both reflow (paste solders) and wave (bar solder) assembly processes for each of the solder alloys. For reflow application, inventory data were measured directly during testing conducted at two manufacturing facilities using an identical protocol. Testing sites were selected to vary the type and age of the reflow equipment so that the inventory would represent a range of industry conditions. Energy consumption data collected were converted to a functional unit basis and then averaged. Additional inventory data (e.g., flux consumption) were estimated from established usage rates and experience. Wave application data were measured during performance testing at a single facility and then compared to published data to validate the testing. Inventory data for each of the bar solders was collected using a single protocol developed by industry experts.

Inventory data collected for this life-cycle stage are considered to be of high quality. Alternate analyses were conducted using the high and low energy consumption values to address the potential effects of uncertainties in the data.

End-of-Life (EOL) Methodology

The EOL stage assumes that the solder on a PWB is in a product that has reached its end of life. The EOL analysis does not address the disposition of the entire PWB. To be consistent with the functional unit, the focus is on the solder and where the associated metals in the solder are distributed at the EOL. The EOL dispositions that are considered in this analysis, followed by the assumptions for the percent distribution of electronics to those dispositions are as follows:

- landfilling (solid and hazardous)—72 percent;
- incineration (waste to energy)—19 percent; and
- recycling—9 percent;
  - demanufacturing (i.e., disassembly/shredding and copper smelting)—4.5 percent;
  - unregulated recycling and disposal—4.5 percent.

The unregulated recycling and disposal disposition was included based on an acknowledgment that electronics sent for recycling are sometimes diverted to locations where unregulated recycling and disposal may be occurring.

Primary data were collected for demanufacturing and copper smelting, while secondary data were used for the landfilling and incineration processes. Assumptions based on the physical properties of the solder were used to estimate releases in the unregulated recycling and disposal disposition. The demanufacturing data were collected from three companies, and the copper smelting data were obtained from two smelters. The data from these companies represent facility operations ranging from 2001 to 2003.

LCI Limitations and Uncertainties

Several factors contribute to the overall quality of data for each life-cycle stage. For example, the manufacturing stage includes data that were collected from several different companies. The quality of one data set from one company may be different from that of another company. Relative data quality estimates have been made for each life-cycle stage (Table ES-3). The table also lists the major limitations associated with each life-cycle stage.

Table ES-3. Relative data quality and major limitations

Life-cycle stage	Relative data quality	Major limitations
Upstream	Moderate	Used only secondary data, not originally collected for the purpose of the LFSP.
Manufacturing	Moderate to high	SnPb data expected to have few limitations; more uncertainty with alternatives, which were not yet in full production when data were collected.
Use	High	Data are based on testing protocols developed for the LFSP, thus few limitations expected; however, data that were averaged had a relatively large range.
EOL	Moderate	Used secondary data or assumptions for incineration, landfilling, and unregulated recycling/disposal processes.

Baseline LCI Results

Figures ES-2 and ES-3 present the total mass quantity of inputs and outputs, respectively, for each paste alloy. Figures ES-4 and ES-5 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 paste solders show similar total mass input quantities for SnPb, SAC and SABC, with SAC having the greatest mass inventory inputs (Figure ES-2). 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 ES-3) show SnPb, SAC, and SABC to be about equivalent to one another and BSA to have a lower mass output. The outputs also are dominated by water emissions.

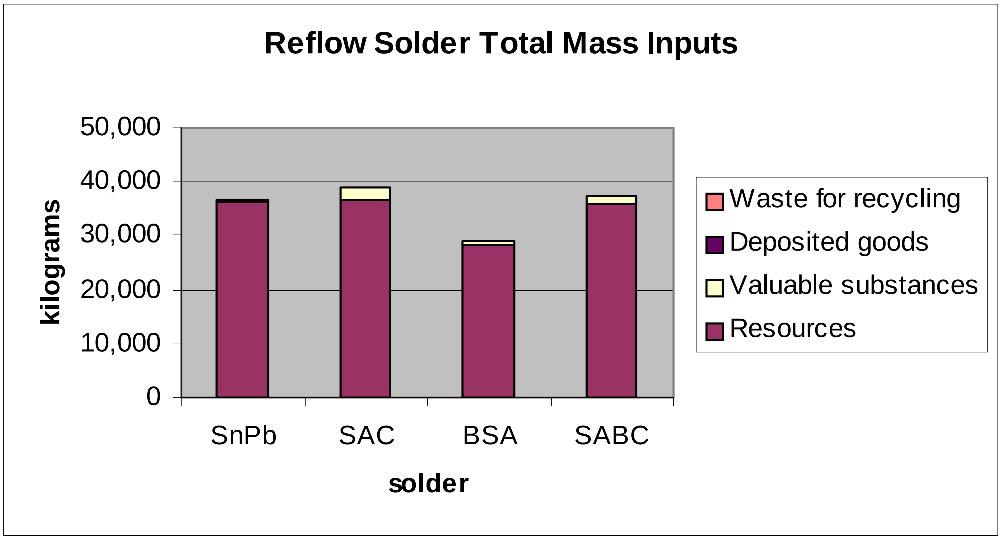

Figure ES-2. Paste Solder Total Mass Inputs

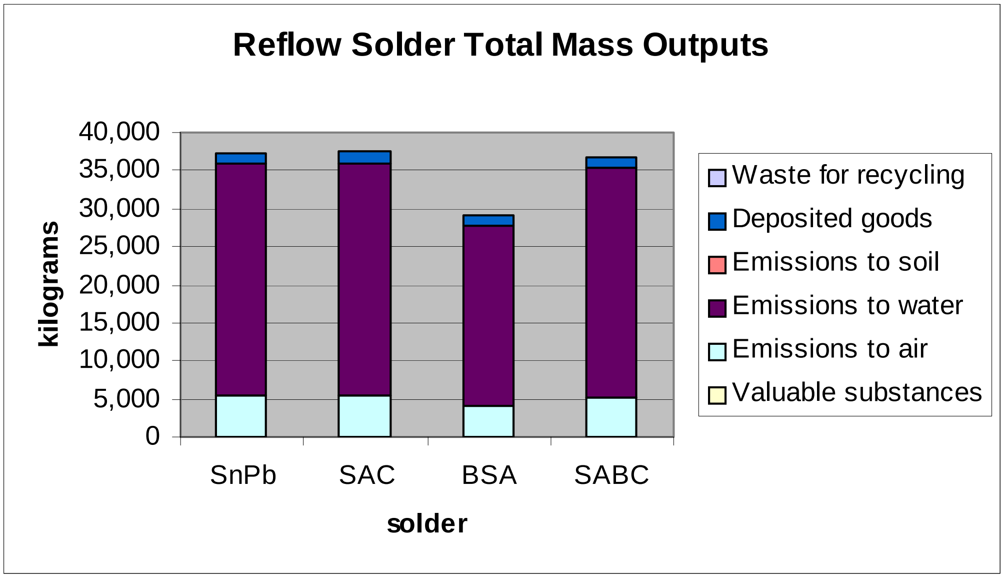

Figure ES-3. Paste Solder Total Mass Outputs

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 also are dominated by emissions to water.

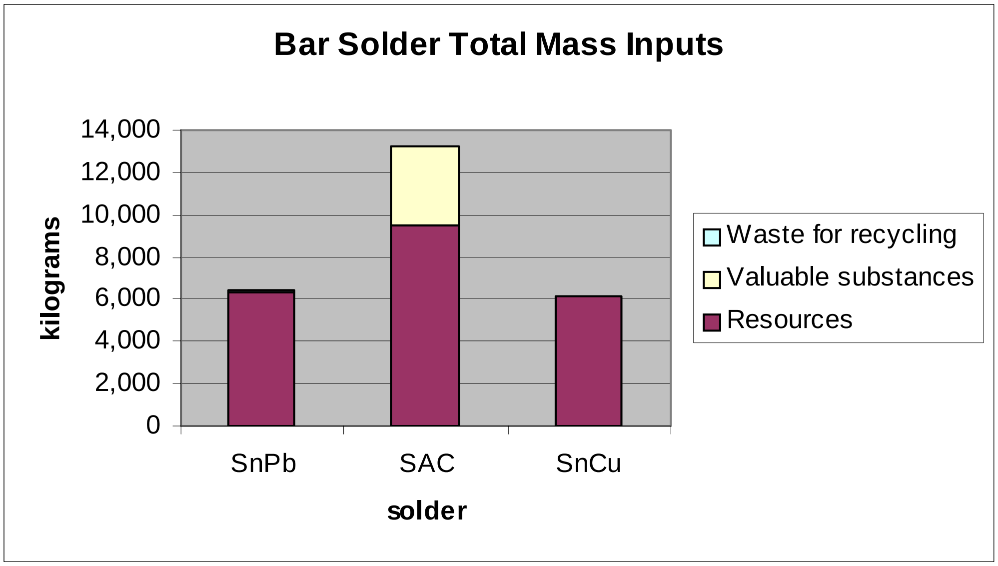

Figure ES-4. Bar Solder Total Mass Inputs

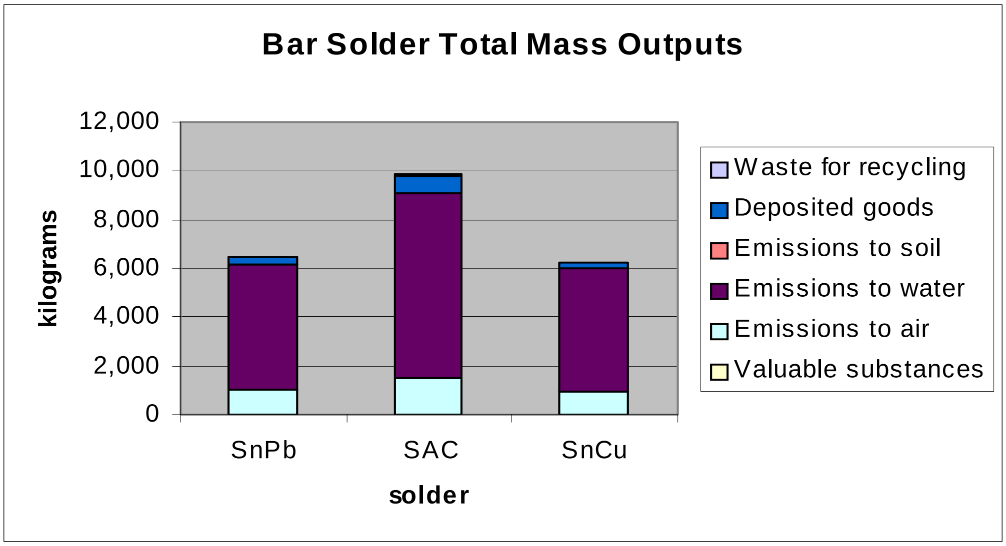

Figure ES-5. Bar Solder Total Mass Outputs

III. LIFE-CYCLE IMPACT ASSESSMENT (LCIA)

LCIA Methodology

LCIA involves the translation of the environmental burdens identified in the LCI into environmental impacts. LCIA does not seek to determine actual impacts, but rather to link the data gathered from the LCI to impact categories and to quantify the relative magnitude of contribution to the impact category (Fava *et al.*, 1993; Barnthouse *et al.*, 1997). Further, impacts in different impact categories are generally calculated based on differing scales and, therefore, cannot be directly compared.

Within LCA, the LCI is a well-established methodology; however, LCIA methods are less defined and continue to evolve (Barnthouse *et al.*,1997; Fava *et al.*, 1993). For toxicity impacts in particular, there are some methods being applied in practice (Guinee *et al*., 1996; ILSI, 1996; Curran, 1996), for example, toxicity potentials, critical volume, and direct valuation, while others are in development. There is currently no general consensus among the LCA community as to one method over another.

The UT LCIA methodology employed in this study calculates life-cycle impact category indicators for a number of traditional impact categories, such as global warming, stratospheric ozone depletion, photochemical smog, and energy consumption. Furthermore, the method calculates relative category indicators for potential chronic human health, aquatic ecotoxicity, and terrestrial ecotoxicity impacts in order to address the interest of project partners in human and ecological toxicity, and to fill a common gap in LCIAs.

LCIAs generally classify the consumption and loading data from the inventory stage into various impact categories (know as “classification”). “Characterization” methods are then used to quantify the magnitude of the contribution that loading or consumption could have in producing the associated impact. The impact categories included in the LFSP LCIA are as follows: renewable resource use, nonrenewable materials use, energy use, landfill space use, global warming, stratospheric ozone depletion, photochemical smog, air acidification, air particulates, water eutrophication (nutrient enrichment), water quality (biological oxygen demand [BOD] and total suspended solids [TSS]), occupational human health effects (cancer and non-cancer), public human health effects (cancer and non-cancer), and aquatic ecotoxicity.

Classification of an inventory item into impact categories depends on whether the inventory item is an input or output, what the disposition of the output is, and, in some cases, the material properties of the inventory item. Outputs with direct release dispositions are classified into impact categories for which impacts will be calculated in the characterization phase of the LCIA. Outputs sent to treatment or recycle/reuse are considered inputs to treatment or recycle/reuse processes, and impacts are not calculated until direct releases from these processes occur. Once impact categories for each inventory item are classified, life-cycle impact category indicators are quantitatively estimated through the characterization step.

The characterization step of LCIA includes the conversion and aggregation of LCI results to common units within an impact category. Different assessment tools are used to quantify the magnitude of potential impacts, depending on the impact category. Three types of approaches are used in the characterization method for the LFSP:

- **Loading—**An impact score is based on the inventory amount (e.g., resource use).
- **Equivalency**—An impact score is based on the inventory amount weighed by a certain effect, equivalent to a reference chemical (e.g., global warming impacts relative to carbon dioxide [CO_2]).
  - *Full equivalency*—All substances are addressed in a unified, technical model.
  - *Partial equivalency*—A subset of substances can be converted into equivalency factors.
- **Scoring of inherent properties—**An impact score is based on the inventory amount weighed by a score representing a certain effect for a specific material (e.g., toxicity impacts are weighed using a toxicity scoring method).

The scoring of inherent properties method is employed for the human and ecological toxicity impact categories, based on the CHEMS-1 method described by Swanson *et al*. (1997). The scoring method provides a hazard value (HV) for each potentially toxic material, which is then multiplied by the inventory amount to calculate the toxicity impact score.

Using the various approaches, the UT LCIA method calculates impact scores for each inventory item within applicable impact category. Impact scores are based on either a direct measure of the inventory amount or some modification (e.g., equivalency or scoring) of that amount based on the potential effect the inventory item may have on a particular impact category. The specific calculation methods for each impact category are detailed in Chapter 3. Impact scores are then aggregated within each impact category to calculate the various life-cycle impact category indicators.

General LCIA Methodology Limitations and Uncertainties

The purpose of an LCIA is to evaluate the *relative potential* impacts of a product system for various impact categories. There is no intent to measure the *actual* impacts or provide spatial or temporal relationships linking the inventory to specific impacts. The LCIA is intended to provide a screening-level evaluation of impacts. In addition to lacking temporal or spatial relationships and providing only relative impacts, LCA also is limited by the availability and quality of the inventory data. Data collection can be time consuming and expensive. Confidentiality issues may also inhibit the availability of primary data.

Uncertainties are inherent in each parameter used to calculate impacts. For example, toxicity data require extrapolations from animals to humans and from high to low doses (for chronic effects) and can have a high degree of uncertainty.

Uncertainties also are inherent in such chemical ranking and scoring systems as the scoring of inherent properties approach used for human health and ecotoxicity effects. In particular, systems that do not consider the fate and transport of chemicals in the environment can contribute to misclassifications of chemicals with respect to risk. Also, uncertainty is introduced where it was assumed that all chronic endpoints are equivalent, which is likely not the case. The human health and ecotoxicity impact characterization methods presented here are screening tools that cannot substitute for more detailed risk characterization methods. It should be noted, however, that in LCA, chemical toxicity is often not considered at all. This methodology is an attempt to consider chemical toxicity where it is often ignored.

Uncertainty in the inventory data depends on the responses to the data collection questionnaires and other limitations identified during inventory data collection. These uncertainties are carried into the impact assessment. In this LCA, there was uncertainty in the inventory data, which included, but was not limited to the following:

- missing individual inventory items,
- missing processes or sets of data,
- measurement uncertainty,
- estimation uncertainty,
- allocation uncertainty/working with aggregated data, and
- unspeciated chemical data.

The goal definition and scoping process helped reduce the uncertainty from missing data, although it is certain that some missing data still exist. As far as possible, the remaining uncertainties were reduced primarily through quality assurance/quality control measures (e.g., performing systematic double-checks of all calculations on manipulated data).

Baseline LCIA Results

Tables ES-4 and ES-5 display the baseline LCIA indicator results for paste and bar solders, respectively. Bolded numbers in the tables indicate a score that is the greatest score for that category among all of the solders displayed in a table. Likewise, results that are shaded indicate the lowest impact score among the solders for that category. The indicator results presented in the tables are the result of the characterization step of LCIA methodology, where LCI results are converted to common units and aggregated within an impact category. It should be noted that the impact category indicator results are in a number of different units and, therefore, cannot be summed or compared across impact categories.

For paste solders, as shown in Table ES-4, SnPb solder has the highest score among the solders in six impact categories, while SAC has the highest impact score in the remaining ten impact categories. Conversely, BSA has the lowest impact scores in eleven of the 16 categories, with SnPb having the lowest scores in the remaining five categories. When considering only the lead-free solder paste alternatives, SAC has the highest impact scores of the remaining solders in fourteen of the sixteen categories, with SABC having the highest impact score in the remaining two categories (occupational cancer and aquatic ecotoxicity). BSA has the lowest impact scores among the lead-free alternatives in every category except non-renewable resource consumption.

As shown in Table ES-5 for bar solders, it is SAC with the highest impact score among the bar solders in twelve of sixteen impact categories, while SnPb has the higher score in the remaining four categories. On the other hand, SnCu has the lowest impact score of any of the three bar solder alloys in eleven of the sixteen categories. When only the lead-free solders are considered, SAC has the highest impact score in every impact category, while SnCu has the lowest scores. Details of each impact category and major contributors to the impacts in those categories are presented in Chapter 3.

Table ES-4. Paste solder LCIA results

Impact category	Units per functional unit*	Quality rating**	SnPb	SAC	BSA	SABC
Non-renewable resource use	kg	M-H	1.61E+03	**1.82E+03**	1.76E+03	1.72E+03
Renewable resource use	kg	M-H	**3.48E+04**	3.47E+04	2.64E+04	3.41E+04
Energy use	MJ	H	1.25E+04	**1.36E+04**	9.76E+03	1.31E+04
Landfill space	m^3	M-H	2.75E-03	**1.62E-02**	6.57E-03	1.13E-02
Global warming	kg CO_2-equiv.	H	8.17E+02	**8.73E+02**	6.31E+02	8.49E+02
Ozone depletion	kg CFC-11-equiv.	L-M	9.95E-05	**1.10E-04**	7.98E-05	1.04E-04
Photochemical Smog	kg ethene-equiv.	M-H	3.13E-01	**6.18E-01**	3.61E-01	5.05E-01
Acidification	kg SO_2-equiv.	M-H	6.50E+00	**1.25E+01**	7.32E+00	1.03E+01
Particulate matter	kg	M-H	4.52E-01	**1.30E+00**	5.85E-01	1.01E+00
Eutrophication	kg phosphate-equiv.	H	**1.22E-01**	1.18E-01	9.06E-02	1.17E-01
Water quality	kg	H	1.79E-01	**2.26E-01**	1.64E-01	2.06E-01
Occupational non-cancer	kg noncancertox-equiv.	M-H	**5.60E+05**	8.12E+03	2.34E+03	5.25E+03
Occupational cancer	kg cancertox-equiv.	L-M	**7.62E+01**	7.20E+01	6.34E+01	7.23E+01
Public non-cancer	kg noncancertox-equiv.	M-H	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03
Public cancer	kg cancertox-equiv.	L-M	6.96E+00	**7.05E+00**	5.15E+00	6.51E+00
Aquatic ecotoxicity	kg aquatictox-equiv.	M-H	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01

* The functional unit is 1,000 cc of solder applied to a printed wiring board.
** Quality rating summarizes the overall relative data quality associated with each impact category: high (H), medium (M), or low (L). Further explanation is provided in Section 3.2.1.3.
Notes: Bold impact scores indicate the alloy with the highest score for an impact category.
Shaded impact scores indicate the alloy with the lowest score for an impact category.

Table ES-5. Bar solder LCIA results

Impact category	Units per functional unit*	Quality rating**	SnPb	SAC	SnCu
Non-renewable resource use	kg	M-H	3.15E+02	**7.68E+02**	3.12E+02
Renewable resource use	kg	M-H	6.03E+03	**8.76E+03**	5.83E+03
Energy use	MJ	H	2.91E+03	**5.77E+03**	3.40E+03
Landfill space	m^3	M-H	1.34E-03	**2.14E-02**	1.33E-03
Global warming	kg CO_2-equiv.	H	1.87E+02	**3.57E+02**	2.16E+02
Ozone depletion	kg CFC-11-equiv.	L-M	1.87E-05	**4.13E-05**	1.78E-05
Photochemical smog	kg ethene-equiv.	M-H	6.98E-02	**5.51E-01**	7.06E-02
Acidification	kg SO_2-equiv.	M-H	1.43E+00	**1.10E+01**	1.53E+00
Particulate matter	kg	M-H	1.49E-01	**1.47E+00**	1.99E-01
Eutrophication	kg phosphate-equiv.	H	2.14E-02	**2.57E-02**	2.06E-02
Water quality	kg	H	3.98E-02	**1.20E-01**	3.64E-02
Occupational non-cancer	kg noncancertox-equiv.	M-H	**7.15E+05**	1.09E+04	6.53E+01
Occupational cancer	kg cancertox-equiv.	L-M	**5.94E+01**	5.75E+01	5.49E+01
Public non-cancer	kg noncancertox-equiv.	M-H	**1.33E+05**	1.22E+04	7.26E+02
Public cancer	kg cancertox-equiv.	L-M	4.13E+00	**5.04E+00**	2.58E+00
Aquatic ecotoxicity	kg aquatictox-equiv.	M-H	**1.55E+03**	1.98E+02	8.70E+00

* The functional unit is 1,000 cc of solder applied to a printed wiring board.
** Quality summarizes the overall relative data quality associated with each impact category: high (H), medium (M), or low (L). Further explanation is provided in section 3.2.1.3.
Notes: Bold impact scores indicate the alloy with the highest score for an impact category.
Shaded impact scores indicate the alloy with the lowest score for an impact category.

Top Contributors by Impact Category for Paste Solders

For paste solders, Table ES-6 through ES-9 list the top contributing flows and their associated processes and life-cycle stages for each impact category for each of the solders. The tables show that the majority of impact categories are driven by resource flows from processes associated with either the use/application or upstream life-cycle stages. Resource flows from use/application life-cycle stage processes are the primary contributor to fourteen of sixteen impact categories for SnPb, and to at least ten or more categories for each of the lead-free alternatives, with the electricity generation process being the single largest driver. While the upstream life-cycle stage does not drive any of the impacts for SnPb, resource flows from upstream processes are the primary contributors to six impact categories for SAC, two categories for SABC, and one for BSA. When considering the impacts from all of the resource flows from each life-cycle stage, however, not just the top contributors are shown in the tables; upstream processes are the major contributors to at least three, and as many as six categories for each of the lead-free alternatives.

Many top contributing flows comprise a large majority of the total contribution to the alloy's life-cycle impacts within a category. In the SnPb results, eleven of the sixteen impact categories had top flows representing a majority of total impacts. By contrast, for lead-free solders, only seven of the sixteen categories had flows contributing fifty percent or more. The major contributing flow for a particular impact category varied depending on the solder.

Table ES-6. Top contributing flows to SnPb solder paste impacts

Impact category	Life-cycle stage	Process	Flow	% Contrib.
Non-renewable resource use	Use/application	Electricity generation	Inert rock	76.8
Renewable resource use	Use/application	Electricity generation	Water	88.8
Energy	Use/application	Electricity generation	Hard coal (resource)	46.8
Landfill space use	Use/application	Electricity generation	Sludge (hazardous waste)	64.8
Global warming	Use/application	Electricity generation	Carbon dioxide	87.7
Ozone depletion	Use/application	Electricity generation	CFC-114	39.3
Photochemical smog	Use/application	Electricity generation	Sulphur dioxide	65.1
Air acidification	Use/application	Electricity generation	Sulphur dioxide	65.4
Air particulates	Use/application	Electricity generation	Dust (unspecified)	79.1
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	97.1
Water quality	Use/application	Electricity generation	Solids (suspended)	86.9
Occupational health—non-cancer	Use/application	Sn-Pb reflow application	SnPb solder paste	31.2
Occupational health—cancer	Use/application	Electricity generation	Natural gas	43.2
Public human health—non-cancer	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	72.6
Public human health—cancer	Use/application	Electricity generation	Nitrogen oxides	32.8
Aquatic ecotoxicity	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	78.3

Table ES-7. Top contributing flows to SAC solder paste impacts

Impact category	Life-cycle stage	Process	Flow	% Contrib.
Non-renewable resource use	Use/application	Electricity generation	Inert rock	64.1
Renewable resource use	Use/application	Electricity generation	Water	83.7
Energy	Use/application	Electricity generation	Hard coal (resource)	40.5
Landfill space use	Upstream	Silver production	Slag (hazardous waste)	77.8
Global warming	Use/application	Electricity generation	Carbon dioxide	77.1
Ozone depletion	Use/application	Electricity generation	CFC-114	33.4
Photochemical smog	Upstream	Silver production	Sulphur dioxide	47.9
Air acidification	Upstream	Silver production	Sulphur dioxide	49.5
Air particulates	Upstream	Silver production	Dust (unspecified)	63.9
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	94.1
Water quality	Use/application	Electricity generation	Solids (suspended)	64.7
Occupational health—non-cancer	Use/application	SAC reflow application	SAC solder paste	31.5
Occupational health—cancer	Use/application	Electricity generation	Natural gas (resource)	43.0
Public human health—non-cancer	Upstream	Silver production	Sulphur dioxide	38.7
Public human health—cancer	Use/application	Electricity generation	Nitrogen oxides	30.4
Aquatic ecotoxicity	Upstream	Silver production	Cadmium emissions to water	45.7

Table ES-8. Top contributing flows to BSA solder paste impacts

Impact category	**Life-cycle stage**	**Process**	**Flow**	**% Contrib.**
Non-renewable resource use	Use/application	Electricity generation	Inert rock	51.7
Renewable resource use	Use/application	Electricity generation	Water	85.9
Energy	Use/application	Electricity generation	Hard coal	44.0
Landfill space use	Upstream	Silver production	Slag (hazardous waste)	57.1
Global warming	Use/application	Electricity generation	Carbon dioxide	83.4
Ozone depletion	Use/application	Electricity generation	CFC-114	36.0
Photochemical smog	Use/application	Electricity generation	Sulphur dioxide	41.5
Air acidification	Use/application	Electricity generation	Sulphur dioxide	42.7
Air particulates	Use/application	Electricity generation	Dust (unspecified)	45.0
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	95.7
Water quality	Use/application	Electricity generation	Solids (suspended)	69.8
Occupational health—non-cancer	Use/application	BSA reflow application	BSA solder paste	32.5
Occupational health—cancer	Use/application	Electricity generation	Natural gas (resource)	37.9
Public human health—non-cancer	Use/application	Electricity generation	Sulphur dioxide	41.2
Public human health—cancer	Use/application	Electricity generation	Nitrogen oxides	32.4
Aquatic ecotoxicity	End-of-life	Unregulated recycling and disposal (BSA)	Silver emissions to water	63.3

Table ES-9. Top contributing flows to SABC solder paste impacts

Impact category	Life-cycle stage	Process	Flow	% Contrib.
Non-renewable resource use	Use/application	Electricity generation	Inert rock	67.9
Renewable resource use	Use/application	Electricity generation	water	85.5
Energy	Use/application	Electricity generation	Hard coal	42.0
Landfill space use	Upstream	Silver production	Slag (hazardous waste)	71.3
Global warming	Use/application	Electricity generation	Carbon dioxide	79.6
Ozone depletion	Use/application	Electricity generation	CFC-114	34.5
Photochemical smog	Use/application	Electricity generation	Sulphur dioxide	38.1
Air acidification	Use/application	Electricity generation	Sulphur dioxide	39.0
Air particulates	Upstream	Silver production	Dust (unspecified)	53.2
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	95.1
Water quality	Use/application	Electricity generation	Solids (suspended)	71.2
Occupational health—non-cancer	Use/application	SABC reflow application	SABC solder paste	31.5
Occupational health—cancer	Use/application	Electricity generation	Natural gas (resource)	42.9
Public human health—non-cancer	Use/application	Electricity generation	Sulphur dioxide	33.7
Public human health—cancer	Use/application	Electricity generation	Nitrogen oxides	33.1
Aquatic ecotoxicity	End-of-life	Unregulated recycling and disposal (SABC)	Silver emissions to water	32.8

Top Contributors by Impact Category for Bar Solders

Tables ES-10 through ES-12 list the top contributing flows and their associated processes and life-cycle stages for each impact category for the bar solders. Like the paste solders, the majority of impact categories are driven by resource flows from processes associated with the use/application or upstream life-cycle stages. Resource flows from use/application life-cycle stage processes are the primary contributor to twelve of sixteen impact categories for SnPb, and to at least six or more categories for each of the lead-free alternatives. Flows associated with electricity generation are the largest contributors to the impacts in these categories.

While the use/application stage is the primary driver for the SnPb and SnCu, resource flows associated with upstream processes are top contributors to nine impact categories for the SAC alloy, and for two categories for the SnCu alloy. Flows from EOL processes also are significant, being the top contributor to three impact categories for the SnPb alloy and two categories for SnCu.

Many top contributing flows comprise a large majority of the total contribution to the alloy's life-cycle impacts within a category. For each of the solder alloys, a minimum of eight of the sixteen impact categories had top flows contributing fifty percent or more, with the major contributing flow for a particular impact category dependent on the solder type.

Table ES-10. Top contributing flows to SnPb bar solder impacts

Impact category	Life-cycle stage	Process	Flow	% Contrib.
Non-renewable resource use	Use/application	Electricity generation	Inert rock	62.3
Renewable resource use	Use/application	Electricity generation	Water	81.1
Energy	Use/application	Electricity generation	Hard coal (resource)	31.8
Landfill space use	End-of-life	Landfilling	SnPb solder to landfill	53.7
Global warming	Use/application	Electricity generation	Carbon dioxide	60.5
Ozone depletion	Use/application	Electricity generation	CFC-114	33.1
Photochemical smog	Use/application	Electricity generation	Sulphur dioxide	46.3
Air acidification	Use/application	Electricity generation	Sulphur dioxide	47.2
Air particulates	Upstream	Tin production	Dust (unspecified)	56.3
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	87.4
Water quality	Use/application	Electricity generation	Solids (suspended)	62.0
Occupational health—non-cancer	Use/application	SnPb wave application	SnPb bar solder	29.8
Occupational health—cancer	Use/application	SnPb wave application	SnPb bar solder	15.5
Public human health—non-cancer	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	53.3
Public human health—cancer	Use/application	Sn-Pb wave application	Flux material F	25.5
Aquatic ecotoxicity	End-of-life	Solder landfilling (SnPb)	Lead emissions to water	71.4

Table ES-11. Top contributing flows to SAC bar solder impacts

Impact category	Life-cycle stage	Process	Flow	% Contrib.
Non-renewable resource use	Upstream	Silver production	Zinc-Pb-Cu Ore	26.7
Renewable resource use	Use/application	Electricity generation	Water	56.5
Energy	Use/application	Electricity generation	Hard coal (resource)	16.2
Landfill space use	Upstream	Silver production	Slag (hazardous waste)	87.2
Global warming	Use/application	Electricity generation	Carbon dioxide	32.1
Ozone depletion	Upstream	Silver production	Halon (1301)	20.3
Photochemical smog	Upstream	Silver production	Sulphur dioxide	79.9
Air acidification	Upstream	Silver production	Sulphur dioxide	83.5
Air particulates	Upstream	Silver production	Dust (unspecified)	83.8
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	73.5
Water quality	Upstream	Silver production	Solids (suspended)	69.8
Occupational health—non-cancer	Use/application	SAC wave application	SAC bar solder	29.1
Occupational health—cancer	Upstream	Tin production	Natural gas (resource)	20.7
Public human health—non-cancer	Upstream	Silver production	Sulphur dioxide	49.6
Public human health—cancer	Use/application	SAC wave application	Flux material C	16.9
Aquatic ecotoxicity	End-of-life	Unregulated recycling and disposal (SAC)	Silver emissions to water	81.8

Table ES-12. Top contributing flows to SnCu bar solder impacts

Impact category	Life-cycle stage	Process	Flow	% Contrib.
Non-renewable resource use	Use/application	Electricity generation	Inert rock	63.5
Renewable resource use	Use/application	Electricity generation	Water	84.8
Energy	Use/application	Electricity generation	Hard coal (resource)	28.0
Landfill space use	End-of-life	Landfilling	SnCu solder to landfill	53.8
Global warming	Use/application	Electricity generation	Carbon dioxide	53.3
Ozone depletion	Use/application	Electricity generation	CFC-114	35.2
Photochemical smog	Use/application	Electricity generation	Sulphur dioxide	46.3
Air acidification	Use/application	Electricity generation	Sulphur dioxide	44.5
Air particulates	Upstream	Tin production	Dust (unspecified)	68.9
Water eutrophication	Use/application	Electricity generation	Chemical oxygen demand	91.6
Water quality	Use/application	Electricity generation	Solids (suspended)	68.5
Occupational health—non-cancer	Use/application	SnCu wave application	SnCu bar solder	14.8
Occupational health—cancer	Upstream	Tin production	Natural gas (resource)	16.7
Public human health—non-cancer	Use/application	Electricity generation	Sulphur dioxide	61.9
Public human health—cancer	Use/application	SnCu wave application	Flux material C	21.3
Aquatic ecotoxicity	End-of-life	Unregulated recycling and disposal (SnCu)	Copper emissions to water	90.4

Alternate Reflow Energy Analysis

Several alternate analyses were performed to evaluate the impact of key assumptions and uncertainties on the overall results of the LCA. These analyses either were performed because they evaluated data with the largest uncertainty or were major contributors to the inventory results. One such analysis focused on the potential effect that the large range in energy consumption data measured during reflow testing might have on the LCA results.

Energy consumed during the use/application life-cycle stage constituted a majority of the impacts for many of the impact categories evaluated. For paste solder, nearly all of the use/application energy consumption occurs during the reflow soldering process. The power consumed during the reflow application process was based on primary data collected from two facilities where test runs were conducted. The two ovens in which these tests were performed represent different technologies with different thermal efficiencies resulting in a large range in energy consumption rates. For the baseline analysis, an average energy consumption value from these two test runs was used in the determination of the life-cycle impacts. The alternate analyses re-evaluate the impacts using both the high and low energy consumption values measured during the performance testing to determine the sensitivity of the baseline impact results to these variations. Only the impacts for the energy use impact category were re-evaluated. Other impacts categories would also be affected by the differences in power consumption, but are unlikely to be as sensitive given the dominance of the reflow process on energy use.

As shown in Figure ES-6, for all three scenarios (low energy, baseline, and high energy), SAC has the highest impacts, followed by SABC, SnPb, and finally BSA. When the low and high energy data points are used to generate life-cycle impact results for each type of solder paste, the magnitude of the impact scores change; however, the relative comparison among alloys remains the same. The analyses indicated that the contribution of the reflow energy to the energy use impact category remains substantial, even when the low energy value is used (from seventy-three to ninety percent, depending on the alloy).

Although only the energy use impact category was re-evaluated using the alternate data, it is not necessary to re-evaluate the other impact categories. None of the other categories had a higher percentage of their impacts attributable to the reflow energy consumption and are unlikely to be as affected by a change in the reflow data. Overall, this analyses suggests that the relative results between solders and the overall conclusions of the study are not too sensitive to the variations in the reflow energy data (assuming the range used in this sensitivity analyses represents a true or realistic range of the energy estimates for reflow applications process).

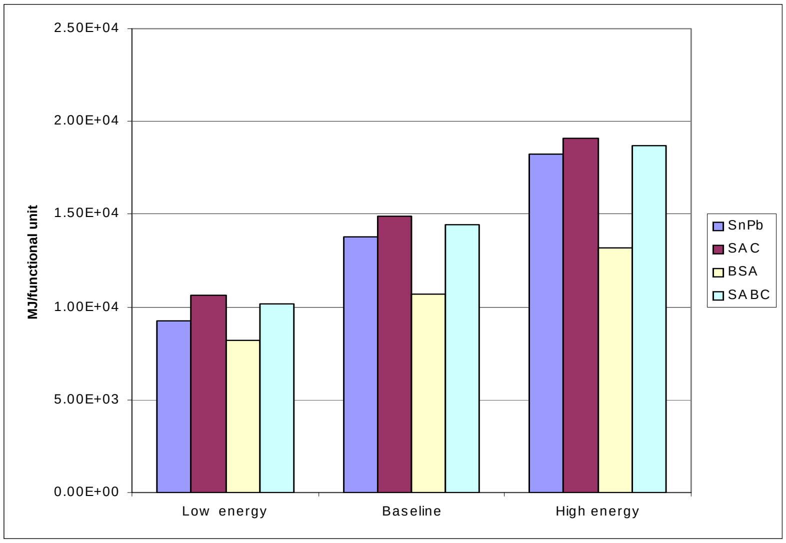

Figure ES-6. Sensitivity Analysis of Energy Consumption during Reflow Solder Application

Alternate Silver Inventory Analysis

Upstream silver production was the greatest contributing process group for many of the impact categories of the lead-free solder pastes in the baseline LCA. For example, silver production during the SAC life-cycle dominated six of the sixteen impact categories evaluated, and was a major contributor in several others. The production of silver also contributed significantly to the other silver-based lead-free alternatives, though to a lesser extent. Due to the large influence that silver production had on many of the impact categories, an alternate analysis was performed by substituting a DEAM silver data set for the GaBi silver mix data set used to calculate the baseline results.

The results of the alternate analysis are dramatic and can be readily observed in Tables ES-13 and ES-14, which compare the results of the alternate analysis to the baseline results for both paste and bar solders, respectively. For the paste solders, the DEAM silver data set resulted in a significant shift in the relative scores of the solders, increasing the number of categories in which SnPb has the highest impact score from six to fourteen impact categories. SAC on the other hand, while having many scores very close to SnPb, has the highest score in only one category. BSA remains the solder with the lowest relative impacts compared to the other solders. The overall shift in results is due to various flows in the DEAM silver inventory that have lower values than the associated flows in GaBi. Due to a lack of available documentation for the DEAM data, it is unclear what is causing the differences in the data sets. Some potential reasons could be different scoping boundaries of the inventories, different processes included, or different mines or processing plants represented.

Table ES-13. Comparison of paste solder baseline and alternate LCA analysis

Solder Alloy	Baseline		Alternate	
	Highest Score*	Lowest Score*	Highest Score*	Lowest Score*
SnPb	6	5	14	0
SAC	10	0	1	1
BSA	0	11	1	15
SABC	0	0	0	0

* Numbers indicate the number of impact categories where solder has the highest or lowest score.

Table ES-14. Comparison of bar solder baseline and alternate LCA analysis

Solder Alloy	Baseline		Alternate	
	Highest Score*	Lowest Score*	Highest Score*	Lowest Score*
SnPb	4	6	9	6
SAC	12	0	7	5
SnCu	0	10	0	5

* Numbers indicate the number of impact categories where solder has the highest or lowest score.

Likewise, the alternate analysis for bar solders results in an overall decrease in importance of the silver mining process. As shown in the table, the number of categories for which SnPb has the highest relative impact score rises from four to nine, while SAC decreases from twelve to only seven. This is not as dramatic a change as was seen with the paste results; however, several impact-specific conclusions were altered. Unlike the paste solders results, the solder with the lowest relative impact score for any category is split among the solders.

These results indicate the high sensitivity of the overall life-cycle results for paste solders to the silver data set. The baseline GaBi data set is believed to be of good quality and attempts to verify the DEAM data set were inconclusive. Thus, the GaBi data set was chosen for this analysis. These results show the possible variability and sensitivity of the results to the silver inventory data, and suggest that additional effort to further resolve the silver mining and extraction data would be well spent.

Alternate Leachate Analysis

The leachability study conducted for this project was used to estimate the outputs of metals from landfilling PWB waste or residual metals in ash. Lead was found to leach to a much greater extent than the other metals in the solders being analyzed in this study. These leachability results contributed to the large public non-cancer and aquatic ecotoxicity impacts for the SnPb as compared to the other alloys for both the paste and the bar solder results (see Sections 3.2.12 and 3.2.13). The toxic characteristic leachate procedure (TCLP) leachability study is based on a standard EPA TCLP test protocol using acetic acid, a substance known to readily leach lead. It is unknown to what extent these test conditions represents actual landfill conditions, which can vary dramatically over the lifetime of a landfill. As a result, the alternate analysis was conducted using the detection limit of lead during the testing as a lower bound to determine the sensitivity of the results to the lead leachability.

Results of the analysis indicated that even with the assumption that the lead essentially does not leach (i.e., assuming the study detection limit for the leachability of lead), the SnPb alloy impact scores are still at least 2.5 times higher than the score of the next closest alloy for public non-cancer impacts, and a full order of magnitude higher for aquatic ecotoxicity. The relative differences between SnPb and the lead-free alloys are far less than in the baseline analysis. This analysis suggests that any elevation of the leachability data for SnPb due to the aggressive nature of acetic acid towards the lead-based solder was unlikely to have changed the overall impacts for SnPb relative to the other solders. The SnPb alloy would still have the higher potential impacts for both public non-cancer and aquatic ecotoxicity than the other solder alloys, based primarily on its relative toxicity.

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